A novel surface profile measurement system

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A Novel Surface Profile Measurement System

by

Nashtara Islam

A doctoral thesis submitted in partial fulfillment of the requirements for the award of Doctor of Philosophy degree of Loughborough University

May 2009

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ABSTRACT
Surfaces are commonly formed in woodworking by planing and molding timber. Due to the nature of machining, these operations inevitably leave cutter marks on the surface of machined artifacts. These marks, though unavoidable, need to be monitored, measured and controlled to obtain the required surface finish.

This research work presented here is an investigation on the use of commercially available devices to realize a highly cost-effective surface profile measurement system geared towards measuring non-ideal surfaces, e.g., timber. It looks into the development of a novel low-cost surface profile measurement system using off-the-shelf devices – an optical mouse sensor, acting as an encoder and a Digital Video Disc (DVD) reader, providing the vertical profile information.

The developed profile measurement system has been used to measure both machined nylon and timber samples and compared with benchmark traces from a commercial profilometer.

From the comparison of results between the Talysurf and the DVD profiler, it can be seen that the sensor works best on white nylon samples, achieving around 90% correlation with the benchmark. Its performance is satisfactory while measuring timber samples, with correlation of 80% in some areas of the sample, while less in others.

However, the correlation between the traces provided by the developed system and the Talysurf is only about 20% for a black nylon sample, which can be attributed to the sample's high light absorbing nature. In all cases, the FFT and mean feature spacing value $R_{sm}$ analysis on the DVD profile traces shows good agreement with the benchmarks.

The promise shown here by the reported results, points towards the development of a reliable, light-weight and low-cost surface profile measurement system, which can be widely employed in woodworking or other similar industries.
Keywords: Surface profile measurement, mechanical stylus, non-contact optical methods, optical mouse sensor, DVD reader, auto-focusing mechanism, robust PID control, Talysurf, FFT, correlation coefficient.
Dedicated to my parents – Khaleda and Nazrul Islam
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NOMENCLATURE

\( R_a \) Average roughness \( \mu m \)
\( R_q \) Root mean square roughness \( \mu m \)
\( R_{sm} \) Mean spacing mm
\( \lambda_c \) Long-wavelength roughness cut-off mm
\( \lambda \) Wavelength of different sinusoidal profiles mm
\( H \) Cutter-mark wave mm
\( NA \) Numerical Aperture -
\( FES \) Focus Error Signal V
\( V_{\text{max}} \) Maximum speed of measurement m/s
\( V_f \) Feed speed m/s
\( p \) Wave pitch mm
\( f_s \) Sampling frequency Hz
\( \Delta x \) Resolution \( \mu m \)
\( u \) Control variable -
\( \varepsilon \) Error signal -
\( N \) Reaction rate %/min
\( \Delta C_p \) Variable change %
\( K_{cr} \) Critical gain -
\( T_{cr} \) Critical period min
\( T_i \) Integral time min
\( T_d \) Differential time min
\( I \) Performance integral -
\( T(s) \) Closed loop transfer function -
\( G_c(s) \) Controller transfer function -

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Introduction

1.1. Introduction

This chapter introduces the background of the research work presented in this thesis. It sheds light on the importance of surface profile measurement system in woodworking in mainly maintaining quality of surface finish as well as optimizing the process of planing. A non-contact surface profile measurement system has been proposed to be used in woodworking along with an introduction to two possible applications of the system. An overview of the thesis chapters follows, to draw this introductory chapter to an end.

1.2. Research Background

*When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it or express it in numbers, your knowledge is of a meager and unsatisfactory kind.*

Lord Kelvin (1824 – 1907)

A wide range of machining operations is performed to process materials in various manufacturing industries. These operations generate a variety of surface shapes on the product. Thus, profile measurement systems have been widely used in various process industries for the purpose of surface profile measurement of finished goods (e.g. timber products) to ensure a minimum level of surface finish quality (Cutri et al, 1991).
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In addition to that, surface profiling technique has been successfully employed to detect defects in tools (Jurkovic et al, 2005) and in condition monitoring of process machineries (Notini et al, 2003a).

A great deal of research is being conducted to develop systems to evaluate a number of engineered surfaces e.g., timber (Rovati et al, 2004), CNC turned metals (Jurkovic et al, 2005), optical lenses (Ehrmann et al, 1998), turbine blade assembly (Bradley 2000) and so on.

One of the most common and primitive method of surface quality or defect detection is the visual inspection approach (Sandak and Tanaka 2003). In many industries this method to this day remains a valid procedure for surface inspection. This is a very subjective way of looking into product finishes and in most cases fail to ensure a minimum standard of end product finish.

To overcome the limitations imposed by visual inspection, a host of contact and non-contact accurate measurement techniques have emerged over the years (Jolic et al, 1994).

Despite advances in other technologies, mechanical stylus based contact measurement remains the most widely used surface measurement system.

A detailed literature review has revealed that, substantial amount of research has been conducted towards developing systems for the measurement of surfaces for various purposes. Despite that, there are still opportunities for novel contributions in this area.

This research work mainly concentrates on the use of non-contact measurement sensors to create a novel surface profile measurement system, to be mainly used in wood machining industry.
1.3. **Motivation behind the Research**

Surface profile measurement is an important issue for various process and manufacturing industries. As Cutri et al (1991) have rightly pointed out; quality of the end commodity will always remain one of the highest production constraints. Thus to ensure this quality, a competent inspection system is an absolute necessity.

According to Parkin and Jackson (1996), most of the engineering surface forming and inspections systems employed in relevant industries are for metals. Their view is also echoed in a research work published much later by Gordon and Hillery (2003). A common biasness towards metalworking can be easily observed in various research literatures. A perception common within the research community and industry is that, any process or the subsequent quality inspection valid in metal works is equally adoptable in processes involving wood or other similar materials. This has proven to be incorrect and the need for inspection instruments for wood is now overdue.

Most of the non-contact devices currently in use to measure surface profiles are too expensive, lack the measurement speed and fragile, making them only suitable for laboratory applications (Sandak and Tanaka 2005).

The above points can be simply illustrated by the research carried out by Kiran et al (1998). They have employed a vision-based surface profile measurement system, which is depicted in Figure 1-1.

![Proposed surface vision-based surface profile measurement system by Kiran et al (1998)](image)

*Figure 1-1 Proposed surface vision-based surface profile measurement system by Kiran et al (1998)*
Although the setup above looks quite straightforward, it is quite difficult to implement in a practical machining environment. Among other factors, total cost of the camera, data acquisition card and software is prohibitive. There are also issues such as the incidence angle of light, positioning of the camera etc involved in the measurement setup. An extensive and complex image processing software algorithm is also required for carrying out the profile measurement. The whole setup is bulky and occupies a large area to set up.

The motivation for this particular research work has thus been derived from the above scenario, which is a familiar one, especially in woodworking. It is perceived that a novel optical sensor can be researched into, which will be able to detect the required surface characteristics and also be able to replace or complement the current sensors in operation.

1.4. Proposed Surface Profile Measurement Scheme

The proposed surface profile measurement scheme involves the use of an optical DVD reader HOP-1000 from Hitachi Semiconductor and an optical mouse sensor (ADNS-2051) from Agilent Technologies.

The DVD reader is to track the vertical variation in surface height, whereas the optical mouse sensor will provide the exact location of the sensor on the surface under test. Thus, this will act as a non-contact precision encoder. The measurement scheme is further illustrated in Figure 1-2.
There are some distinct advantages of the proposed method. One of the important attributes is the smaller footprint of this sensor in comparison to the ones currently being used. Thus integration of this monitoring system to an existing setup will be much easier.

The signal processing and data acquisition hardware is quite simple in nature and can be built by commercially available components. Some of the current measurement systems like computer vision require significant computing power (Lanzetta 2001). As the proposed technique’s computing requirements are low, this could lead to great deal of cost saving and thus can be cost-effective solution to the surface measurement needs.

In all of the similar research carried out with a laser based probe to measure surface profile, the displacement information was obtained by the use of ultra-precision stage. This adds considerably to the cost of the sensor system and is not feasible for an industry oriented metrology solution. Therefore, an equally effective but cheaper solution to the linear encoding solution is needed. The proposed optical mouse sensor based non-contact encoder provides this desired solution.

Data acquisition systems employed in previous researches have been mostly PC-based. Although, this adds to the flexibility and ease of developing the profile measurement system, the whole system becomes bulky and expensive. Therefore, a new embedded
data acquisition and processing system has been demonstrated in this research to make the footprint of the developed sensor smaller than any other system currently being researched upon. This also leads to significant cost saving as discussed in latter part of the thesis. Figure 1-3 shows the basic block diagram of the proposed system.

![Figure 1-3 Proposed block diagram of surface profile measurement system](image)

1.5. **Research Scope**

The proposed novel sensor to perform surface profile measurement of timber can be developed into two different systems. Depending on the speed of measurement and other criterion, the following implementation of the system is proposed.

1.5.1. **In-process Measurement System**

One of the major applications of the surface profile measurement system can be foreseen as an integrated sensor within a high-speed woodworking machine to provide near real-time surface measurement data.
The idea of in-process measurement system is given in Figure 1-4. The cutter head of the wood planer can be seen to create waviness on the surface of the machined timber. This needs to be controlled to a certain level of precision to provide a suitable surface finish. Thus, the proposed measurement system can do the post-process inspection to provide the machine controller with data that can in turn be used to change the machine parameters for achieving the desired surface finish. This would enable the realization of an autonomous woodworking machine.

However, the implementation of the sensing system in an in-process manner needs to take into account the speed at which both the optical reader and the linear encoder are capable of carrying out the required measurements. From the data sheet of the optical mouse sensor, it is apparent that the maximum speed at which the sensor is capable of measurement is limited to 12 inch/sec, which equates to 0.3048 m/sec (Agilent 1999).

According to Jackson et al (2002), the work piece feed speed in woodworking industry is in the region of 5 to 120 m/min, equaling to 0.0833 m/s to 2 m/s. While the optical mouse sensor is capable of carrying out the measurements in the lower region of industrial feed rate, it will clearly struggle around the upper limits. Thus, its suitability is limited in real wood machining scenario.
Despite somewhat limiting aspect of the probe with in-process measurement schemes, the system can be successfully employed in measurement systems where the speed requirement is slower than the one just mentioned above.

1.5.2. Hand-held Measurement Device

As pointed out in the previous section, the speed requirement for surface profile measurement of machined timber is somewhat prohibitive for the sensor proposed in this research. However, the system can be used in measurement schemes with lower speed requirements.

The optical mouse reader and mouse sensor assembly can be integrated into a stand-alone hand-held surface scanning device. This would enable the operator to quickly determine the surface roughness parameter of the piece of timber under inspection. This system could be invaluable as an inexpensive post-process quality monitoring system.

![Figure 1-5 Hand-held implementation of the surface profile measurement system](image)

The above figure (Figure 1-5) depicts the hand-held measurement scheme. This method is not affected by the speed limitation of the mouse sensor. Nevertheless, other practical problem such as vibration contributes to the error in measurement. The system design in the following chapter of this thesis deals with the ways of compensating for this shortcoming.
### 1.6. Summary of Research Contribution and Further Work

<table>
<thead>
<tr>
<th>Past Research</th>
<th>Current Research</th>
<th>Future Work</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal conditioning</strong></td>
<td>Integrated components — low noise and high repeatability</td>
<td>More integration of components with automatic gain control to reduce footprint</td>
</tr>
<tr>
<td>Sensors only calibrated for ideal surfaces, e.g., CD, mirror, metals etc</td>
<td>Sensors calibrated for various non-ideal surfaces, e.g., timber, nylon etc</td>
<td>Calibration of sensors for other species of wood and other materials, e.g., transport belt</td>
</tr>
<tr>
<td>Expensive precision stage used to obtain displacement information</td>
<td>Low-cost optical mouse encoder developed to eliminate precision stage</td>
<td>Use of Laser mouse sensor to increase the speed and resolution of measurement</td>
</tr>
<tr>
<td>Simple PID controller for focusing the probe</td>
<td>Robust PID controller for fast and accurate focusing action</td>
<td>Adaptive control technique to accommodate uncertainty in measured surface profile</td>
</tr>
<tr>
<td>PC-based expensive data acquisition and controller cards</td>
<td>Low-cost embedded microcontroller based system</td>
<td>DSP based controller for faster data acquisition and control, increasing system bandwidth</td>
</tr>
<tr>
<td>No measure of surface characterization data</td>
<td>FFT and $R_m$ values along with correlation coefficient</td>
<td>Wavelet analysis and determination of more parameters, e.g., $R_m$, $R_h$ etc.</td>
</tr>
</tbody>
</table>

**Figure 1-6** A summary of the past, present and future work on the DVD reader based profile measurement system
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The diagram presented in Figure 1-6 summarizes the research carried out in the past, contribution of the author within the current scope of this research and future work that needs to be carried out to realize a fully-fledged surface profile measurement system.

It can be seen from the diagram that, the research work presented in this thesis adds to the work done by previous researchers in the areas of signal conditioning, focusing control of the probe, surface characterization and so on.

1.7. Thesis Overview

The research project was mainly divided into five phases. These are –

- Literature review
- Sensor selection and evaluation
- Calibration tests
- Integration of the sub-systems
- Benchmarking of the system

The thesis consists of nine chapters with the following organization.

Chapter 1: this chapter mostly consists of the background and introduction for the research work. An explanation for the requirements of a cost-effective sensor system for surface profile measurement in wood machining industry has been given. The motivation behind the research has also been reviewed.

Chapter 2: contains the background of wood machining and surface quality determination. This chapter also introduces the concept of smart machining with the help of active vibration control. This lays down the foundation for the chapter containing integration of the profile measurement system in a small-scale woodworking planer.

Chapter 3: contains the complete proposal for the optical surface profile measurement system. A review of the currently employed methods and their disadvantages are
discussed in certain detail. A comparison with these is then drawn up to indicate the suitability and advantages of the proposed system.

Chapter 4: introduces the requirements that need to be addressed for the surface profile measurement system in woodworking environment. This chapter explores both the in-process and hand-held device requirements.

Chapter 5: contains detailed sub-system design and validation tests. Both the DVD optical head and optical mouse sensor has been discussed in this chapter.

Chapter 6: discusses the design, implementation and performance analysis of a robust PID controller to effectively control the auto-focusing mechanism of the profile measurement probe.

Chapter 7: discusses the integration of the two sub-systems both from the hardware and software point of view. Various software issues and performance analysis of the system have also been presented.

Chapter 8: documents the results from measurements carried out by the commercial 3-D profiler, the Talysurf. These results are then compared with the ones obtained from the DVD profiler. Analysis and discussion on various aspects of the developed system including its performance and limitations have been included in the chapter.

Chapter 9: concludes the thesis with discussion on further work that can be carried out on the proposed research.

Appendices: several appendices follow the main content.
1.8. **Summary**

- Surface profile measurement systems play an important role to ascertain quality of surface finish in woodworking industry.

- There is need for a cost-effective system capable of carrying out non-contact profile measurement in wood machining environment.

- The proposed system can carry out the required measurements in a non-contact manner to meet the current industry demands.

- Although, the speed requirement for in-process measurement might be prohibitive, a slower speed hand-held device can be developed.

- The proposed system offers cost-effective measurement solution, with a smaller foot print coupled with simpler data processing method.
2.1. Introduction

This chapter discusses the various aspects of wood machining with particular focus on planing. The proposed surface profile measurement system is being designed to provide surface finish information after the planing operation. Thus, this chapter effectively introduces the theories behind this machining operation for better understanding of the measurement parameters. Some quantitative analysis of surface parameters has also been included to provide background on the measured quantities.

2.2. Wood Machining Processes

Wood machining is an essential part of the furniture and wooden product manufacturing industry. This speeds up the whole process as well as maintaining the quality of product finish (Palmqvist et al, 2003). Machining of wood consists of various processes such as sawing, rough planing, planing, molding, sanding and so on.
Among all these, two widely employed processes in wood machining industry are planing and molding (Jackson and Parkin 1996). In order to carry out these operations, rotary machining processes are used in woodworking (Taşcioğlu and Jackson 2006). A conventional planing and molding machine has been depicted in Figure 2-1.

![Figure 2-1 Conventional planing and molding machine (Taşcioğlu and Jackson 2006)](image)

Rough sawn pieces of timber of rectangular constant nominal cross-section along the length are used as the raw material for the planing and molding machines (Jackson et al., 2002). The end sections have dimensions typically ranging from 10 to 100 mm thick and from 20 to 300 mm wide. The length of the work piece can be in the range of 250 mm to 6m. The feed rate of the work piece is in the range of 5 to 120 m/min (Jackson et al., 2002).

Timber lengths are usually fed to the machine by hands and the feed is taken up by powered rollers. They are tired with a soft material to avoid damaging the surface of the product (Brown and Parkin 1999). Machining is then carried out by the knives mounted on the cutter blocks.
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During the process of planing, the cutter heads contain straight cutters on all the four faces. On the other hand, during the molding operation, one or more surfaces of the section are produced by cutter heads containing suitable shaped cutters (Jackson et al., 2002).

Sanding is also an important part of the wood process industry. It is employed after the planing operation to get rid of surface finish irregularities and smoothing the surface (Taylor et al., 1999). Thus, this ensures that the finished product meets the aesthetic requirement of the customers.

In order to carry out these machining operations, rotary machining technique has been used in industry for over two centuries (Elmas et al., 2007). It is a very well established fact that the rotary machining operation is able to provide the woodworking industry with the required surface finish of products coupled with the desired speed, lower labor cost and thus, cost-effectiveness. In the current ultra competitive business environment these are the required attributes for a manufacturing establishment to survive and prosper.

Since, the surface profile measurement system proposed in this thesis mainly deals with post-planing wooden surfaces, the background on rotary machining applied to surface planing will be discussed in this chapter.

2.3. Rotary Machining Process

The rotary wood machining process is similar in nature to the up-cut milling of metals (Paimqvist and Gustafsson 1999). The reason behind preferring up-milling operation to down-milling in woodworking is mainly due to safety considerations (Jackson et al., 2007). The principle of the operations is given in Figure 2-2.
Although, the milling operation is similar to the one of metal working, there are some significant differences between the two processes. The primary one is the cutting speed. While cutting speed for metal lies in the region of 0.5 to 1.5 m/s, the wood machining speed is in the region of 30 to 80 m/s. Also, the feed speed of the woodworking process is higher, at around 0.08 to 1.6 m/s (Brown and Parkin 1999).

Due to the nature of the machining process, planed and molded surfaces appear to have a series of waves whose peaks are perpendicular to the passage of the product through the machine (Brown and Parkin 1999). The shape of the cutter mark left by rotary machining process is depicted in Figure 2-3.

The relationship between the cutter mark or surface wave (p), work piece feed speed (Vf), cutter head speed (Vc) and the number of finishing knives (N) can be expressed as:
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\[ p = \frac{V_f}{V_c \cdot N} \]  

(2.1)

And, the waviness height (h) of the machined surface can be given as:

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

(2.2)

According to Jackson et al (2002), the kinematics of the rotary machining process is curvate trochoid. However, for simplicity in measurement and calculation, the surface waves are treated as circular and visualized in by a series of intersecting circular arcs (Figure 2-4).

![Figure 2-4 Circular arc concept in timber machining (Jackson et al, 2002)](image)

A good quality machined surface has a typical wave pitch of lower than 1.5 mm, whereas a lower quality surface more than 2.5 mm. The wave height of a high quality surface is lower than 20 μm.

In order to assess the surface finish of machined timber, the wave width variation is generally taken into account. This is due to ease of measuring this parameter with the help of vernier calipers. The wave height variation is quite difficult to measure as an instrument better than 1 μm resolution is required. Furthermore, the wood processing industry uses wave width variation as a measure of surface quality (Jackson et al, 2002).
Two commonly used techniques of surface finish are presented in the following subsections.

### 2.3.1. Single Knife Finish

In Single knife finish condition, the generated timber surface wave form is determined by the cutter with the largest radius in the cutter head (Elmas et al., 2007). This condition results from the insufficient precision of the cutting knives due to the tolerance of the cutter sharpening machine and also the relocation inaccuracies between grinding machine and planing machine spindles.

The term “total indicated run-out” (TIR) is widely used in wood machining domain and is basically defined as the difference between the cutting knife with the largest radius and the cutting knife with the shortest radius. Typical manual setting of cutters with tool room equipments results in a TIR of 50 μm. The TIR value can be reduced to in the range of 5 to 10 μm with the help of grinding the cutters in the cutter head. Further improvement to the TIR between the grinding machine and planing machine can be achieved by using high-precision spindles on both machines along with the use of ‘Hydrogrip’ tooling cutter heads.

Even with the introduction of small values of TIR (e.g. 5 μm), in a two-knife cutter head, the cutter with the smaller cutting radius will remove timber chips from the bulk of the material but will not produce a surface wave. Therefore, in order to achieve satisfactory surface finish in a two-knife condition, a TIR of less than 1 μm is required. This is impossible to achieve technically at an economic price (Jackson et al., 2002).

This phenomenon also applies to three-, four-, six-, eight-, ten- and 20-knife cutter heads. But as the cutting edges increases, it will create surface waviness, although at irregular pitch and height. The more commonly used cutter head configuration of four- and six-knives also produces single-knife finish condition.

The main problem associated with the single-knife finish is the inability to carry out satisfactory wood surface finish at higher feed speeds. This severely counters the economics of timber processing, which requires the feed speed to be as high as possible
to obtain reasonable payback of capital plant on a relatively low added value work piece.

Advantages of single-knife finish lies in the absence of jointing equipments in the process and the use of smaller diameter tooling. This results in quick set-up, reduced job changeover times and tool servicing costs.

### 2.3.2. Multi-knife Finish

The increase of timber feed speed to obtain a satisfactory scale of economics within woodworking industry is possible with the help of the technique termed as Multi-knife finish. A process known as ‘jointing’ is applied to the rotating cutter head in order to reduce all the cutting edges to the same cutting radius. This is a similar process to that of dressing of a grinding wheel at the operating speed to true the wheel at the cutting point.

The jointing operation is shown below in Figure 2-5. Jointing produces a ‘land’ on the cutting edge, which removes any back clearance angle on the cutter. The jointing stone also touches all the cutters. This ensures that all the cutting edges are dressed to a common cutting radius. If there is a difference in the radius of individual cutters, the cutter with larger radius value will remove more material from the work piece than others. The land width of these cutters will be correspondingly larger.

The early types of equipment had typical cutter tracking error of 75 μm and this led to unacceptable differences in joint land width between cutters, resulting in increased cutting force and waviness quality.
As discussed in single-knife finish sub-section, introduction of Hydrogrip tooling also contributed significantly to reduce the variation in land width between adjacent cutters to an acceptable level. This has resulted in improvements in surface finish within the woodworking industry using multi-knife finish.

The larger cutter heads used in this technique are more difficult to handle manually, more difficult to service and the time required to set-up the machine is significantly longer. Thus, multi-knife finish technique is suitable only for establishments using longer production runs and is required to produce medium to high quality surface finish.

### 2.3.3. Fixed-knife Finish

Apart from the above techniques, another technique termed fixed-knife finish is being used in wood machining industry to carry out wood surface forming. It has been shown that, fixed knife planing produces excellent surface finish and demonstrates none of the defects present in rotary machining process (Brown et al, 2002). The schematic of the fix knife planing machine has been shown in Figure 2-6.
However, this method requires very high feed forces to draw the work piece across the stationary knife and the toothed wheels used to feed the work piece can also mark the product. And, this method is unsuitable for molding altogether as only a small amount of material can be removed from the work piece. Therefore, despite the high quality of surface finish, it is not a practical method of machining timber.

As discussed in the previous section, widespread use of rotary machining processes has contributed to improvements in surface finish in woodworking industry. However, it also comes with drawbacks. The cutter marks produced due to the machining process in unavoidable and is generally considered as acceptable within the wood machining industry. However, sanding operation is applied afterwards to generate products of acceptable standard (Brown and Parkin 1999).

To overcome this shortcoming imposed by rotary machining process, a novel technique of cutter block motion has been put forward by Jackson and investigated at research level by Brown (Jackson et al, 2002).

The following section deals with this novel technique, its application and implication within wood machining industry.
2.4. Overview of Mechatronic Approach in Wood Machining

A modification of the rotary machining process has been proposed, simulated and demonstrated by Brown and Parkin (1999) and Brown et al (2002). This enables improvement in the surface finish in comparison to the conventional machining techniques. Further improvements to this novel technique have been provided in a later research published by Hynek et al (2004).

The idea behind this novel technique is to oscillate the cutter head in the horizontal plane by an amplitude that is of the order of one wave pitch at a frequency of the finishing cutter period. This approach has been proven to reduce the wave height in the region of 75 percent over conventional machining. This mechatronic approach provides a virtual cutter head radius far greater than the actual radius. This typically tends to be four times than the actual cutter head radius. This technique also enables the two-knife cutter head to perform at much higher feed speeds and produces a surface form far superior to a 20-knife cutter head.

The proposed methodology of the cutter block oscillation is, when each knife makes contact with the wood surface, the cutter is advanced in a horizontal plane in order to produce trough-like cutter mark instead of the conventional scallop-shaped mark (Figure 2-7). This is followed by the rapid retraction of cutter head prior to the next knife contacting the work piece. This results in a reduction in cutter wave height to an extent that the finished surface bears no visible cutter marks to the naked eye.

![Lateral Cutter Motion](image)

Figure 2-7 Overview of cutter motion during cutter advance (Hynek et al, 2004)
Another mechatronic approach to reduce the waviness height during the planing operation has been proposed and demonstrated by Hynek et al. (2004). This particular technique uses the idea of oscillating the cutter head vertically (Figure 2-8). In this proposed technique, when a knife is at the start of the cutting path, the cutter head moves upwards and reaches its point of maximum displacement when the line connecting the knife tip and cutter head center is perpendicular to the machined surface. After this point the cutter head moves downwards. The limitation with this technique is that, it is only valid when the knives are straight and cannot be used with helical knives.

![Figure 2-8 Vertical cutter head movement (Hynek et al., 2004)](image)

The vertical movement of the cutter head must take place within a very narrow time window ($\Delta t_k$) of approximately 18 to 50 $\mu$s (Hynek et al., 2004). This time frame is calculated using typical machining parameters of cutting speed, feed speed and length of cutter mark. Since the time window is very small, this approach is only suitable for lower cutting speeds. The time window can be expressed as:

$$\Delta t_k = \frac{p}{v_c + v_f}$$  \hspace{1cm} (2.3)

where, $p$ is the cutter mark length, $v_c$ is the cutting speed and $v_f$ is the feed speed.

Vertical cutter head movement reduces the waviness height roughly by its magnitude $y_v$ within the aforesaid time window. The reduced surface waviness can be expressed as follows:
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\[ h_k = R - \sqrt{R^2 - \frac{(p-x_k)^2}{4}} - y_v \]  

(2.4)

Where, \( h_k \) is the reduced waviness height, \( p \) is the length of the cutter mark, \( x_k \) is the distance traveled by the cutter head for the time that the knife tip needs to travel the distance of the cutter mark, \( R \) is the cutter head radius and \( y_v \) is the magnitude of the vertical movement within the time window.

2.5. Surface Quality Determination

The previous sections provided insight into surface forming operations employed in typical wood machining environments. Apart from the conventional techniques, principles behind a mechatronic approach in woodworking are also introduced. The following sub-sections deal with various aspect of surface finish and the parameters involved in carrying out the surface profile measurement.

A surface can be defined as the boundary between one material and another (Dagnall 1980). For engineering applications, one of the boundaries is inevitably air. Due to various manufacturing processes and finishes, surface texture can be complex. But the terms roughness, waviness and form are well-defined and deemed important to describe a particular surface. A schematic representation of these terms is given in Figure 2-9.

Figure 2-9 Roughness and waviness in a surface (Raja et al, 2002)
Roughness can be defined as the irregularities which are inherent in the production process, left by the actual machining agent (e.g. cutting tool, grit spark etc.).

Waviness is the component of the texture upon which roughness is superimposed. It may result from such factors as machine or work deflections, vibrations, chatter, various causes of strain in the material, and extraneous influences.

Form is said to be the general shape of the surface, neglecting variations due to roughness and waviness.

### 2.5.1. Need for surface finish determination

It is quite obvious from aesthetic and commercial point of view that, the surface of finished timber products must be free from machining marks visible to the naked eyes. To ensure this high quality and consistency in surface finish, there is a need for surface profile measurements.

Not only addressing the aesthetic aspect of the machined piece, surface quality can also contribute to the way machining is carried out. According to Cutri et al (1991), the planing and molding operations generate a variety of surface shapes on the product, which are dependant on the machine operating conditions. Therefore, the monitoring of surface profile is important to ensure economic running of the process machineries as well as to optimize the process parameters through the adjustments of machine operating conditions.

As depicted in figure 2.9, the flaw in the machined piece can be detected with the help of a finish quality monitoring system. Not only that, the roughness and waviness parameters can also be observed through a proper measurement system. These usually results from faults in cutter heads or improper setting of cut depth and so on. Excessive vibration within the machine can also result in surface defect (Elmas et al, 2007).

Therefore, if the surface defect, roughness, waviness errors can be detected, the machining parameters can be set up accordingly to avoid the defects from occurring. This would inevitably save a lot of man and machine-hour and more importantly
prevent the industry from producing huge quantity of unwanted machined timber. With strict environmental and legal obligations attached with management of industrial wastage, an efficient surface quality monitoring system is a necessity within the woodworking industry.

2.5.2. Quantitative vs. qualitative methods

Since the inception of rotary machining techniques, inspection of machined surface has been an integral part of the industry. As pointed out in the previous sub-section, a competent surface finish monitoring system is required both to address the aesthetic aspect of wood machining as well as optimization of the process. These issues can have huge commercial and environmental impact on the woodworking industry.

Despite the importance of a surface profile measurement system in wood machining industry, even up until now, human inspection has been the most popular method in determining the surface finish quality (Sandak and Tanaka 2003). This method is unacceptable due to the facts that such classification is subjective, depends on personnel knowledge and experience and is influenced by worker’s fatigue.

Hence, quantitative measurement systems and parameters needs to be developed, which can on one hand provide automated inspection system and on the other hand be free from the drawbacks experienced by humans. However, almost no or very little quantitative techniques have been implemented within the industry to carry out finish quality assessment. This research work in essence tries to quantitatively define the surface finish characteristics in wood machining and the way of obtaining them.

The quantitative parameters commonly used in metrology to describe surfaces are discussed in the next sub-section.

2.5.3. Quantitative parameters used in measurements

As discussed above, various definitions have been developed to describe the surface form, which are all qualitative. The universal method of quantifying one feature of
surface texture is the Roughness Average (Ra). It is the average value of the departure of profile from the center line, throughout the sampling length.

![Diagram of a surface line measured from mean line](Jolic et al., 1994)

In the above measurement diagram (figure 2.10), mean line is defined by:

\[ \int_{x=0}^{a} f(x) dx = 0 \] (2.5)

The average roughness is defined as:

\[ R_a = \frac{1}{a} \int_{x=0}^{a} |f(x)| dx \] (2.6)

Another method of calculating the roughness is the Root Mean Square value (Rq). It is defined as:

\[ R_q = \left[ \frac{1}{a} \int_{x=0}^{a} f^2(x) dx \right]^{\frac{1}{2}} \] (2.7)

The RMS measurement has the effect of giving extra weight to the higher values in comparison to the arithmetic average. Thus for statistical manipulation, this is preferred to the average roughness value. However, the measurement of this parameter proves to
be difficult due to the computations involved, as demonstrated in equation 2.7 (Whitehouse 1994).

The mean spacing of surface irregularities is a more suitable measure for evaluating timber surfaces formed by planing. This spacing parameter is given by $R_{sm}$ and can be defined as:

$$R_{sm} = \frac{1}{N} \sum_{i=1}^{N} X_{S_i}$$  \hspace{1cm} (2.8)

where, $N$ is the number of profile elements and $X_{S_i}$ is the width of the $i$-th profile element.

**2.5.4. Surface Filtering Techniques**

Most of the surface generated by machining processes comprises of a range of spatial wavelengths. Filtering techniques are commonly employed to separate different wavelength components into well-defined bandwidths (Raja et al, 2002). In most cases, filtering is done before numerical characterization. It also helps in extracting information needed to provide process feedback and establish functional correlation.

Basic filtering techniques include 2RC, Gaussian, Rk etc., while spline, robust spline, Gaussian regression, zero-order Gaussian regression, second-order Gaussian regression, robust Gaussian regression etc. are more sophisticated methods of surface filtering.

Some of the surface filtering techniques are discussed in general terms in the following sub-sections.

**2.5.4.1. 2RC Filter**

The analog 2RC filter has been the earliest one used in surface metrology. The high-pass 2RC filter can be realized digitally using the weighing function of equation 2.9:

$$S(x) = \frac{A}{\lambda_c} (2 - \frac{x}{\lambda_c}) \exp(-\frac{|x|}{\lambda_c})$$  \hspace{1cm} (2.9)
where, \( A = 3.64 \) for 75% transmission at the cutoff, \( x \) is the position from the origin of the weighing function \( (-\infty < x < 0) \) and \( \lambda_c \) is the long wavelength roughness cut-off. The mean line is obtained by convolving the profile with the weighing function in equation 2.9. The mean line is then subtracted from original profile to obtain the roughness profile. The transfer function of the 2RC high-pass filter is:

\[
\frac{\text{output}}{\text{input}} = (1 - ik\frac{\lambda}{\lambda_c})^{-2}
\]

(2.10)

where, \( i = \sqrt{-1} \) and \( k = \frac{1}{\sqrt{3}} = 0.577 \)

The major disadvantage with the 2RC filter is its nonlinear phase. The effect becomes severe as the cut-off increases. However, Whitehouse (1994) and others have put forward methods of rectifying this problem.

Also, in a 2RC filter, waviness cannot be obtained by simply subtracting the profile from roughness because the transmission at the cut-off is 75% (Raja et al, 2002). Therefore, a complimentary filter that transmits at the 75% cut-off is necessary to capture waviness.

A better alternative to the widely used 2RC filter has been developed to overcome the two primary drawbacks mentioned. This is called the Gaussian filter.

### 2.5.4.2. Gaussian Filter

The most widely used filter in surface metrology is the Gaussian filter (Hendarto et al, 2005). The weighing function and transmission characteristics of a Gaussian low-pass filter are given by:

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

(2.11)

\[
\frac{A_{\text{output}}}{A_{\text{input}}} = \exp(-\pi (\alpha \frac{\lambda_c}{\lambda})^2)
\]

(2.12)
\[ \alpha = \sqrt{\frac{\ln 2}{\pi}} = 0.4697 \]

where, \( x \) is the position from the origin of the weighing function, \( \lambda_c \) is the long wavelength roughness cut-off and \( \lambda \) is the wavelength of different sinusoidal profiles on the surface.

A major attribute of the Gaussian filter is its linear phase, which is an advantage over the 2RC filter. The filter is designed such that, the transmission is 50% at the cut-off. Thus, waviness can be obtained by simply subtracting the roughness from the raw profile. This is a significant improvement over the 2RC filter.

However, there are some disadvantages associated with this sort of filters. Edge effects prevent the use of the first and last cut-off and the filter performs poorly on profiles with deep valleys such as the ones found in plateau honed surfaces. An empirical filtering technique for dealing with such profiles was developed. This is termed as the Rk filter.

### 2.5.4.3. Rk Filter

It has been pointed out previously that the Gaussian filter doesn't perform well with profiles having deep valleys, which in turn means that the Gaussian filter is not robust enough against outliers. Thus, a two-step filtering technique has been proposed by ISO 13565 standards.

In the first step, the primary profile is filtered using a low-pass Gaussian filter. All the points in the primary profile that lie below the mean line are replaced by the mean line itself. Thus, all valleys are suppressed for the second stage. The modified profile is sent through the same low-pass Gaussian filter and the new mean line obtained becomes the final mean line. The primary profile is subtracted from this mean line to obtain the roughness profile. Artificial features are introduced into the roughness profile because the filter is not robust against outliers or valleys.

The roughness amplitude transfer function is given by:
\[
\frac{A_{\text{output}}}{A_{\text{input}}} = 1 - \left( \frac{\lambda}{\pi \alpha \lambda_c} \right)^2 \sin^2 \left( \frac{\pi \alpha \lambda_c}{\lambda} \right)
\]  
(2.13)

where, \( \lambda \) is the wavelength of the sine wave to be filtered, \( \alpha = 0.44294647 \) and \( \alpha \lambda_c = B/2 \).

Despite the improvements over the Gaussian filtering technique, Rk filters also suffer from robustness issues with very deep valleys.

Some of the basic surface filtering method has been discussed in this section. Some advanced and more specific filtering techniques suitable for timber surfaces will be covered in detail in later chapters.

It is worth mentioning here that, most of these surface parameters are measured with the help of mechanical stylus based measurement systems. These instruments are widely used in industries for measurement of various engineering surfaces. They have wider acceptability in metrological applications due to well-established standards. However, these instruments suffer from some serious setbacks (Jolic \textit{et al}, 1994).

The next chapter will deal in some detail with this and other measurement systems and their shortcomings in the context of measuring surface finish of machined timber.
2.6. **Summary**

- Various machining processes are employed within the woodworking industry to form timber surfaces.

- Due to the advantage in speed of machining and thus improved economies of scale, rotary machining techniques are widely employed in wood forming machines as opposed to fixed-knife ones. However, they produce cutter-marks due to the kinematics of the machines.

- Inspection of machined timber surface is necessary to maintain the product finish quality as well as to optimize the process to minimize wastage of raw materials.

- Human inspection is most popular but suffers from various drawbacks. Thus, an automated system needs to be developed for this purpose.

- Various quantitative parameters are used to describe surfaces. These are well-established and frequently used within manufacturing facilities.

- Surface filtering techniques are also required to separate different wavelengths of cutter-marks on the processed surface.
Chapter - 3.

Current Techniques for Surface Profile Measurement

3.1. Introduction

The previous chapter introduced the processes and machines used within wood machining industry to form timber surfaces. It also discussed various parameters involved with the measurement of surface finish. This chapter gives an insight into various surface profile measurement systems currently employed in industry to carry out the inspection of timber surfaces. The proposed method of profile measurement is introduced here and comparisons are made with its suitability and advantages when compared to conventional techniques. Working principles of the proposed sensors are also described in this chapter. The chapter rounds off by pointing out some of the previous applications of the sensors in various metrology applications.

3.2. Currently Employed Methods for Surface Profile Measurements

As discussed in the previous chapter, the most commonly used method of inspecting engineering surfaces (e.g., wood) in industries is to use human to carry out the required work (Sandak and Tanaka 2003). But this is becoming increasingly unacceptable due to the subjective nature of the inspection, and being heavily dependant on one’s personal skills and experience. This sort of measurement setup is also greatly affected by human fatigue. Thus there is a great need for cost-effective in-process surface roughness measurement system.
A range of surface profile measurement systems have been developed in the recent years to meet the demand for surface roughness or smoothness measurement in an automated environment. These purposes include but not limited to, real-time inspection of finished wooden products (Jackson et al, 2002), contact lens curvature measurement (Ehrmann et al, 1998), CNC cutting tool condition monitoring (Jurkovic et al, 2005), straightness monitoring of knife edge (Fan et al, 2003), edge profile measurement for die and mould model surfaces (Lee et al, 2002) and so on.

The measurement techniques can be divided into two main groups, the:

- contact and
- non-contact method

Contact methods are most commonly in the form of mechanical stylus-based profilometers (Kiran et al, 1998). Ultrasonic methods are also deemed to be contact methods in certain measurement scenario as discussed by Blessing et al. (1993). They can also be used in non-contacting orientation, which will be discussed in this section in certain detail.

Some of the research carried out has contributed to the use of hybrid approach as well. Lu et al, (2001) has designed and demonstrated such a system with successful integration of contact and non-contact sensors.

Apart from the contact and non-contact measurement methods, various indirect methods have been used in academia to determine the surface profile or condition of cutting tools. They include among others, accelerometer-based in-process surface roughness recognition (ISRR) system (Lou and Chen 1999), acoustic emission (AE) and power sensor based grinding monitoring system (Inasaki 1999), current sensor based intelligent estimation of feed cutting force and tool wear condition monitoring system (Li et al, 2000), DC motor current sensor based cutting tool condition monitoring system (Szecsi 1999). As these are beyond the scope of this research, detailed discussions have not been carried out in the literature review.
3.2.1. Contact-based Measurement Systems

The most common method of obtaining surface profile data is to pass a mechanical stylus probe across the surface and trace the movement of the probe to obtain surface profile information (Wong and Li 1999). This is essentially a contact method for obtaining the surface data. These measurements are usually carried out in the micrometer range for most industrial applications. However, techniques to use mechanical profilometers in finer nanometer range have been explored in publications by Garratt and Nettleton (1992), Whitehouse et al (1988) and in a more recent research by Groeger et al (2005). The nanometer range measurements have found applications in wide ranging fields of manufacturing laser optics, electro optic devices, semiconductors, computer memory devices etc. (Whitehouse et al, 1988).

According to Bennett (1992), Talysurf equipment manufactured by Rank Taylor and Hobson is one of the most common contact measurement instruments in use across the industry.

In this sub-section, two types of instruments will be discussed in detail. One is the above-mentioned mechanical stylus based profilometer and the other is the ultrasonic sensor. However, ultrasonic method can also be used as a non-contact instrument for surface roughness measurement. That technique will be dealt in the next sub-section of the thesis.

3.2.1.1. The Stylus Instrument

The schematic diagram in Figure 3-1 shows the conceptual idea and basic components of a mechanical stylus based surface profile measurement system. The stylus is traversed across the surface and the pick-up converts the movements into an electrical signal, which upon amplification, is used to operate a recorder. From the filtered signal, the $R_a$ value is derived, which is then displayed in an analog or digital meter.
In this system, the stylus is the only active contact between the surface under test and the instrumentation system. The stylus's shape and size affects the accuracy with which the stylus traces the surface profile. The following figure (Figure 3-2) shows the range of error due to the finite radius of the stylus.

The force with which the stylus scans the surface is also a consideration that needs to be addressed. If the loading is too great, then it will scratch or deform the surface. An
insufficient force on the stylus would mean that the stylus might lose contact with the surface under investigation and thus leading to erroneous results. The blunter the tip is, the more loading can be allowed to it as opposed to the finer ones.

The function of the pickup is to convert the minute vertical movements of the stylus into proportionate variations of an electrical signal (Dagnall 1980). The pick-up must be sensitive enough to respond to a movement of 0.01 \( \mu \text{m} \) or less. They are classified into two groups according to their principle of operation.

**Position-sensitive:** These give a signal proportional to the displacement, even when the stylus is not in motion. The output is thus independent of the speed of the stylus’s displacement. These pick-ups enable the true recording of the waviness and form. Examples of these pick-ups are the variable inductance and opto-electrical ones.

**Motion-sensitive:** An output from these pickups is obtained only when the stylus is in motion. The output is related to the speed at which the stylus is displaced and drops to zero when the pick-up is stationary. With this pick-up waviness and form variations are excluded from the profile. They are used in instruments without recording facilities. Piezo-electric and moving coil pick-ups fall into this category.

A transverse drive used in the instrument provides the movement of the stylus across the surface. The drive is constructed by means of electric motor and can accurately maintain a steady speed across the surface.

The work of the amplifier is to amplify the minute signal obtained from the pick-up and drive the \( R_a \) meter accordingly. For this purpose, low-noise variable gain amplifiers are generally used.

Finally the filtering unit is used in the system for the purpose of selecting the correct sampling length. This helps to suppress the waviness and form constituents of the profile, thus enabling the roughness to be more clearly seen. It also helps to reduce the effect of vibrations on the graph, without losing essential surface information.
3.2.1.2. Ultrasonic Measurement

Ultrasonic transducers are commonly used for non-destructive detection of internal flaws in materials and determination of the thickness of sheets and plates (Jolic et al., 1994). Well-known ultrasonic methods include pulse echo and standing wave resonance methods. For normal incidence and having the beam width of ultrasonic beam dimension less than surface feature dimensions, time-of-flight measurements yield meaningful profilometry data (Blessing et al., 1993).

The well-known methods include pulse-echo and standing wave resonance methods (Jolic et al., 2003). The basic construction of the surface profile measurement system using the pulse-echo method is given in Figure 3-3.

![Figure 3-3 Ultrasonic pulse-echo system for evaluating surface roughness (Blessing et al., 1993)](image)

Good acoustic coupling is required for the ultrasonic wave to travel efficiently from one medium to other. So, in order to ultrasonically measure the profile of a particular surface, the sample as well as the transducer must be immersed into a liquid bath or a thin layer of oil must be used between the two. Water jet can also be used within the transducer to achieve this coupling.
Thus, ultrasonic method is contact in nature and hence has been documented in this section of the report. Non-contact ultrasonic sensing is also possible and will be discussed in the later section.

From the discussion of contact methods for surface roughness measurement, it is apparent that this method suffers from some serious drawbacks. The main drawbacks of the stylus based measurement are slow measurement speed, inability to be able to integrate into in-process control, destructive nature of measurement, error in surface texture determination due to finite tip radius and so on. Hence, an alternative to this most popular measurement method is sought with great interest around the globe.

The ultrasonic method is suitable for a number of surface profile measurement e.g., checking bimetallic strips for lack of bonding between layers, maintenance checking for corrosion and checking the presence of slag in metal (Jolic et al., 1994). Due to the fact that ultrasonic sensors require good acoustic coupling and immersion of the sample in liquid is needed for that, most of the engineering surfaces apart from metals are beyond the scope of this measurement scheme.

So, the surface profile of timber is impossible to measure with ultrasonic transducers as these materials cannot be immersed in liquid without deforming them. Also, it is not possible to automate or integrate this instrument into an in-process measurement setup due to the aforesaid constraints. As a result, it is very much a laboratory oriented approach and unsuitable for most industrial applications.

### 3.2.2. Non-contact Measurement Techniques

The main focus of this research work is to develop a non-contact measurement system for the measurement of engineering surfaces, with particular interest on measurement of timber surfaces. Thus, the literature review goes into detailed coverage of the non-contact measurement techniques currently being investigated or already been in use in industries.

The non-contact methods can be classified into the following categories -
• Machine vision based surface measurement system. In most cases, Charge Coupled Device (CCD) cameras are being used. Both tool wear and surface texture determination has been carried out with the help of such systems. Hybrid vision systems have also been demonstrated in research carried out by Tian and Lu (2006).

• Fiber-optics based systems with Light Emitting Diodes (LED) are also being used for surface roughness measurement.

• Various Laser sensors have been investigated for the measurement of surface texture.

• Other optical devices, such as pickup of a DVD/CD player can also be used as a focusing probe for determination of surface profile.

• Ultrasonic systems are also investigated as an instrument to obtain the surface profile of various materials.

• Capacitance and pneumatic sensors have been explored for non-contact surface profile measurement. But they are not in general use and do not offer the same versatility (Yilbas and Hasmi 1999). So, these methods are not discussed in this thesis report.

3.2.2.1. Machine Vision Based Systems

A machine vision based tool condition monitoring system has been proposed by Jurkovic et al (2005). The system mainly consists of light source to illuminate the tool surface, CCD camera, a laser diode with linear projector, grabber for capturing images and a PC for image processing. The main advantage of this system is the ability to capture 3D images as opposed to only 2D ones measured with most such measurement system. The schematic idea of the system is shown below in Figure 3-4.
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The system has been mounted on a machine tool to obtain the tool condition data (Figure 3-5).

The shape, tangency and curvature of projected laser beam changes in the setup with the change in surface slope, while the turret head with a tool insert travels at a very slow feed rate. The wear images were recorded at different stages of the wear process. The Image Tool software was used to analyze the images and obtain the distribution as in Figure 3-6. For a particular type of wear, the grey values along with the mean and standard deviation gives an idea of the area under investigation. With the help of various software macros, a particular tool wear can be detected.

The authors have acknowledged the fact that, without the proper illumination adjustment, the measurement will not be valid and this is a serious obstacle in
automating the system. The other aspect of this particular system that is deemed to be a major drawback is the software system being used. The macros written have to be adjusted according to the measurement setup and the type of wear being measured. This also does not help when developing an automated tool condition monitoring system.

Chen and Duffle (1996) and Chen et al (1998) have researched into developing an Automated Surface Finishing System (ASFS), which inspects the machined metal surfaces in CNC machines. They have also developed a novel 3-D filtering technique to compliment the measurement system. A laser probe has been used for this system and not much detailed explanation has been given of the experimental setup. However, it is evident that this setup is only intended for metals and in particular to the ones formed with the help of CNC machines. Thus, its application is only limited to a certain industry.

A similar method has been proposed and tested by Zhao (1995). This system is also based on machine vision using CCD camera and an illumination source. The measurement system has been used in detecting the surface texture of wood. The Angular Second Moment (ASM), Contrast (CTR) and Correlation (CORR) of the grey-scale image were calculated. Based on the ASM, CTR and CORR the wood samples were classified into fine, coarse and rough wood by the help of a supervised learning based Artificial Neural Network (ANN).

This paper does not go into detail on the implementation of the system and the associated procedures of setting up the test rig. However, as the setup is exactly similar to the one used by Jurkovic et al (2005), the aforesaid drawbacks of illumination and complicated software manipulation hold true in the case of this technique as well.

Almost similar method of obtaining surface profile information of wooden panel has been discussed by Pham and Alcock (1998). The wooden samples were then classified with the help of an ANN to determine the type of defects present in them.

The surface roughness assessment approach adopted by Tsai et al (1998) is also based on using machine vision and the subsequent use of ANN to extract the features from the captured images. This technique was used to relate the $R_{\text{max}}$ values of milled and shaped
specimens to various feature patterns. The system is based on methods comparing various specimens which are used to train the ANN. Thus to obtain a fairly accurate surface roughness assessment, a large amount of training data must be made available and the neurons must be trained accordingly. This is essentially time consuming and performance of the system is completely dependant on the specimens and the training process.

Speckle is the random pattern of bright and dark regions that can be observed when a surface is illuminated with a highly or partially coherent light beam. It has been reported that the pattern formed is dependent on the roughness of the illuminated surface – a rough surface shows a small central bright region with gradually decreasing intensity towards the edge. A surface roughness quantifier estimation system has been proposed by Sodhi and Tiliouine (1996) using the speckle pattern observed by impinging a laser beam on the metal surface. This method of estimation has been applied in real time monitoring of surface grinding process. A similar method has been employed by Luk et al, (1989) to measure surface roughness based on the scattering effect of white light.

In contrast to the rough surface, a smooth surface will have a larger area of high average intensity at the center with a gradual decrease in the average intensity towards the edge. This change in the size of the illuminated area has been used by the authors as an estimate of the surface roughness by defining the parameter Optical Roughness Indicator (ORI).

\[
\text{Optical Roughness Parameter (ORI)} = \frac{1}{I_{\text{sat}}} \left( \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} I'(i, j)}{NM} \right)
\]  

(3-1)

where, \(I'(i,j)\) is a function of the intensity of pixel \(ij\) of the image of the speckle, \(M\) and \(N\) are the number of pixel columns and rows respectively, and \(I_{\text{sat}}\) is the intensity corresponding to the maximum grey level in the image. The relationship between \(I'(i,j)\) (the measured intensity) and \(I(I,j)\) (the actual intensity of the region corresponding to pixel \((i,j)\)) is:
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\[ I(i,j) = \begin{cases} I_{\text{sat}} & \text{if } I(i,j) > I_{\text{sat}} \\ \left\lfloor \frac{I(i,j)(2^n - 1)}{I_{\text{sat}}} \right\rfloor & \text{otherwise} \end{cases} \]  

(3-2)

where, \( n \) is the number of bits used for the grey level of the captured image.

In the next figure (Figure 3-7) the flowchart of processing the data is given. Figure 3-8 gives the schematic idea of the measurement system based on speckle pattern recognition.

The suggested relationship between ORI and \( R_a \) is given in equation 3.3.

\[ \text{ORI} = a + b \log(R_a) \]  

(3-3)

And consequently,

\[ R_a = 10^{\frac{\text{ORI} - a}{b}} \]  

(3-4)

where \( a \) and \( b \) are constants dependent on the wavelength used and the angle of incidence.
It has been reported that, a smaller wavelength of the illumination source leads to better resolution, although this claim could not be backed up with the test results obtained by the authors. Also, the developed system was not able to accurately measure roughness with a $R_a$ of less than 0.25 $\mu$m. However, the accuracy of measurement using this method does not seem to suffer from minor misalignment of the light source as was the case with the previous method. Bearing that in mind, the method suffer drawbacks in the form of the need for high computing power, complicated software algorithms and the smaller range of reliable measurement.

Oh and Kim (2005) have proposed the use of femtosecond laser pulses as the illumination source for vision system based surface roughness measurement schemes. As opposed to white light illumination, ultrashort-pulsed lasers provide low temporal coherence while maintaining high spatial coherence. This was verified with the help of Fizeau and Twymann-Green type scanning interferometers.

Kiran et al (1998) have evaluated rough ground, milled, shaped, cast and sand blasted surface with the help of direct image processing. The 3D reconstruction of cast and
sandblasted surfaces extracted from their literature is given in Figure 3-9 and Figure 3-10 respectively.

![Figure 3-9 3D plot of cast surface (Kiran et al, 1998)](image1)

![Figure 3-10 3D plot of sandblasted surface (Kiran et al, 1998)](image2)

No error analysis or comparative study has been carried out by the authors in literature. Thus, the accuracy of the system in various measurement techniques cannot be assessed.

Another method of evaluating the surface smoothness is the shadow sectioning method. Sandak and Tanaka (2005) as well as Yang et al (2005) have used this technique to evaluate machined wood surface. Light emitted with a fixed small angle to the surface plane by a projector is directed onto the measured surface. A curtain installed in the light path close to the surface creates a shadow on the measured surface. The shape of the border between bright and dark is a profile section of the surface. A camera installed over the surface captures an image of the border and a digital signal processor using image analysis techniques digitizes the profile section. The following figure shows the shadow sectioning idea in schematics (Figure 3-11).
The reconstructed profile surface from the shadow scanner has been depicted in Figure 3-12. The figure also gives the chronological reconstruction of the profile section using the Digital Signal Processor (DSP). After the capture of image and the subsequent transfer of data to a DSP running either on a Personal Computer (PC) or a specialized vision system unit, the image is binarized into two segments corresponding to shadow and illuminated areas. Then, the boundary between the shadow and illuminated area were mapped and edge detection algorithm had been used for this purpose. A single calculation of the edge position provided the location of the pixel for only one column. For the total surface section, the edge was detected for each column of the image, one by one. This process was carried out for the total length of measurement area. The matrix of data thus obtained was graphed as in figure 3.11 and was used for further analysis of surface smoothness parameters.

The results documented in the paper of Sandak and Tanaka (2005) and Yang et al (2005) does not contain the error analysis of profile measurement system using the shadow sectioning method. Albeit the apparent accuracy with which the reconstruction of the scanned surface has been carried out, absolute value corresponding to surface roughness cannot be obtained from the shadow sectioning method. Thus, it is not suitable for surface profile measurements carried out by Ehrmann et al (1998) on contact lenses or the surface profiles of glass, CD and Silicon substrates as obtained by
Fan et al (2001). So this cannot be used versatilely to various engineering surfaces. This somewhat restricts the use of the system in a host of applications as mentioned just now.

Xu et al (1998) and Tatsubo et al (2004) have proposed sensors based on light sectioning principle to measure the surface profile of fabric and width of steel plates respectively. In a more recent and relevant research published by Yang et al (2006), this light sectioning method has been used to determine the surface profile of wood. This method requires oblique illumination and a laser light stripe is projected from the side of the sample on to the surface to produce light section. The light section is actually a wavy line produced by the projected light due to the waviness of the surface under test. Also, there is a triangular relationship between the height of the cutter mark wave \( H \), and the height of its corresponding wave \( L \) in the light section. This can be given by –

\[
H = L \tan \theta
\]  

(3-5)

where, \( \theta \) is the angle of incidence of the projected light with respect to the surface.

Thus, 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 experimental setup consists of a CCD camera, personal computer, suitable software to implement image processing algorithm and a laser light stripe generator. The setup is depicted in Figure 3-13.

Figure 3-13 Test rig set-up for light sectioning method (Yang et al, 2006)
The experimental results were benchmarked with an optical profilometer with a vertical resolution of 20 nm. The results were in good agreement with each other as given in Figure 3-14. However, the authors have expressed their concern with misalignment of the light source. Also, the surface profile measurements can only be carried out with static work-piece, which limits the use of the system in on-line measurement of machined timber. Apart from that, use of expensive camera, high signal processing requirements and speed of measurement are the major drawbacks of the system, which restricts its implementation in timber machining industry.

![Figure 3-14 Surface profile of machined timber with interferometer and light sectioning method (Yang et al, 2006)](image)

The measurement system also doesn't provide the information of absolute profile measurement. This fact is evident from the scaling in Figure 3-14. Thus, in case where this profile information needs to be fed back to a machine controller for implementing an autonomous system, the system fails to deliver the required parameters.
Wang et al (1998) has used the combined effect of speckle and scattering phenomena to obtain the surface texture of steel and copper. Measurements on dynamic surfaces were also carried out. In this particular technique the dimensions of the dark or bright area in the speckle pattern is used to infer the surface roughness. According to the authors, this method provides with a large measurement range and a good accuracy.

A laser beam was projected on to the specimen surface and the image of the illuminated surface was captured with the use of CCD camera (Figure 3-15).

Figure 3-15 Dark-bright ration based surface roughness system (Wang et al, 1998)

The same technique has been used by Wong and Li (1999) to perform analysis of various tooling stages in a CNC machine. The dark-bright ratio during the machining process is given in Figure 3-16.

Figure 3-16 Variation of dark ratio during machining (Wong and Li, 1999)
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The rougher the surface, the closer the darkness ratio in the image approached unity. Thus, the relationship between the dark-bright ratio and surface roughness was established and used to measure the roughness of various specimens. Although this is a comparison based technique, good agreement between the stylus measurement and the dark-bright ratio based measurement has been reported.

This measurement setup involves the use of microscope and substantial computing power. These could lead to substantial development and operational cost. Furthermore, the use of microscope could raise the question of this method's suitability in rugged industrial environments. Because of this, the use of this method could only be limited to laboratory based metrology.

Optical ring image sensor is another optical method to obtain the surface texture of a given profile. Lee et al. (2002) have used this method to measure 3-D edge profile for die and mould model surface.

The Figure 3-17 gives the setup of this method in determining surface texture.

![Construction of automated 3D edge profile measurement system (Lee et al., 2002)](image)

This method is particularly useful when there is a need to actually re-create models of artifacts for reverse engineering and so on (Carbone et al., 2001). As it is a slow and expensive method of obtaining surface profile measurement data, its application in industry cannot be foreseen.
A similar method to re-create object profile using variable-resolution optical measurement system (VROPMS) has been discussed by Tsai et al (2002). They have successfully re-constructed a model of a human sculpture. However, the arrangement of the sensors is complicated as well as requiring complex image processing. Therefore, its suitability in industrial measurement is limited due to complication of the system and the associated cost of optical hardware.

A tool condition monitoring sensor based on morphological comparison has been proposed by Lanzetta (2001). The system is essentially based on obtaining the surface image of a tool and performing the required image processing to determine various wear within. A comprehensive database of various tool wear was constructed by the author and comparison algorithm was developed to determine exact nature of the tool wear.

As with all other comparison methods, the main drawback of the system is the large amount of specimen data needed to train the system. Also, only relative measurement of a given surface is possible without the capability of obtaining actual surface parameters.

Suzuki et al (1989) has proposed a phase locked laser diode (PLLD) interferometer as given in the above figure (Figure 3-19). In this technique, the laser diode has been used as the illumination source, while the CCD camera serves as the detector. The
measurement result obtained by the interferometer is given in Figure 3-18 (a) along with the corresponding stylus measurement (Figure 3-18b).

A highly integrated single sensor system has been proposed by Astrand and Astrom (1994) for wood surface measurements. Their approach is based on using the smart sensor MAPP2200. This is a photo-diode based sensor capable of capturing grayscale image of the surface under test. Three line lasers were used to illuminate the specimen and the MAPP camera was used to obtain the surface image. Subsequent signal processing was carried out to determine the surface texture of the wood specimen. Although, this is a single sensor approach, thus enabling a small sensor footprint, high speed measurement of textures has not been possible. So, for most industrial applications, this method will not be useful.

A recent research carried out by Tian and Lu (2006) has proposed a novel technique of using two cameras for online measurement of surface roughness. These cameras capture the laser speckle pattern and the scattering images. Then an image processing algorithm is applied to obtain several features of texture and shape to eventually determine the surface roughness.

Figure 3-20 Hybrid vision system technique for online surface roughness measurement (Tian and Lu 2006)
The setup is depicted in Figure 3-20 and involves the use of two CCD cameras, a diffuse screen and a laser diode of wavelength 660 μm and 35 mW. A feature fusion algorithm is also discussed by the authors that will enable the measurement of surface roughness. However, no error analysis or validation of test results has been put in place to evaluate the performance of the aforesaid system.

Apart from the fact that the measurement results cannot be validated upon a trusted source, the system has several drawbacks. One of the major drawbacks of the system is the use of two cameras to capture the images, which is an expensive venture. Besides that, the high powered laser sources used in this method is a health and safety hazard and requires the operator to undergo extensive training in laser safety. The time required for measurement is also an issue in online measurements. Depending on the software and hardware being used, the time required in acquiring the data from the two cameras and then to carry out the feature fusion is a time consuming task. This casts doubt on the system’s ability in performing online measurements required for applications in process industries.

In a similar research carried out by Brillaud and Lagattu (2005), an algorithm based on digital correlation of grainy shadow images were applied to carry out surface profile measurement. This technique has been applied to polycarbonate samples and has shown to obtain absolute measurement values. The results were also not benchmarked and this system is apparently developed with measurement of step height in mind.
3.2.2.2. Fiber-optic Sensors

A range of fiber-optics based surface profile measurement system has been developed in the recent years. Figure 3-21 depicts the measurement setup discussed by Yilbas and Hasmi (1999). This system employs a He-Ne Laser beam to scan the surface under test and a fiber optic probe collects the reflected beam from the surface. The principle of measurement is based on the fact that, as the surface roughness of the test piece increases, the laser beam reflected from the surface broadens.

![Fiber-optic sensor setup](image)

This broadness was evaluated by the use of standard deviation (S.D.) of a Gaussian function. A relationship between this Gaussian S.D. (B) and surface roughness parameter (Ra) was developed. This has been described as:

\[
Ra = 0.08369B + 0.022774 \tag{3-6}
\]

There is a need to combine the intensity profiles associated with every point at the surface to give an intensity profile representative of that particular surface. Thus this system would slow down the surface inspection process considerably and a large number of calculations have to be performed in order to establish the surface roughness of a given material. With a Ra value of greater than 1 μm, the error has been reported to
be considerably high. For these reasons, the system would be difficult to integrate in in-process measurement setup. Furthermore, it lacks credibility when it comes to accuracy of measurement with surfaces having a $R_a$ value of greater than 1µm.

A multi-beam scanning system involving the use of fiber-optic light emitting and detection assemblies have been discussed by Abuazza et al., (2004). In this method, five emitting diodes and five receiving photodiodes were used as the illuminating and detecting instrument respectively. The setup of the profile measurement system is shown in Figure 3-22.

![Figure 3-22 Fiber-optic light emitting and detection assembly (Abuazza et al, 2004)](image)

The surface profile plot in Figure 3-23 has been extracted from the literature and provides an example of the profile measurement carried out with the help of this system. This system was able to measure the profile of specimen up to 3.96 mm in length. The optimum scan rate was found out to be 1.91 mm/s. This measurement length is a serious drawback of the system and this method would be time consuming in scanning large surfaces. Thus it would make the system unsuitable for most industrial inspection processes. Also, this is mainly a defect detection system, which cannot serve the purpose of measurement of surface roughness parameters.

A fiber-optic based surface roughness sensor has been discussed by Persson (1999). The schematic idea of the system is given in Figure 3-24. The surface profile measurement results reported in the paper has been shown in Figure 3-25. This sensor has successfully measured surface in the range of nanometers. But it also suffers from the
disadvantages as discussed in case of the previous method. Thus its suitability is limited in an automated rugged industrial environment.

A surface finish sensor based on a similar concept of fiber-optic assembly has been proposed by Cahill and Baradie (2001). The schematic setup of their method is given in Figure 3-26. Improved noise rejection over the existing systems has been reported with the use of an electronically modulated LED light source. The system has been said to be more sensitive to surfaces with $R_a$ below 0.1 µm. So, it can only be used with relatively smoother surfaces, having lower $R_a$ values.
This method uses high powered laser devices and this leads to safety concerns for the operator. Also delicate nature of fibers makes it difficult to integrate the system into in-process machineries.

The Coordinate Measurement Machine (CMM) is usually used to inspect high-valued, geometrically complex and dimensionally precise components (Fan 1997). A fiber-optic texture sensor has been integrated into a (CMM) by Bradley (2000) for surface profile measurement of turbine blades (Figure 3-27). The controller of the CMM uses the part program obtained from Computer Aided Drawing (CAD) model to move the touch probe around the specimen and perform the spatial measurement at each required location (Figure 3-28).

Although, the measurement carried out with the help of this method is essentially extremely accurate it can be really time consuming (Zhao et al., 2000). A precision path planning method must also be employed to obtain the measurement across the surface under test (Lu et al., 1999). This leads to higher complexity in both hardware and software. So, the suitability of this CMM-based system is extremely low in process industries, where a rugged, simple, and cost-effective system is desirable.

A similar technique of CMM based measurement has been proposed by Le et al (2004). The sensor used is a CCD camera instead of the fiber-optic sensor. The measurement
techniques are essentially same and suffers from the problems as just discussed in the previous paragraph.

Design and fabrication of fiber-optic sensor for measurement of small internal curved surface has been carried out by Zhao et al (2000). The measurement system involves the arrangement of eight symmetrically cross arranged receiving fibers with an emitting fiber in the center. This sensor arrangement can accomplish distance measurement with high vertical resolution of 0.1 μm. Its use has been established in a highly specialized application of internal surface measurement and virtually outside the current scope of this literature review. Thus, detailed discussion of this technique has been avoided.

3.2.2.3. Laser-based Metrology

Another frequently used technique of obtaining surface profile measurement has been reported to use lasers. Huang and Xu (1999) has mounted a laser probe on a CMM and scanned the surface of a concave mirror to determine its surface profile. Their experimental setup is shown in Figure 3-29.

![Figure 3-29 Surface profile measurement of a spherical mirror using laser beam (Huang and Xu 1999)](image)

Figure 3-30 Surface profile measurement result of the mirror (Huang and Xu 1999)

The principle of angle measurement based on internal reflection effect (AMIRE) was used in this case to obtain the slope of a point on the mirror surface. Numerical integration of successive points along the scanned line was carried out to obtain the
surface profile. Figure 3-30 shows the result obtained with the help of the measurement setup.

The problems associated with measurements using CMM has been discussed in the previous sub-section. This particular method also suffers from the same drawbacks and thus not suitable for use in industrial environments. They are more relevant to laboratory-based high precision metrology.

Pugh et al (2003) has proposed a hybrid method of obtaining surface profile measurements. Their method employs an adaptive development of traditional phase locked loop, while a laser modulator-demodulator has been used as the principal instrument. This approach is only suitable for remote sensing rather than shape determination due to the methodology used in measurement.

Optical profilometer to obtain the surface roughness of super-smooth surfaces has been developed by Dawei (1995). The main measurement principle in use is the common-mode rejection technique and several advantages in industrial measurement environment were observed. With the help of this profilometer, effects of vibration, air turbulence near the surface, improper surface preparation were avoided. The measurement scheme is given in the figure below (Figure 3-31).
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The graph in Figure 3-32 shows the deviation in results obtained by the common-mode rejection method in comparison to stylus measurements. The measurement deviations are quite small, in the scale of nanometers. This is a successful approach in laboratory environment but the use of telescope, phase bias unit etc. makes it complicated, expensive as well as a slow method. Also high power He-Ne laser could prove to be a source of health hazard for operators.

A laser interferometer based on the principle of instantaneous phase shift has been researched by Sivakumar et al (2006) and Wang et al (2004). The main attribute of the system is its robustness in vibrating environment. It has been shown that the system could effectively carry out measurements, even when the work piece is under vibration of up to 1 kHz. The system suffers from the drawbacks of using high powered He-Ne laser devices and complicated sensor alignment and complex signal processing algorithm.

An interferometer based on the differential phase quadrature principle has been proposed and demonstrated by Basil et al (1990). The system consists of He-Ne laser source of 10 mW as well as photodiodes to sense the reflected signal off the surface under test. A personal computer with the right software and relevant algorithm then calculates the phase of interference and hence the gradient of the surface between the probe beams. Sequences of gradients are calculated along the length of the sample and the addition of the discrete gradients gives the surface profile information. Although the principle of operation is quite straightforward, this system requires complicated optical arrangements, high powered laser sources, special software and algorithm to compute the surface profile. Apart from that, it needs a stable micro-stage for providing the scanning motion of the work-piece. This stage alone is cumbersome and expensive for industrial applications.

Another essentially laboratory oriented surface measurement system is the Atomic Force Microscope (AFM) based technique (Chen and Huang 2004). AFM images provide surface topography in the nanometer scale, thus providing rich information on the surface structures. However, they are also employed to measure surface roughness of a given specimen. Lack of speed, expensive hardware, complicated arrangement etc.
makes this method unattractive for the purpose of surface quality measurement or tool condition monitoring.

A laser displacement sensor (LDS) based surface profile measurement system has been proposed by Sandak and Tanaka (2003) as well as Shinozaki et al (2004) and Shinozaki and Sasaki (2006). This method uses a triangulation measurement approach. Laser light emitted by a semiconductor laser diode passes through a transmitter lens and is focused on the target surface. The reflected light is focused on a position-sensitive detector (PSD) after passing through a receiver lens. The detector uses the distribution of the entire beam spot entering the light-receiving element to determine the beam spot center of gravity and identifies it as the target position. Of the LDS’s distance to the measured surface changes, the position of the reflected spot on the detector changes proportionally. This process can be correlated to the smoothness of the measured surface.

The schematic diagram in Figure 3-33 shows the measurement setup used by the researchers.

![Figure 3-33 LDS based surface profile measurement scheme (Sandak and Tanaka 2003)](image)

Profile measurement obtained by the LDS method and mechanical stylus has been reported in the literature and is given in Figure 3-34. The error in measurement seems to be quite low with the use of LDS sensors.
It has been reported that, the accuracy of the measurement is dependent on the density of the specimen (in this case wood). Also, rounding off of profile valleys and peaks has been observed by the investigators. As a result, the use of such a system has not been recommended in industrial or laboratory-based metrology (Sandak et al, 2003). The performance of the system was somewhat improved with the introduction of a CCD sensor in place of the PSD (Sandak et al, 2004). Despite that, accuracy of the whole system could be questioned as long as experimental results concretely show otherwise.

Akiyama et al (2005) has proposed a surface profile measurement system based on the sinusoidal wavelength-scanning interferometer, while Quan and Thakur (2005) have demonstrated a profile measurement system based on fringe projection method. These instruments have been used to measure the profile and thickness of thin films and coins respectively. These systems are similar to the one mentioned above and also use CCD devices to capture the reflected lights from the surface. Very high precision (typically in the range of nanometers) measurements can be carried out with the help of the system, which is not essential in wood or metal forming industries. Thus, this system’s applications lie in laboratory-based metrology or in nano-fabrication industry.

Shen and Zhou (2001) have shown that the optical scattering property of wood can be used to determine the fiber orientation in wood samples. This has been essentially done with the help of He-Ne laser and sensing head consisting of photodiode assembly. In this technique, surface profile measurement of the timber surface has not been carried out and only the wood fiber orientation has been discussed.
Another PSD-based system has been implemented by Mertens et al (2005), whereby they use this technique to sense the profiles of cantilever arrays in nano-mechanical sensors. Thus, this technique has not been discussed in detail here as it is outside the scope of this research.

Kagami and Hatazawa (1989) have explored measurement technique based on the focusing method. They have focused a laser beam onto the surface of the object by a lens driven through a magnetic system by differential electrical output fed back from two photo-sensors.

The schematic idea of the method is given in Figure 3-35. The measurement carried out with the help of the focusing method and a mechanical stylus has been compared in the literature (Figure 3-36). The system has been able to trace the surface with certain accuracy, although its response to peaks in the texture is not particularly very accurate. Frequency response of the system has been reported to be about the 50 Hz mark. This is unsuitable for dynamic measurements in most industrial environments. Nevertheless,
this method has laid the foundation of future work in surface profile measurement using the focusing method.

3.2.2.4. Ultrasonic Measurement Technique

It has been discussed previously that ultrasonic sensors can be used as non-contact measurement instrument. The measurement setup is essentially the same as in contact method. Non-contact measurement of surfaces using the ultrasonic method usually involves the use of electromagnetic coupling of the test surface and the sensor. The received signal is very weak when compared to conventional coupling (e.g., oil), which severely hampers the accuracy of measurement (Jolic et al, 1994). Air coupling needs high power transmitters as well as high gain receiver amplifiers. The sensitiveness in measurement also degrades with the use of air as the coupling medium.

It is evident that, the use of ultrasonic method in non-contact orientation is not suitable for most industrial measurement purposes.

3.2.2.5. Hybrid Technique

The discussions on various techniques so far has concentrated on either the contact or non-contact method of obtaining the surface profile. Lu et al (2002) have been successful in integrating the two techniques and thus yielding a hybrid system.

In the measurement setup, both the optical and mechanical stylus shares the same signal conditioning system (Figure 3-37). The optical sensor is based on the focusing principle, where the focal length of the objective lens changes according to the change in the surface topography of the specimen under test. The servo control system acts to rectify this change by moving the lens and keeps the focus in optimal position on the surface. The surface profile information has been extracted by measuring the change in movement of the lens with the help of a Linear Variable Displacement Transformer (LVDT).
The philosophy behind the hybrid approach is to facilitate the measurement of various materials with the same measuring equipment. For instance, the mechanical stylus would be most suitable for measuring the surface texture of metals, whereas the surface roughness measurement of wood would be better served by the optical stylus. The difference in result obtained from the surface texture measurement with both the sensors has been reported in the literature (Figure 3-38).

Due to the usage of a LVDT to measure the change in vertical position, the accuracy of the system has been reduced significantly. A much better approach is to measure the current used in driving the motor of the lens mechanism. A more recent research (Chu et al, 2004) has shown that this current is almost linearly related to the movement of the lens and is thus suitable for obtaining the surface profile of the material under test.
3.3. **Summary of the Drawbacks of Currently Employed Techniques**

The previous section discusses various surface profile measurement systems currently employed in industries or being researched in laboratories. The mechanical stylus surface profile measurement system is still one of the most widely used profile measurement system. However, due to various factors, non-contact measurement systems are currently being extensively researched and their feasibility into various measurement purposes is investigated.

Although contact type stylus profilometers are most common instruments for measuring machined surfaces, they are unsuitable due to the contact nature of measurement. They tend to scratch or deform softer surfaces because of the stylus loading force. Thus, such a system is unsuitable for materials like timber. Also, the speed of measurement is quite slow, which restricts its in-process use in high speed machining environment. The finite tip radius as well as the tip’s decay from long term usage introduces error to measurements carried out. So, the need for obtaining surface profile information based on non-contact method has arisen.

A great deal of the non-contact methods uses vision-based system to obtain surface profile information. In most cases, the cameras being used are expensive, although the cost of such systems is falling recently. Still in most cases, the development cost of these systems is quite high (in the region of thousands of pounds).

Apart from that, positioning of the camera and the entire setup for a vision-based system is very difficult to achieve in an industrial setup. Fragile nature of the camera is also an issue when the system is integrated within a process line.

In order for the vision-based profile measurement system to work, the specimen under test must be illuminated properly. Thus, this poses a great challenge to the operator. A small misalignment leads to total loss of measurement data or erroneous results. This is highly undesirable in an automated and rugged industrial environment.
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The laser and fiber optics based systems offer good measurement resolution. However, the high-powered lasers used for this technique is a health and safety hazard in itself. The operators need to go through extensive laser safety training and also strict guidelines to minimize the hazards need to be adhered to. Also, the fiber optics assembly is very sensitive and fragile in nature. As a result, proper shielding and careful practices must be in place not to rapture the sensor components.

Ultrasonics is a promising field in metrology and surface inspection. However, this method is almost exclusively suitable for metals and will not work for softer materials. Some of the microscope based systems (e.g. AFM) are entirely laboratory oriented method and is prohibitively expensive and slow for any sort of industrial application.

The literature search has quite comprehensively pointed out that most of the non-contact methods used in surface profile measurement are developed with a focus on metal working industry. Among others, Yang et al (2005, 2006), Cutri et al (1991), Sandak and Negri (2005), Sandak and Tanaka (2003, 2005), Sandak et al (2004) have done substantial work in developing system geared towards measurement of wood surfaces.

Considering the amount of research done in surface profile measurement of machined metals, wood working has received astonishingly low attention. This is despite woodworking being considered as sophisticated and technologically advanced as precision milling of metals (Jackson et al, 2002).

So, there remains the need for the development of surface inspection systems which facilitates exclusively the surface profile measurement of timber and similar composites.
3.4. **Summary**

- Surface profile measurement is extensively carried out in industry to determine the surface roughness of machined material. This enables the quality control of finished products as well as optimization of process parameters when used in a closed-loop system.

- The age-old technique of visual inspection is still used within various industries to ensure the quality of surface finish. However, this highly subjective way of looking into finish quality fails to deliver a consistent standard of inspection and is affected by numerous factors beyond control.

- Due to the shortcomings of the visual inspection method, automated mechanical stylus based systems have emerged and taken up the leading position in metrological applications. They are also prone to various problems and unsuitable for many materials especially the softer ones.

- To accommodate various products and machining methods, a host of non-contact methods have hit the commercial and research scenes recently.

- Despite the abundance of non-contact surface profiling equipments, the timber machining industry is yet to get a system capable of high-speed, accurate, robust, cost-effective, customizable measurement system.
Chapter - 4.

Proposed Technique for Surface Profile Measurement

4.1. Introduction

The previous chapters have introduced the basic concepts of woodworking and the importance of surface profile measurement within a wood planing machine. A novel sensor has been proposed in chapter 3, which overcomes the shortcomings of the currently used surface profiling techniques. This sensor provides the desired attributes required for the surface profile measurement of timber. In the introductory chapters, two modes of implementation have been proposed. The technical requirements and limitations of the sensors are discussed in this chapter and benchmarked against the requirements in woodworking. Thus, the feasibility of using the sensor in real wood machining scenario will be explored here.

4.2. Requirements of sensor system for surface quality evaluation in wood machining

There are two potential approaches in using this surface profile measurement system in timber machining scenario. The first would be to integrate the sensor assembly into currently investigated high-speed mechatronic woodworking machine (Hynek et al., 2004). This would enable on-line measurement of the processed surface. Measurement results obtained through the sensor would then be fed back to the main machine controller for controlling the machining process to obtain the desired surface smoothness.

The second approach could be to develop a hand-held device which can be used for off-line measurements of a section of timber to evaluate its surface profile. Both approaches
will be investigated in the presented in this thesis report. While, both of them promise important industrial contributions, the first approach has the potential to make an immediate impact of improving the machining process in an on-going research study within the research group.

4.2.1. On-line measurement requirements

The online measurement setup of the surface profile measurement system has been shown in the figure below (Figure 4-1).

Main objective of integrating a surface profile measurement system in an online woodworking machine is to evaluate the surface finish of the timber after machining. Numerous techniques have been used for this purpose in the past as discussed in the earlier sections of the report. Now, this novel optical non-contact technique is being investigated with the foreseeable advantages of cost-effectiveness, seamless integration into the current setup due to small footprint of the sensor, computing requirement with low complexity and cost etc.

![Figure 4-1 On-line measurement setup within a small-scale planer](image)
In a typical woodworking machine, the feed speed ranges from 5 to 120 m/min. This results in a feed speed of 83 mm/s to 2 m/s (Jackson et al. 2002). However, the current machine in operation in the Mechatronics research lab has a much lower feed speed of 25 to 33 mm/s.

The wave created on the timber surface as depicted in Figure 4-1 can be perceived as a series of intersecting circular arcs, having regular intervals. Thus, the frequency at which the arcs appears to a sensing device can be given by the following relationship:

\[ f = \frac{V_f}{p} \]  

(4-1)

where, \( V_f \) is the feed speed of a timber piece to the planer and \( p \) is the wave pitch.

According to Jackson et al. (2002), the wave width for highest quality surface finish is 1.0 mm with a 63 mm cutter head. Keeping these specifications in mind, with a feed speed of 1 m/s, the frequency of the wave pattern appearing to the sensor can be calculated as,

\[ f = \frac{1}{p} \]

\[ \Rightarrow f = \frac{1}{1 \times 10^{-3}} = 1 \text{kHz} \]

According to Whitehouse (1994), it has been empirically determined that 10 samples within a given sampling period are required to successfully carry out the measurements and reconstruct the measured wave. Although this value has not been proven theoretically, it has been taken as the empirical basis for calculations.
Therefore, assuming that 10 samples (Figure 4-2) are required for reconstructing the wave pattern,

\[ f = 10 \times 1kHz = 10kHz \]

Thus, the sampling frequency has to be at least 10 kHz and considering a 10% tolerance for proper reconstruction, the frequency required comes to,

\[ f_s = 10kHz + 10\% \text{ of } 10kHz \]
\[ \Rightarrow f_s = 11kHz \]

Therefore, for the system to carry out the required surface profile measurement, the sampling frequency must be at least in the region of 11 kHz. In the latter part of this thesis report, the measurement capabilities of the sensors used for the measurement purpose will be compared with the requirements and their suitability pointed out for such measurement purpose.

4.2.2. Hand-held measurement requirements

Another potential measurement approach could be to develop a hand-held device for offline measurement of timber surface. The profile measurement data obtained through the sensor can then be displayed in an embedded LCD display.

In order to achieve a handy surface profile measurement system, the DVD pickup head and the optical mouse sensor assembly can be mounted on a rail-wheel system. With the
specimen in between the two rails and underneath the sensor assembly, a slow scan across the timber will yield the measurement result.

The bandwidth requirement of this method is somewhat less demanding than online measurement scheme. The vibration compensation required for online measurement can be avoided by designing a robust and stable mechanical scanning structure.

As mentioned previously, the feed speed of the woodworking machine currently in operation within the research center is in the region of 20 to 33 mm/s. For portable offline measurement, this speed has been observed to be sufficient.

For a feed speed of 33 mm/s and a pitch length of 1mm, the frequency of the cut wave appearing to the sensor is:

\[ f = \frac{V_f}{p} \]

\[ \Rightarrow f = \frac{33 \times 10^{-3}}{1 \times 10^{-3}} = 33 \text{ Hz} \]

If 10 samples are required for each wave pitch, the frequency becomes,

\[ f = 10 \times 33 = 330 \text{ Hz} \]

Thus, the sampling frequency has to be at least 330 Hz and considering a 10% tolerance for proper reconstruction, the sampling frequency required comes to,

\[ f_s = 330 \text{ Hz} + 10\% \text{ of } 330 \text{ Hz} \]

\[ \Rightarrow f_s = 363 \text{ Hz} \]
4.3. **Low-cost Non-contact Approach to Surface Profile Measurement – OWSMS**

It is apparent from previous discussions that there is a need for the development of a sensor capable of measuring wood surface profiles. The sensor needs to be non-contact, compact and cost-effective as well as being able to easily integrate within a given process setup.

The surface profile measurement system proposed in this research thesis addresses all the aforementioned issues and aims to deliver a sensor specifically for the measurement of timber surfaces.

The Optical Wood Surface Measurement System (OWSMS) contains two main components. The component used to obtain the vertical surface profile information is the optical DVD reader and the sensor used to obtain the horizontal positioning information is the optical mouse sensor. Both of these devices are used in consumer products and are being manufactured in mass quantity. The size of the sensors is also quite small and they can be easily accommodated into a woodworking machine. This fact is demonstrated in Figure 4-3. Thus, the availability of components, small size and low cost of developing the system are the important attributes of the proposed surface profile measurement system.

In order to reflect on the development cost of the system, the individual components do not cost more than £20 each, while the instrumentation and data acquisition hardware costs in the region of £50. The software, such as mikroBasic and MPLAB used to develop the system are free and readily available on the internet. Thus, a system capable of carrying out the required surface profile measurements can be developed at a cost totaling to £100. When compared to the fact that, a precision stage used in some of the systems, for instance by Fan *et al* (2001), itself costs in the region of a thousand pounds. Therefore, the cost-effectiveness of the proposed system is quite evident.
The following sub-sections look into the detailed construction and working principles of the two sensors used in the development of this novel surface profile measurement system.

4.3.1. Optical DVD reader as a Profile Measurement Probe

Absence of mechanical contact with the measured surface and non-destructiveness makes the optical method most in demand by industry. Some evidence is also found that optical methods are encroaching on the typical domain of the mechanical stylus (Yilbas and Hasmi 1999). Thus it was natural to turn our focus on the research of developing an optical system for the measurement of engineering surfaces.

One of the first attempts to use focusing method in surface profile measurement was carried out by Kagami and Hatazawa (1989). This technique has been discussed in certain detail in the previous section of the report.
Chapter 4: Proposed Technique for Surface Profile Measurement

Research carried out in the more recent past has used the same principles of Kagami and Hatazawa (1989) but with a less complicated optical arrangement. For the obvious reasons of practicality and cost-effectiveness, the trend seems to be the move towards using commercially available devices as the focusing probe.


The reasons behind the emergence of the pickup head as the focusing probe is because it is inexpensive, highly sophisticated and compact (Ehrmann et al, 1998).

This section of the report will provide an in-depth discussion of a surface profile measurement system with DVD pickup head as the main optical probe.

The optical reader head (HOP-1000 from Hitachi Semiconductor) of the DVD player has been proposed here as the measurement probe for the surface profile measurement. The sensor is depicted in Figure 4-4. This compact and versatile sensor has been used in various metrology applications and has been widely improvised.

![Figure 4-4 HOP-1000 Optical DVD Reader from Hitachi](image)

The attractive feature of the sensor is its compactness, cost-effectiveness, ease of data acquisition, simple interface and plug and play configuration. The sensor also comes with a robust housing, which shields the sensitive components inside the probe. Despite the metal protective casing, the weight of the sensor is only 33 grams. The electrical
power requirement to drive the sensor is also comparatively low, which is a highly desirable attribute for portable hand-held applications.

The following sub-sections discuss the working principle, construction and various other aspects of the DVD reader head.

4.3.1.1. **Construction of the Probe**

The DVD pickup head design varies from manufacturer to manufacture. However, the basic principle of operation and construction are the same. A schematic diagram of the optical path and components inside the DVD reader is given in Figure 4-5.

![Figure 4-5 Construction of the DVD optical reader head (Fan et al, 2000)](image)

To achieve sharp focus on the disc surface and proper intensity modulation of the pit height, it is necessary to use a laser as a light source (Pohlmann 1989). A laser uses an optical resonator to stimulate atoms to a higher energy level that induces to radiate in phase. Laser light differs from white visible light. A light bulb for example, radiates all the frequencies of the spectrum at all different phases. A laser light is monochromatic (composed of a single frequency), and is coherent in phase (Figure 4-6 and Figure 4-7). Phase coherency is vital, of course, to implement phase cancellation in the beam produced by disc pits so that disc data can be read. The pickups usually use an
Aluminum Gallium Arsenide (AlGaAs) semiconductor laser with a 0.5 mW optical output radiating a coherent-phase laser beam with a wavelength approximately 635 nm. This beam is somewhat visible in comparison to the CD pickup head, which emits at a wavelength of 790 nm (Sun et al, 2005).

The laser diode is placed at the focal point of a collimator lens with a long focal distance. Its purpose is to make the divergent rays parallel. A monitor diode is also placed next to the laser diode to control power to the laser. It compensates for temperature changes and prevents thermal run-away. The monitor diode conducts current in proportion to the laser's light output. In other words, it stabilizes the semiconductor's output.

A three-beam pickup uses three beams for tracking and reading. To generate these beams, the light from the laser passes through a diffraction grating, a screen with splits spaced only a few laser wavelengths apart, as shown in Figure 4-8.
Figure 4-8 In a three-beam pickup a diffraction grating (a) splits the beam into successively less intense secondary beams (b) (Pohlmann 1989)

As the beam passes through the grating, the light diffracts; when the resulting collection is again focused, it will appear as single, bright, centered beam with a series of successively less intense beam on either side. It is this diffraction pattern that actually strikes the disc. A three-beam pickup uses the center beam for reading data and focusing and two secondary beams for tracking only.

The next part of the optical system, a polarization beam splitter (PBS), directs the laser light to the disc surface and angles the reflected light to the photo sensor. The PBS consists of two prisms with a common 45 degree face acting as a polarization prism. The collimator follows the PBS. The light then passes through a quarter-wavelength plate (QWP), as an-isotropic material that rotates the plane of polarization of light beams (required to make the PBS work). Light which has passed through the QWP and been reflected from the disc back again through the QWP will be polarized in a plane at right angles to that of the incident light. As the PBS passes light on one plane, (e.g. vertically polarized), it properly deflects the reflected beam toward the photodiode sensor to read the digital data.
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The final piece of optics in the path to the disc is the objective lens that is used to focus the beams on the disc data surface, taking into account the refractive index of the polycarbonate substrate (Figure 4-9).

Figure 4-9 The refractive index of the disc substrate contributes to the focusing of the laser beam (Pohlmann 1989)

The objective lens focuses the laser light into a convergent cone of light. The convergence is the function of the numerical aperture (NA) of the lens. Most pickups use an objective lens with an NA of about 0.45, which corresponds to the f/1.0 in a photographic lens. The main spot is about 800 $\mu$m in diameter on the outer surface of the disc’s transparent polycarbonate substrate. The refractive index of the polycarbonate substrate is 1.55 and its thickness is 1.2 mm, so the spot is narrowed down to 1.7 $\mu$m at the reflective surface. This is slightly wider than the pit width of 0.5 $\mu$m and comparable in width to the wavelength of the light itself.

All three intensity-modulated light beams return through objective lens, the QWP, the collimator lens and the PBS. Finally, they pass through a singlet lens and a cylindrical lens en route to the photodiode.
4.3.1.2. Working Principle

In a three-beam optical pickup system discussed earlier, the unique property of astigmatism is used to achieve focusing (Hnilicka et al., 2005). The principle is based on the optical aberration called astigmatism, which is usually introduced with the use of cylindrical lens.

The cylindrical lens just prefacing the photodiode (Figure 4-10) is used to detect an out-of-focus condition. As the distance between the objective lens and disc reflective surface varies, the focal point of the optical system also changes, and the image projected by the cylindrical lens changes its shape. This is illustrated in Figure 4-10.

Figure 4-10 Schematic idea of astigmatic focusing (Fan et al., 2000)

The change in the image of the photodiode generates the focus correction signal. When the disc surface lies precisely at the focal point of the objective lens, the image reflected through the intermediate convex lens, and a circular spot strikes the center of the photodiode. When the distance between the disc and the objective lens decreases, the image projected by the objective lens, the convex lens and the cylindrical lens moves further from the cylindrical lens, and the pattern becomes elliptical. Similarly, when the distance between the disc and the objective lens increases, the image moves closer to the lens, and an elliptical pattern again results, but it is rotated 90 degrees from the first elliptical pattern.

The four-quadrant photodiode uses the light's intensity level from each of the quadrants to generate focus correction voltages. An elliptical pattern mainly striking quadrants A and C, as shown in Figure 4-11, indicates the disc is too near, and a positive voltage is created.
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When the disc is in focus, no net voltage is created from the round pattern. An elliptical pattern striking quadrants B and D indicates the disc is too far, which creates a negative voltage. This varying voltage, as shown in Figure 4-12, is used to correct the focusing mechanism continually towards the, thus maintaining a focused laser beam. This curve obtained is known as the ‘S-curve’.

\[ SUM = A + B + C + D \]  \hspace{1cm} (4-2)

A correction voltage is generated with the help of proper signal conditioning, which helps a servo controller to keep focus on the disc. The equation for the Focus Error Signal (FES) is given in equation 3.8:
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\[ FES = (A + C) - (B + D) \]  (4-3)

This electrical signal is fed to the servo motor controlling the movement of the objective lens. The motor moves the objective lens along the optical axis in response to vertical disc movement. This voice coil motor (VCM) consists of a coil and permanent magnet structure similar to that used in a loudspeaker.

4.3.1.2.1. Focusing and Auto-focusing Principles in Metrology Applications

In order to focus the laser diode beam onto the surface under test, Fan et al (2000) have used the fixed focusing method. In a later research work (Fan et al, 2001), the researchers have opted for using the auto-focusing method. This enables the increase in the range of measurement whilst reducing the resolution. For most engineering applications apart from high-precision nano measurements, the larger range of auto-focusing method is most suitable even though the resolution has been sacrificed.

As discussed just now, the technique used by Fan et al (2000) is called the focusing method. In the original setup of a DVD pickup, the objective lens is suspended by a voice-coil motor (figure 3.36). The lens is actuated to vary its position dynamically in order to track the disc in focus when the fly height changes. Since their focus was only to obtain the signals within a fixed focusing range, the voice-coil motor was glued to make it inactive. This has basically yielded a focusing probe for the measurement of surface profile.

The auto-focusing method was later investigated in a literature by Fan et al (2001). When the object moves either closer to the objective lens or away from it, there will be a non-zero FES output (figure 37). This signal has been processed and used to generate a current source to drive the VCM, which actuates the objective lens in order to reduce the FES. When the FES reaches to zero, the lens stops moving and settles to a mechanical equilibrium. The steady-state current needed to keep the lens in equilibrium has been converted to a corresponding voltage signal, termed as the servo-FES. The results obtained from the tests show a much larger linear range when compared to the fixed-focusing method (Figure 4-13).
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Figure 4-13 Relationship between the Servo-FES and lens displacement (Fan et al, 2001)

It has been advised in the paper to use the central range of 500 to 800 μm for measurement purposes. Thus this limits the measurement range to around 300 μm.

The measurement setup proposed by Fan et al (2000, 2001) is given in the Figure 4-14.

Figure 4-14 System setup for surface profile measurement proposed by Fan et al (2001)

A micro-stage (similar to the one in Figure 4-15) has been used to provide the scanning motion for the pickup head in the above measurement scheme. A micro-stage finds successful application in micro and nano metrology (Zhang et al, 2003). Although it is a very precise method, providing an ultra-stable motion with incremental movement in the range of nanometers, the cost is prohibitive for most industrial applications. Also the range of travel is limited to only a few millimeters (Micos catalog 2007).
Another reason for using this micro-stage is that, the displacement of the DVD pickup across the surface of the test material can be extracted for the surface profile plot. This data acts as the x-axis of a surface profile plot. Due to the high cost of such stage, a novel technique of obtaining the positional distance traversed by the pickup probe has been proposed later in this thesis chapter.

Another approach adopted by Zhang and Cai (1997a, b) has resulted in using the Piezoelectric Translator (PZT) for focusing the lens instead of using the VCM drive already embedded in the pickup head. According to them, there are several advantages with this technique. The major advantage they reported is that the measurement range was not longer limited by the depth of focus, rather by the stroke range of the PZT, which was substantially larger. The interferometric readout had also contributed to very high resolution and repeatability over the entire range of measurement.

Despite the improvement in reported measurement range and resolution, this method has some serious drawback. As PZTs are high power devices, suitable power amplifiers must be designed for accommodating such setup. This would substantially increase the cost and complexity of the system. Given the improvements in measurement actually achieved and the cost incurred, this system would not be suitable for most industrial applications.
4.3.1.3. Vibration Suppression in Measurements

In a typical woodworking environment, there are various sources of vibration during the process of planing. Vibrations mainly occur between the relative movements of the cutter head and the work piece (Elmas et al, 2007). The source of vibrations is mainly due to the inaccuracies present in the cutter head and the vibration within the spindle system itself. Various researchers have proposed and implemented methods to suppress these vibrations within the timber forming process, thus, preventing the degradation in the quality of surface finish.

However, from a post-process inspection point of view, the main source of vibration is the transport mechanism used to carry the machined timber through the inspection system. This mechanism could be made up of transport belts as demonstrated by Yang et al, (2006) or linear motorized stages made up of primarily lead-screw as implemented by Hynek et al, (2004).

Vibration induced by these transport mechanisms poses great problems for the surface profile measurement systems. This degrades the measurement accuracy and too much vibration of the test specimen leads to totally incorrect measurement results.

Whilst measurements carried out by some of the CCD based systems are less susceptible to vibration of the test piece, due to the principle of operation the focusing technique is heavily influenced by this phenomenon. To obtain sound profile measurement results from the focusing method, proper compensation must be accommodated for noise induced by vibrations. Thus, noise filtering techniques must be applied to the measurement system to suppress the effect of vibration of the work piece under measurement.

One way of eliminating effects of vibration induced noise from measurement results is to monitor the vibration with the help of an accelerometer and then mathematically subtract this reading from the actual measurement. However, this method has some severe drawbacks.
First and foremost, the mathematical relationship between the parameters obtained with the help of accelerometer and the focusing probe must be established. This would require rigorous and tedious analysis. Secondly, it must be ensured that the accelerometer is mounted on the exact location (or considerably close) where the probe carries out the measurement. This is almost impossible to achieve and involves very accurate positioning of the vibration sensor, practically unattainable in most woodworking industries. Lastly, the vibration sensor and signal conditioning system must be calibrated at all times to ensure proper functioning of the noise suppression scheme. Therefore, it can be clearly seen that this method is unsuitable for the proposed measurement system.

Differential method has been used previously within metrology applications to eliminate noise from measurements using stylus probes. Among others, Kiyono and Gao (1994) and Gao and Kiyono (1996, 1997) have carried out substantial research work in this field. The basic idea behind the scheme is that similar probes carry out the measurements on the test sample but at slightly different points. Thus, the common measurement parameter between the probes would be the vibration acting on the sample. By extracting and subsequently subtracting this common signal from the measurement, the actual traced profile can be obtained.

The idea of the method is schematically given in Figure 4-16.

Figure 4-16 Measurement principle for differential method (Kyono and Gao 1994)
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In the Figure 4-16, two probes are mounted on a stage and can scan surface while the stage moves. The surface is described by the function \( f(x) \). For simplicity, only the cross-sectional profile in the X-Z plane is considered here. The orientation of the fixed coordinate axes XYZ is shown in the figure. Let \( C_0 \) be a representative point of the stage, \( L \) is the probe interval and \( s \) is the sampling period.

If the output of the probe 1 at point A is denoted by \( m_A \) and that of the probe 2 is denoted by \( m_B \), then \( m_A \) and \( m_B \) can be expressed as

\[
m_A(x_n) = f(x_n) - e_z(x_n)
\]

\[
m_B(x_n) = f(x_n - L) - e_z(x_n)
\]

where, \( x_n = n \cdot s \) (\( n = 0, 1, 2, ... \)). It denotes coordinate of the point \( C_0 \).\( e_z(x) \) is the z-directional error in the scanning motion, which in this case is induced by the vibration from the transport mechanism of the planer.

Since \( e_z(x) \) is sensed by both probes, it can be cancelled from the differential output of the probes. Thus, the differential output \( \Delta m(x_n) \) is denoted as

\[
\Delta m(x_n) = m_A(x_n) - m_B(x_n) = f(x_n) - f(x_n - L)
\]

An approximate derivative \( m'(x_n) \) of \( f(x_n) \) can be defined by \( \Delta m(x_n)/L \) as follows

\[
m'(x_n) = \Delta m(x_n)/L = (f(x_n) - f(x_n - L))/L
\]

The integration of \( m'(x_n) \) approximately represents the profile. If this integration is denoted by \( z(x_n) \), then

\[
z(x_n) = \sum_{i=1}^{n} m'(x_i) \cdot s = z(x_{n-1}) + m'(x_n) \cdot s
\]

If \( S = L \) then equation 3.13 becomes,
Thus, this evaluated profile $z(x_n)$ is the approximation of the real profile $f(x_n)$. Using the method described above, vibration induced noise present in profile measurements can be eliminated.

### 4.4. Optical Mouse Sensor as a Linear Encoder

In the surface profile measurement system demonstrated by Fan et al (2001), the optical head is driven in a micro-stage. The benefit of such an arrangement is two-fold. While highly accurate vibration free measurement is possible, the exact distance traveled by the head can be determined easily. Hence, the plot of the surface profile with respect to the position can be obtained quite effortlessly.

As discussed earlier, the main drawback of such an arrangement is the cost of micro-stages as well as the distance they are able to traverse. Although, for laboratory metrology this method is acceptable, these issues are unacceptable in any given industrial measurement setup. Thus, an alternative to the micro-stage is necessary.

An alternative approach to the abovementioned problem could be to use a motor-driven linear stage coupled with a low-cost precision sensor for distance measurement. The optical sensor system of a PC mouse could be foreseen to be used for this purpose.

ADNS-2051 from Agilent Technologies has been used for this purpose for implementing a low cost precision non-contact encoder. The sensor is depicted in Figure 4-17.

The aforesaid sensor has been used previously in metrology application successfully by Ng (2003), where the visco-elastic elongation of polyethylene was measured. Also, Mattolli (2004) and Palacin (2005) have used the sensor for odometry measurement purposes in climbing and mobile robots respectively. Ng and Ang (2003) have proved that the sensor can be used successfully to measure vibrations of up to 35 Hz. However, no research has been conducted on the usage of the sensor in the measurement of
surface profile of timber or similar material. Thus, this is a novel approach with regards to the use of optical mouse sensor in encoding applications.

Figure 4-17 ADNS-2051 optical mouse encoder

The sensor embedded in the mouse takes 2D pictures of the surface and translates any motion into a corresponding coordinate signal. This signal can be extracted and used for the purpose of measuring the distance it has moved over a surface. A similar approach has been applied to a climbing robot project by Mattoli (2004). The reported resolution of the system stands at 30 µm with a repeatability error of only 0.5%. However, a later research (Islam et al, 2006) has shown that the resolution is dependant on the actual sensor used and can be toggled between 31.75 and 63.50 µm. Currently available sensors are capable of carrying out finer measurements, which can lead to measurements with a resolution as fine as 25.4 µm.

In any case, the sensor offers the accuracy and resolution good enough for most engineering metrology. With the low development cost of the sensor (in the range of £12), it makes an attractive proposition for linear displacement measurement.
4.4.1. **Construction of the Sensor**

The exploded assembly diagram of the optical mouse sensor is given in Figure 4-18. The sensor assembly consists of –

**Clip**: to hold the optical mouse sensor and other components firmly to the base-plate

**LED**: to act as the source of illumination for the camera.

![Exploded assembly diagram of the optical mouse sensor](image)

**Figure 4-18** Optical mouse sensor components (Minoni and Signorini 2006)

**ADNS-2051 sensor**: the main part of the whole encoder system. This IC contains the CMOS camera, signal processing and DSP circuits.

**Printed circuit board**: is used to provide the power and other electrical connections to the ADNS-2051 and LED.

**Lens**: is used for the imaging purpose of the camera. This plastic molded optical component had a numerical aperture of 0.13 and provides one to one magnification.
**Base plate:** houses the whole optical mouse assembly and provides the required mechanical stability to the system.

The schematic block diagram of the optical mouse sensor IC is given in Figure 4-19. The image processor sits in the middle of the chip containing the CMOS camera. There are four quadrature output from the IC - $X_A$, $X_B$, $Y_A$ and $Y_B$.

The outputs of $X_A$ and $X_B$ are used to compare and measure the distance traveled in the X direction of the mouse, while the $Y_A$ and $Y_B$ outputs are used to measure the distance traveled in the Y direction. However, for distance measurement purposes, the motion registers inside the IC can be directly accessed with the help of a microcontroller, which eliminates the need to implement a comparison and calculation algorithm based on the quadrature outputs.

The LED drive component inside the ASND-2051 drives the LED needed for illuminating the surface to carry out surface imaging. The Serial Port component in the IC is used to establish communication between the optical mouse sensor and a serial device. The interface used is an SPI one and an additional IC is needed to convert that signal to RS-232 or USB signal for interfacing the optical mouse to a personal computer (PC).
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The Oscillator block within the IC regulates the clock frequency of operation of the optical mouse and provides timing to all the electronic devices on-board the ADNS. The oscillator component is driven by interfacing an external resonator to the IC. The Voltage regulator and Power Control circuitry on-board the ADNS provides all the components within the IC with power and provides protection as well as regulation to the entire system.

4.4.2. Working principle

As stated earlier, the optical mouse sensor has four main parts in the system. These are: illumination device, illumination lens, camera and camera lens.

The basic working principle of an optical mouse is described in Figure 4-20. A single light emitting diode (LED) with wavelength peak from 639 nm to 875 nm in combination with a plastic lens and mirrors is used to illuminates the surface at an angle (Palacin et al, 2006). The chip contains a CMOS camera as the image acquisition system and a proprietary Digital Signal Processing (DSP) algorithm for image processing. The structure of the mouse protects the camera and limits the incidence of external light. An additional plastic lens collects the reflected light and forms the image in the camera. The illumination lens which provides lateral illumination of the ground, takes the form of a spatial frequency filter that can have a strong influence on the measurements carried out.

The off-axis illumination by the LED helps to put the microscopic textural features of the surface into sharp contrast (Ng 2003).
The CMOS sensor typically comprises 18 pixel x 18 pixel, thus, totaling to 324 pixels in total. The mouse works by comparing the images of the surface that are refreshed approximately every 1500th of a second. As it is too computationally taxing to compare the images at all 324 possible overlaps, a 5 pixel x 5 pixel window, taken from the center of the second image, is normally used for the overlap matching process. This window is moved relative to the first image and the chip rates how the 324 pixels match up. These ratings are added to an overall score for the overlap. Once the chip has found the best overlap, it checks the scores of the eight pixels surrounding the center of the window. Finally, it sends the actual value of the displacement to the computer. The measurement accuracy is usually limited to the pixel spacing of the imaging sensor located on the chip.

The speed at which measurements can be carried out can be defined as –

$$V_{\text{max}} = \frac{f_r \cdot n_s}{r}$$  \hspace{1cm} (4-10)

where, $f_r$ is the frame rate of the sensor, $n_s$ is the quadrature signal states per frame and $r$ is the sensor resolution.
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The algorithm used to process the image acquired by the camera is a proprietary one and has not been released in the public domain by Agilent. However, Horn and Schunk (1981) and Horn (2003) have claimed that the estimation of movement can be carried out by their discussed theory of ‘optical flow’.

4.5. Measurement capabilities of the sub-systems

The previous sections gave an insight into the requirements for surface profile measurement systems in timber machining. Both on-line and off-line capability requirements of the sensors employed have been analyzed. This section will look into the capabilities of individual sensors and analyze how well they perform against the requirements of woodworking.

4.5.1. Optical DVD lens

As per discussions carried out in sub-section 4.2.1, the optical pick-up head must have a bandwidth of around 11 kHz for on-line measurement purpose. There are two components within the optical pickup head whose bandwidth actually limits the measurement range. These are the photo-electronic sensing IC and the voice coil actuator.

In case of carrying out measurements only in the focusing mode, the limiting factor for the bandwidth is the photo-electronic detectors. The data sheet provided with the optical reader states that the Hitachi HOP-1000 DVD reader has a -3 dB cut-off bandwidth (Figure 4-21) of 70 MHz, while the typical cut-off frequency in the document has been reported as 100 MHz.
Therefore, the measurements carried out by the optical sensor can accommodate the frequency response requirements of woodworking planers.

While the opto-electronic sensors are capable of carrying out measurements well above the required range, the frequency response of Voice Coil Motor (VCM) drive is the major factor in determining the bandwidth limitation in the focusing method of surface profile measurements. According to the data sheet of HOP-1000 optical reader, the resonance peak of the system can be found at 19 kHz. Thus, the drive can perform the actuation up to that frequency. This is higher than the required frequency response of 11 kHz as determined by previous calculations.

However, in previous investigations, the bandwidth has been found out to be at least 10 kHz (Fan et al., 2001). In accordance to this finding, with the help of this DVD pick-up based surface profile system, it might not be possible to measure the best possible cut width at a very high speed.

In the case of implementing off-line hand-held measurement device, the DVD pickup head can carry out both focusing and auto-focusing measurements as the bandwidth capability is well beyond the requirement of 363 Hz.
4.5.2. Optical mouse sensor

There are also system limitations of the optical mouse sensor when used as a linear encoder to provide positional information to the surface profiling system. The primary limitation imposed on the sensor is the surface texture and the speed of measurement.

It is well documented that the optical mouse sensor doesn't work well with clear surfaces, as the on-board camera fails to distinguish features in these materials. However, any opaque surface yields good measurement results as reported by Ng (2003) and supported by further tests carried by Minoni and Signorini (2006).

![Figure 4-22 Resolution vs. height for ADNS-2051 (Agilent 2002)](image)

Figure 4-22 Resolution vs. height for ADNS-2051 (Agilent 2002)

The mouse sensor demonstrates better resolution when tested on walnut or burl formica surfaces in comparison to white papers (Agilent 2002). This has been demonstrated by the figure presented in Figure 4-22. Thus, it can be safely ascertained that the sensor will work on most planed timber surfaces.

Speed of measurement is also an issue which potentially can influence the accuracy of measurements. There are various optical mouse sensors available in the market with varying capabilities. However in most cases, the commonly used one is the ADNS-2051, which is currently being investigated for this particular research work.

The theoretical maximum speed \( V_{\text{max}} \) at which the optical mouse sensor can satisfactorily perform can be given as –
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\[ V_{\text{max}} = \frac{f \times n_r}{r} \]  \hspace{1cm} (4-11)

where, \( f \) is the frame rate, \( n_r \) is the number of quadrature signal states and \( r \) is the resolution of the sensor given in counts per inch (cpi).

The ADNS-2051 has a normal frame rate of 1500 frames per second and a resolution of 400 cpi. The sensor also guarantees at least 5 quadrature signal states at this frame rate. Thus, the maximum speed can be calculated to be –

\[
V_{\text{max}} = \frac{1500 \times 5}{400} = 18.75 \text{ in/s} = 476.3 \text{ mm/s}
\]

\[
\Rightarrow V_{\text{max}} = 0.4763 m/s
\]

Therefore, the sensor is incapable of carrying out measurements at the maximum feed rate of 1 m/s. Nonetheless, the sensor can carry out the measurements in a hand-held, off-line measurement scenario, where the speed requirement has been determined to be in the region of 33 mm/s. This is well within the capability of the sensor.

Measurement resolution is also an aspect influencing the measurement capabilities of the optical mouse sensor. According to the Figure 4-2, 10 samples must be taken in the 1 mm pitch length to obtain the surface profile measurements. Thus, a resolution of at least 100 \( \mu \text{m} \) or better is required from the optical encoder.

The measurement resolution for the optical mouse sensor can be given as -

\[ \Delta x = \frac{1}{cpi} \]  \hspace{1cm} (4-12)

Thus, for the nominal resolution of 400 cpi for the ADNS-2051, the resolution of measurement comes to –
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\[
\Delta x = \frac{1}{\frac{400}{2.54 \times 10000}} \\
\Rightarrow \Delta x = 63.5 \mu m
\]

This resolution is sufficient and leaves room for up to 36% deviation in measurements when 100 \( \mu m \) resolution is required.

4.6. Filtering

In order to reconstruct the profile of the surface under measurement and to calculate the actual measurement parameters (e.g., \( R_a \), \( R_{sm} \) etc), effective filtering must be carried out on the signal obtained from the measurements. Various common filtering techniques have been discussed in chapter 2, paving the way for more specific discussion on relevant techniques for timber surfaces in this section.

It has been seen that the Gaussian filtering technique has been widely used by researchers to obtain the correct surface profile from stylus measurements. Using the Gaussian filter in surface profile measurements is an attractive proposition due to the simple nature of implementing the algorithm for it. However, it is not robust enough as noted by Raja et al., (2002). The main drawback of this filter is its susceptibility when dealing with surfaces having deep valleys. Wood samples are prone to having such valleys due to the inherited nature of wood and some other composites. Therefore, an enhanced filtering technique is required when dealing with such material.

Hendarto et al., (2005) have carried out a comprehensive study on a robust filtering technique for surface profile measurement of sanded wood. Since the surface profile measurement system presented in this thesis report is intended for a planer providing very good surface finish (i.e. in the micron range), this particular filtering technique can be deemed most suitable. The proposed technique is in fact derived from the standards ISO/DTS 16610-31: 2002(E) and known as robust Gaussian regression filters (RGRF).
In order to implement the filter, the surface profile measurement data using a profilometer must be obtained. Then a polynomial must be fitted into the data to calculate form error using a numerical method using an iterative method or a least squares polynomial fit.

 Afterwards, the form error must be removed from the measured data by subtracting the polynomial estimation from the primary profile to obtain a roughness and waviness profile. The RGRF equations are then applied to this data free from form error.

The filter equation in a discreet form for the RGRF is defined by:

$$\sum_{i=1}^{n} (z_i - w_k^{(m+1)})^2 \cdot \delta_i^{(m)} \cdot s_{i,k} \cdot \Delta x \rightarrow \min_{w_k^{(m+1)}}$$  \hspace{1cm} (4-13)

where, \( n \) is the number of data points in the profile, \( z_i \) is the profile data values before filtering, \( w_k \) denotes the profile values of the filter mean line to be calculated, \( m \) is the index marking the iteration step, \( \delta_i \) is the robust weighting of profile values, \( s_{i,k} \) is the weighting function of the filter, \( \Delta x \) is the sampling interval, \( l \) is the index of the profile points and \( k \) is the index of location of the weighting function in the whole profile with \( s_{i,k} \) obtained from:

$$s_{i,k} = \exp\left(-\frac{\pi^2}{ln(2)} \cdot \frac{(k-l)^2 \cdot \Delta x^2}{\lambda^2}\right)$$  \hspace{1cm} (4-14)

For the first iteration, when \( m = 0 \), the additional weight \( \delta^{(0)} = 1 \) is applied to each data point. In the subsequent iterations, the value of \( \delta \) is given by:

$$\delta_i^{(m)} = \begin{cases} 1 & \text{m = 0} \\ 1 - \left( \frac{z_i - w_i^{(m)}}{c_b^{(m)}} \right)^2 & \text{for} \left| z_i - w_i^{(m)} \right| \leq c_b^{(m)} \\ 0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (4-15)

with
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\[ c^m_B = 4.4478 \cdot \text{median} \left| z_i - w_i^{(m)} \right|, \quad 1 = 1, \ldots, n \]  
\[ (4-16) \]

Profile height that deviates from the mean line by more than \( c_B \), are multiplied by zero. The profile heights close to the mean line are multiplied by a weighting value close to one, and therefore, almost their full value is included in the averaging function:

\[ w_k^{(m+1)} = \frac{\sum_{i=1}^{n} s_{i,k} \cdot z_i \cdot \delta_i^{(m)}}{\sum_{i=1}^{n} s_{i,k} \cdot \delta_i^{(m)}} \]  
\[ (4-17) \]

The iterations are repeated until the difference between the two consecutive median values is smaller than a given tolerance. In their study, Hendarto et al. (2005) has set this value to be 0.1 \( \mu \)m. The exact value corresponding to this particular surface profile measurement scheme will be determined in the latter part of the report.

After applying the RGRF equations to the profile data, the lower valley limit must be calculated. This can be done by first calculating the Abbot curve or bearing-ratio curve of the roughness profile and then calculating its second derivative followed by identifying the first abrupt change in the value of the second derivative. The abrupt changes are determined by calculating the standard deviation of the second quarter of the derivative values, and then adding the data incrementally to the right. The index of the point where ratio of the absolute value of the second derivative to the standard deviation of previous point exceeds a critical value is taken as the index of the inflexion point. The corresponding value of the Abbot curve at this index point is the lower valley limit.

Three methods are then used to filter the data against the valley limit. These methods are:

**Method 1:** if roughness data < valley limit, then roughness data = zero

**Method 2:** if roughness data < valley limit, then roughness data = valley limit

**Method 3:** if roughness data < valley limit, then roughness data removed, i.e., the number of profile data after valley removal will be reduced.
The roughness parameter can then be calculated by the RGRF method using the following equation:

\[
Ra = \frac{1}{N} \sum_{n=1}^{N} z_n
\]

(4-18)

where, \( z_n \) is the roughness profile due to processing or sanding.

In the results published by Hendarto et al. (2005), the results with the help of the three methods show significant improvement over the conventional Gaussian filter. The correlation between the grit number and the three methods is consistently good. However, they were unable to conclude which method gives the best results for a particular species of wood or machining condition.

### 4.7. Discussion on the requirements and capabilities of the sub-systems

The previous sections have described various requirements for the measurement of machined timber surfaces. Discussions have also been put in place to elaborate on the capabilities offered by the two sub-systems proposed for the measurement of surface profile.

From the discussions, it can be seen that the speed requirement for on-line measurement of timber surfaces is somewhat demanding. The feed speed of the timber piece is quite high and hovers around the region of 2 m/s. Also, the cutter mark produced has a consistent repeating pattern with a pitch of approximately 1 mm. This amounts to a required frequency response of the sensor to at least 11 kHz.

As discussed earlier, the system is comprised of two sensors and thus two sub-systems. They work on different principles and have different capabilities in terms of frequency response. The limiting factor for the DVD optical reader is the quad photo-electronic IC assemblies as well as the voice coil motor drive. The photo IC assemblies are fully capable of handling frequencies in the MHz range. But, the voice coil motor has a much smaller range of operation and has been reported in the datasheet to have a maximum frequency response of around 19 kHz. It has been reported by researchers, chiefly by
Fan et al, (2001) that the frequency response of the system is limited to 10 kHz. Thus, this would be an obstacle for the measurement of timber surfaces being fed at a high feed rate.

The other aspect of the surface profile measurement system is the linear encoder made out of the optical mouse sensor. The calculations presented in this chapter clearly shows that the measurement speed of the Agilent sensor is limited to about 0.4 m/s, which is much lower than the industrial feed rate of 1 m/s. Thus, the optical mouse sensor will not be able to carry out the required measurements at the top of the range feed speed.

Another possible use of the surface profile measurement system can be made in hand-held off-line measurements. It has been shown that the speed requirement for this sort of measurement purpose is much lower than the industrial on-line measurement scheme. It has been observed from the calculations that both the optical DVD reader and the optical mouse sensor are fully capable of carrying out the measurements at the required speed for off-line measurements.

Thus, it can be ascertained that the proposed surface profile measurement system is highly effective for profile measurements in lower-speed off-line measurements. This system can also be successfully employed in a given process line where the feed speed of the material is not in the higher end of the industrial feed speed range of 5 – 120 m/min.

4.8. Summary

- There are various requirements for the systems used to evaluate the profile of machined timber. The requirements are slightly different for on-line and off-line measurements.

- The main constraint associated with profile measurement is the speed at which the measurements are carried out and consequently the bandwidth requirement for the sensors.
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- Off-line measurements are carried out at lower speeds in comparison to the on-line measurement scheme and thus require lower sensor bandwidth than the latter.

- It has been determined that the optical DVD reader is capable of carrying out measurements for both the high and low speed applications. However, the sensor might not be able to fully measure the surface profile at the highest feed speed of material.

- The optical mouse sensor is also incapable of carrying out measurements at the top feed speed. The sensor can satisfactorily measure at a feed speed of up to 0.4 m/s. Nonetheless, it can satisfy the bandwidth requirement for the lower-speed off-line measurements.

- An effective filtering technique is also required to recover the roughness profile of the machined timber from the raw measurement data. The robust Gaussian regression filter (RGRF) has been identified as the most suitable filter for this purpose.
Chapter - 5.

Sub-system Design and Initial Calibration Tests

5.1. Introduction

This chapter introduces the design of sub-systems involved in the measurement of surface profile. Various validation tests for the sub-systems are also included in the chapter. There are basically two sub-systems within the proposed surface profile measurement system. The DVD optical reader based system and its signal conditioning unit is the main profile measurement sub-system, while the optical mouse encoder compliments the probe with positional information on the measured piece. The sub-systems are developed and tested separately. The integration of the two sub-systems will be discussed in the latter part of the thesis.

5.2. DVD Probe signal conditioning in focusing mode

As pointed out earlier, the DVD probe can be used in both focusing and auto-focusing configuration. According to Islam et al. (2006), the focusing mode of operation is more suitable for finer measurements with highly reflective surface, while the auto-focusing mode is more appropriate for measuring less ideal surface due to the nature of reflection obtained from the surface. The auto-focusing mode provides a higher linear region of operation and possible compensation for the lower reflectivity. Suitability of both systems from this operational aspect will be discussed later in this chapter.
5.2.1. Signal conditioning requirements

The first stage of building the system to acquire surface roughness data is to provide the pickup head with the necessary power and signal conditioning interfaces. The following sub-sections provide detailed coverage on the hardware architecture of the system.

5.2.1.1. FES Signal Conditioning

![FES signal conditioning scheme](image)

The photo-detector of the DVD pickup provides electrical voltage output according to the incident light on its four quadrants (Figure 5-1). The Focus Error Signal (FES), which is pivotal in the proposed measurement scheme, can be obtained by the following equation (Hnilicka et al, 2005):

\[
FES = (V_1 + V_3) - (V_2 + V_4)
\]  

(5-1)

where, \(V_1\) = voltage output of quadrant A, \(V_2\) = voltage output of quadrant B, \(V_3\) = voltage output of quadrant C and \(V_4\) = voltage output of quadrant D.
5.2.1.2. Signal Conditioning Circuit

The following analog signal conditioning circuit has been proposed by Fan et al. (2001) for this purpose (Figure 5-2).

![Signal conditioning circuit proposed by Fan et al (2001)](image)

The first operational amplifier (Op-amp) obtains the voltages A, B, C and D from the four-quadrant detector and performs the calculation in accordance to the FES equation.

The second amplifier works as an inverting buffer. As the output from the photodetectors is extremely small, amplification is needed to produce larger voltage. In the third stage of signal conditioning, this amplification is carried out. The fourth and last stage of the processing involves the filtering of signal. Since noise can be induced on the obtained signal (e.g., from the power supply mains), it is advisable to perform this operation. Also a zero-span adjustment is carried out in this stage.

Although this setup is theoretically correct, some practical limitations would severely affect the proper functioning of the circuit. First and foremost, the discrete op-amps have finite resistance input which is not same for the positive and negative inputs (kitchin and Counts 2006). Therefore, when voltage is applied to one input while grounding the other, different currents will flow depending on which input receives the applied voltage. This unbalance in the sources’ resistances will degrade the circuit’s CMRR. A high CMRR is imperative for a better noise rejection and proper amplification of signals.
Furthermore, this circuit requires a very close ratio match between the resistor pairs; otherwise, the gain from each input would be different—directly affecting common-mode rejection. For example, at a gain of 1, with all resistors of equal value, a 0.1% mismatch in just one of the resistors will degrade the CMR to a level of 66 dB (1 part in 2000). Similarly, a source resistance imbalance of 100 Ω will degrade CMR by 6 dB.

Secondly, the feedback resistors on the second and third stages have been used to adjust the amplifier gain. This is also correct theoretically but would not work well in a practical scenario. If the value of the feedback resistor falls below the branch resistor, a reduction in amplification will take place instead of amplification. Furthermore, the system will also become unstable if the feedback resistance reaches zero and will work only as a comparator as opposed to an amplifier (Boylestad and Nashelsky 1999). Thus, the feedback resistors cannot be used as the variable adjustment for the amplifier circuit.

Figure 5-3 Proposed amendment to the approach by Fan et al (2000)

In a signal conditioning scenario like this, the best approach is to use Instrumentation Amplifier (IA) instead of discrete op-amps (Johnson 2003). The IA offer very high and equal signal input resistance. The amplifiers are all matched inside, providing excellent noise immunity, high signal to noise ratio (SNR) as well as very compact footprint. For
this project, the low-noise INA118P from Burr Brown has been chosen. The schematic diagram of the IC is given in Figure 5-4.

![Schematic diagram of INA118P from Burr Brown](image)

**Figure 5-4 Construction and schematic of INA118P from Burr Brown**

The gain function for the INA118P is given by:

\[
G = 1 + \frac{50k\Omega}{R_G}
\]  \hspace{1cm} (5-2)

The trim resistance \(R_G\) can be set up to provide the required level of signal amplification. According to the data sheet of the HOP-1000, the output of the FES signal from the sensor is 0.37 V. For interfacing the sensor to an ADC, the required voltage level is determined to be 5 V. Thus,

\[
G = \frac{V_{out}}{V_m} = \frac{5}{0.37} = 13.51
\]

Now, substituting the value in equation 5.2 gives:

\[
R_G = 3.7k\Omega
\]

Thus, the resistor valued at 3.74 kΩ was used for the signal conditioning circuit as it matched closely to the aforesaid calculated value.
The complete circuit diagram is given in Figure 5-3, while the fabricated circuit has been shown in Figure 5-5.

5.2.1.3. Automatic Power Control (APC)

The output power of the laser diode is sensitive to the ambient temperature. Thus to keep the laser power under control, an automatic power control circuit (APC) has been devised by Fan et al, (2000). The APC has been designed to monitor and control the driving power of the laser diode through a power detector and reference voltage. The authors have reported that the input voltage of the laser diode could be maintained within ±0.03V during a four hour run. Without the power control circuit, this would result into a 0.6 V drift. Considering that it is a good improvement, the same scheme has been adopted in this research work. The circuit diagram of the APC is given in Figure 5-6.

![Automatic Power Control Circuit](image)
5.3. **DVD Probe Sub-system Calibration Tests**

In order to calibrate the DVD probe, the following setup in Figure 5-7 has been adopted. A flat highly reflective smear-free mirror was mounted on the precision stage. The stage can move horizontally with a resolution of $0.5 \mu m$. However, the digital readout couldn’t be stably read with the $0.5 \mu m$ and thus a resolution of $1 \mu m$ was used for the calibration purpose.

The optical head was mounted on a stand in front of the mirror and adjusted to an optimum distance away from the mirror. This distance was found empirically through a trial and error method. The distance was found to be approximately 1.7 mm. A Philips precision Digital multi-meter (DMM) was used to record and log the analog data. The distance was read through an incremental encoder-based digital system from Sony. The readout has a precision of $0.5 \mu m$ but as mentioned earlier was used to provide a resolution of only $1 \mu m$ due to the instability in measurement.

![Figure 5-7 Calibration setup for the optical DVD sensor](image-url)
The calibration setup with the mirror and DVD probe can be seen more clearly from Figure 5-8. The distance from the actual base of the stand and the DVD probe has been adjusted so that Abbé error can be avoided.

![Figure 5-8 A Close-up view of optical head and mirror in the calibration setup](image)

Another calibration setup for the optical probe has been shown in Figure 5-9. This is a much more compact setup. There is a precision X-Y precision stage in the setup, while the Z-direction position can be setup using the dial gauge on top.

However, it is different than the one discussed previously. Instead of varying the stand-off distance to calibrate the sensor with the help of the precision stage, the stand-off distance is varied with the help of the VCM which drives the objective lens of the probe. Then at each position of the lens, the value of the FES signal is recorded. This is then used to plot the calibration curve for the sensor.
Figure 5-9 A more compact calibration setup
A close up view of the setup is also shown in Figure 5-10. It can be seen from the figure that the optical probe is held at a certain distance from the surface of the material. It has been observed through a series of measurements that a stand-off distance of 1.5 mm from the test surface is optimum. This distance is adjusted with the gauge on top as shown in Figure 5-9.

![Setup View](image)

Figure 5-10 An up close view of the calibration and measurement setup for the DVD optical lens with a black nylon sample

### 5.3.1. Calibration Tests with Mirror

A typical calibration or S-curve has been shown in Figure 5-11. As stated earlier, the measurement resolution is 1 µm i.e. measurement was taken for every micrometers. It can be observed from the curve has a linear range of approximately 30 µm. This is the operating region of the DVD probe for surface profile measurement. A normalization technique can be applied to the system that will increase this linear region of operation. It is interesting to note that the data-sheet of the reader actually reports this linear range to be only 6 µm and literatures published by Fan et al (2000, 2001) show a linear range
of no more than 20 μm. Thus, the result reported in this thesis is significantly better than what has been stated in the past by the aforesaid researchers.

![Figure 5-11 Calibration test result (S-curve) with the help of a mirror](image)

The forward and backward pass is showing exactly the same curve but with a shift in the horizontal plane. This can be attributed to the hysteresis of the linear stage itself and found to be as 3 μm. Calibration error curve of the stage obtained through interferometer is in good agreement with this value. This effect of hysteresis can be overcome by moving the stage to the end of its length and then bringing it back to the starting point. This same principle has been applied later while carrying out the focusing of the DVD probe.

It can also be observed from the curve that there are multiple small side-curves along with the main S-curve. According to Pohlmann (1989), a CD player has two types of focusing systems, one containing three beams and the other only one. The three beam system (peculiarly resembling the spectrum of an Amplitude Modulated (AM) signal) is more widely used due to its simpler focusing and tracking mechanism. The principle beam is used to read data off the CD surface, while the side-beams are used for tracking the disc. The smaller calibration...
response that can be seen in addition to the main s-curve is generated by these two side-beams. A single-beam reader head should essentially be free from such phenomenon.

More statistical analysis of the linear region for the plain mirror has not been carried out in this thesis. Rigorous analysis of this sensor of ideal surfaces have documented by various researchers as seen in the literature review part of this thesis. Furthermore, the main objective of this research project is to analyze the suitability of this sensor on non-ideal materials, e.g., timber, nylon etc. Thus, detailed analysis of this FES region for timber and nylon has been provided in the following sub-sections.

5.3.2. Calibration Tests with Timber

![Wood sample for the calibration tests](image)

Figure 5-12 Wood sample for the calibration tests

The following figure (Figure 5-13) shows a calibration curve obtained on a piece of Spruce, which closely resembles a piece of timber used in industry.
As explained in the previous sections of this report, the FES response has both the actual response region as well as the response region due to the tilt error of the sensor. The linear region (or the S-curve as commonly known) consists of two linear regions, which are from 1.631 mm to 1.641 mm and 1.641 to 1.651 mm.

The first linear region is shown in Figure 5-14. The linear regression curve-fitting technique was used to determine the linearity of the measurement data. This is a commonly used technique and has also been adopted among others by Fan et al. (2001). The coefficient of determination of the linear region is also calculated to give a quantitative feel to the linearity analysis.
It can be seen that the coefficient of determination ($R^2$) of the curve is 0.9649. According to well-established statistical theory on regression, the closer the value of $R^2$ is to 1, the better the linearity of the data points used in the analysis. In this case, it can be seen that the value is quite close to 1.

The linear region of 1.641 mm to 1.651 mm yields a $R^2$ value of 0.9563 (Figure 5-15). This is almost similar to the one obtained from figure 5, having a deviation of merely 0.44%.

Figure 5-14 Linear region of the FES curve (1.631 to 1.641 mm)

Figure 5-15 Linear region of the FES curve (1.641 to 1.651 mm)
In line with the calibration test just described, more tests were carried out on different regions of the piece of timber under test. This was done to observe the differences in calibration results on different regions of the sample.

![Figure 5-16 FES response for a second region of timber](image)

The FES response curve for a second region of the sample is given in Figure 5-16. It can be seen that the curve looks similar to the one reported earlier. The tilt distortion can also be noted from the response.

The linear range for this region of the sample can be found in three different places of the response curve. They are from 1.565 mm to 1.571 mm (Figure 5-17), 1.571 mm to 1.58 mm (Figure 5-18) and 1.58 mm to 1.587 mm (Figure 5-19).
The measure of linearity of the linear regions \( R^2 \) is found out to be 0.9686, 0.9526 and 0.9298. The deviations are slightly higher than the ones found in earlier analysis for the first region. However, they are quite close to each other and also close to unity. Therefore, it can be safely assumed that linearity exists between the focus distance and the response of the sensor.

An interesting thing to note is that the slope of the linear fit line is very close to each other for the same region of interest (increasing or decreasing S-curve region). Figure 5-14 and Figure 5-18 represent the same region of the S-curve (increasing trend) for two
different region of the timber sample. But their slope value is very close to each other, 29357 and 24303 respectively. Variation between the two measurements is around 9%.

![Graph showing sensor output vs. distance from timber](image)

**Figure 5-19** FES Linear region of 1.58 to 1.587 mm for region 2 of timber

But for the decreasing trend (Figure 5-15 and Figure 5-19), this variation is more and stands at about 16%. This could be due to the fact that one measurement was taken around the relatively darker region of the sample, while the other one in lighter region.

Despite some variation in the slope, the values agree with the fact that, the same materials will have same (or similar) slope values (Fan *et al*, 2001). It can be attributed to the sensor's response to different materials.
5.3.3. Calibration Tests with Black Nylon

Calibration tests similar to the ones reported in the previous two sub-sections have been carried out on a sample of black nylon (Figure 5-20). A total of ten trials were carried out on the same point of the nylon sample under test and the average of these trials was then taken as the reference calibration curve. These curves are shown in Figure 5-21.

Figure 5-20 Black nylon sample

Figure 5-21 FES curve for black nylon
The calibration curves show similar s-shape of the FES curve as reported previously. As pointed out in Figure 5-21, the linear range of response can be divided into two regions. The response curve of region 1 is shown in Figure 5-22, while region 2 is depicted in Figure 5-23.

![Figure 5-22 FES curve of region 1 (8 μm linear range)](image)

Due to the non-ideal nature of the surface, it can be observed from Figure 5-22 that the linear range the FES curve is much smaller than a mirror and is equal to 8 μm. However, region two gives a 50% larger linear range of 12 μm. When the curve from region one is fitted to a straight line, the coefficient of regression is found to be 0.9685. This shows that the response curve is fairly linear in nature.

![Figure 5-23 FES curve of region 2 (12 μm linear range)](image)
The curve of region two, when fitted with a straight line, yields a coefficient of regression of 0.9962. This demonstrates excellent linearity of the curve in this region. As mentioned earlier, the linear range of operation is also substantially increased in this region. Thus, the profile measurements carried out on this sample will be done in this section of the FES curve.

It is worth mentioning here that, no other research have previously shown that this sensor works for such a dark, non-ideal material.

### 5.3.4. Calibration Tests with White Nylon

A typical white nylon sample is shown in Figure 5-24. The cutter marks surface on the edge of the sample is evident from this figure.

![Figure 5-24 A white nylon sample](image)

The static calibration test on the nylon is shown in Figure 5-25 obtained using the calibration setup described earlier. It can be observed that the linear region of the probe for this material is about 18 $\mu$m.
Chapter 5: Sub-system Design and Initial Calibration Tests

Figure 5-25 Calibration curve for a white nylon sample

The linear region of interest is approximately from 0.207 to 0.210 mm. This linear region is shown in Figure 5-26. The regression analysis of the calibration curve in this region shows that a straight line could be fitted with a coefficient of regression of 0.9849, which is a very good fit, thus confirming high linearity of the FES response of the sensor.

Figure 5-26 Calibration curve of region one (linear range of 13 \(\mu m\))

Another detailed analysis of region two has been carried out, which is reported in Figure 5-27. This linear region is much smaller than region one and stand at only 5 \(\mu m\). Nevertheless, when fitted with a straight line, the coefficient of regression is obtained as 0.9818.
As in region one, this value of $R^2$ also corresponds to a high degree of linearity of region two. However, since the range of this region is substantially smaller (in the order of about three times) than region one, the first region is used to carry out the required surface profile measurements.
5.4. **DVD Probe Sub-system Design for Auto-focusing Mode**

It is apparent from the previous section that the measurement range of the DVD profilometer is somewhat limited to 30 μm in case of ideal surface (i.e. a plain mirror) or about 12 μm in case of timber. Thus, in order to meet the requirement of industrial measurement, the focusing mechanism of the objective lens must be effectively energized and controlled to achieve a measurement range of about 30 μm for timber or similar non-ideal surfaces. This section deals with the design and implementation of this auto-focusing mechanism required to drive the Voice Coil Motor (VCM) attached to the objective lens to achieve this required focusing range.

**5.4.1. Actuator Driver**

The signal processor or microcontroller unit used to implement the VCM controller is unable to source enough current to drive the VCM itself. The microcontroller used for this purpose, the PIC 18F4523 can source a maximum of 25 mA. However, the VCM drive requires a current of 120 mA. Thus, it can be ascertained that there is a need for external circuitry to drive the VCM capable of supplying much higher level of current in comparison to the nominal current supplied by the microcontroller.

The VCM is usually powered by a current driver according to the literature published by Oboe et al (2005). This driver is realized by setting up a feedback loop, in which the actual output current is sensed by means on a resistive shunt. The difference between the reference voltage provided by the controller and the actual current is amplified by the power linear amplifier. The schematic diagram of Figure 5-28 shows the simplified version of this configuration.
The main advantage of this configuration is that the current flowing in the VCM does not depend on the motor’s electrical impedance and the rotational speed (i.e. the back EMF). Apart from that, the performance of the current driver is independent of the variations of power supply voltage. Roughly, the transfer function between reference and actual current is constant, thus making the design procedure simple. However, this simplicity makes the system bulky by contributing to increase in components and also the higher power dissipation requirement. These can be overcome by the more complicated voltage driven configuration as demonstrated by both Oboe et al (2005) and Sohn and Chainer (1990). Due to the complexity of this configuration and this topic being beyond the scope of this thesis, discussions on the two configurations have been left out.

The current driver configuration has been implemented in this project to drive the VCM coil of the objective lens due to its system design simplicity.

The circuit diagram on Figure 5-29 shows the implemented circuit of the VCM drive for this surface profile measurement scheme.
The Darlington pairs of TIP110 and TIP116 switches the high current required to drive the VCM lens as mentioned earlier. The VCM drive is powered from the +/-5 V sources. The low noise OPA222 op-amps have been used to construct the low-pass amplifier as well as the analog interface between the controller and the VCM drive. The controller input to the system comes from the PIC 18F4523 based IENSYS microcontroller board, which is discussed later in the next chapter.
5.5. DVD Probe Sub-system Validation Tests in Auto-focusing Mode

In order to formulate an effective auto-focusing control technique for the optical sensor, the response of the Voice Coil Motor (VCM) to voltage or current excitation must be measured first. The static head movement analysis of the VCM-driven objective lens of the DVD pickup head was carried out using the OGP Smartscope 200 Flash microscope, calibrated to UKAS certification. The system is shown in Figure 5-30.

![OGP Smartscope 200](image)

Figure 5-30 OGP Smartscope 200

The microscope has a repeatability of 2 um and resolution of 0.5 um. The optical reader head without any input was placed underneath the scope and an auto-focus lock of the scope was obtained. The VCM drive was then energized and the voltage was set to a certain value (say 0.25 volt). The microscope was then again auto-focused to this new position. The change in z-axis value of the auto-focus determined the movement of the lens with this energizing signal of 0.25 V. In this same manner, a series of measurements were taken and the movement of the lens along with the input voltage was recorded. The resolution of input was set at 100 mV, striking a balance between the accuracy needed and the time taken to carry out the calibration tests.

The response of the VCM driving the objective lens is shown in Figure 5-31. The motor was excited by voltage input of -5 to +5 volts. The corresponding displacement can be observed from the figure.
Figure 5-31 VCM displacement analysis

It can be observed from the above figure (Figure 5-31) that, the movement of the lens reaches saturation point beyond the inputs of +3 or -3 volts. Thus, in the following tests, the input voltage was varied between +3 and -3 Volts. It is worth mentioning here that, the actual amplifier circuit driving the VCM can provide voltage up to +5/-5 V.

Figure 5-32 VCM displacement analysis without saturation

The input voltage was thus limited to the +3 to -3 V range. Figure 5-32 and Figure 5-33 clearly shows the highly linear nature of the VCM’s response to varying voltage. This linearity is highlighted by the high correlation coefficient ($R^2$) of 0.996. These two
measurements were conducted under identical circumstances (room temperature, duration etc).

In both cases, the sensitivity of the VCM can be found out to be 0.349 mm/V. This in turn means that in order to move the objective lens by 1 µm, a voltage of 2.865 mV must be applied to the VCM drive.

![Figure 5-33 A second measurement to determine VCM displacement](image)

The repeatability of the displacement of the objective lens can be observed from the figure below (Figure 5-34).

![Figure 5-34 Repeatability analysis of the VCM drive](image)
In this figure, the red line represents the first measurement, while the blue line shows the second measurement. In can be seen that both the curves are perfectly superimposed on one another, thus confirming the high repeatability of VCM’s positioning of the objective lens.

![Figure 5-35 Time-delayed testing of VCM's displacement](image)

The coils of any electrical machine are susceptible to heating produced by the ohmic resistance of the coil, which is also known as the $I^2R$ loss (Fitzgerald et al, 1992). This heating effect could lead to the degradation of the performance of the system.

Thus, in this case, a time delayed testing was carried out to determine the influence of this heating effect of the VCM’s coil on the positional accuracy of the objective lens. The result of the test is reported in Figure 5-35.

At first the coil was energized with a certain voltage and the positional measurement was taken. After 5 minutes, the positional information of the objective lens was again recorded at the same input voltage. It can be seen from Figure 5-35 that the positional value of the lens was at time zero and then after 5 minutes very closely corresponds to each other. When fitted with a straight line, the coefficient of regression of both the curves is 0.9939. Thus, it can be concluded that, due to the embedded power control circuit of the VCM drive, the variation in positional accuracy due to the coil heating effect is negligible.
5.6. **Optical mouse encoder signal conditioning system**

In chapter 3, the optical mouse based non-contact encoder has been proposed to provide positional data for the profile measurement system. The mouse sensor ADNS-2051 comes complete with an image acquisition and processing system. It also houses a Serial Peripheral Interface (SPI) in order to pass on the measurement data to a PC or microcontroller. This section of the thesis deals in details with the design, implementation and calibration of this encoder.

### 5.6.1. Sub-system design and implementation

Development of an optical mouse sensor based non-contact encoder involves both hardware interfacing and also software programming. The programming task can be divided into two parts; one being programming the PIC microcontroller and the other is the PC based program to carry out data acquisition and analysis.

#### 5.6.1.1. Hardware Interface

The ADNS-2051 IC comes in a complete package and thus needs very little external peripherals. However, an 18 MHz crystal oscillator is required to provide timing information for its internal circuitry. Also, some capacitors are needed for blocking DC voltage in the terminals to prevent the IC from reverse voltages.

The connection block diagram is given in Figure 5-36.

![Connection diagram for the ADNS-2051 based encoder](image)

**Figure 5-36** Connection diagram for the ADNS-2051 based encoder

The circuit interfacing diagram is given in Figure 5-37, while the implemented circuit is shown in Figure 5-38. The protocol for the ADNS-2051 to communicate with other peripherals is termed as ‘Serial Peripheral Interface’ or in short form as SPI.
Figure 5-37 Embedded micro-controller based data acquisition system

The PIC 18F2320 microcontroller from Microchip Inc is used for acquiring data from the mouse sensor. The PIC then converts the data into TTL format, which is passed through the MAX233 from Analog Devices. The MAX converts the data to RS-232 serial format and connects the whole system to a Personal Computer (PC). The PC is basically used as a data logger as well as analyzing the results. Microsoft Excel software is used to generate the measurement curves and carry out the statistical analysis.
5.6.1.2. Software

As mentioned previously, development of software for the system involves two types of programming practices. Microcontroller based software along with a PC-based one must be developed to compliment each other.

The flowchart to accomplish the task for acquiring data from the ADNS IC is in Figure 5-39. The microcontroller waits until the flag that encoder data is available is set. Then it starts to read the fields of data having the encoder information. Once that is done, that particular information is put into a format like the following:

*data1, data2, data3, data4#
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Figure 5-39 Flowchart for reading data from the ADNS to the PIC

The ‘*’ sign denotes the start of data and the ‘,’ sign separates the data fields from each other. The ‘#’ sign signifies the end of the data line. By putting the data in this format, it is ascertained that the data stream sent to the PC for data logging and further analysis contains the actual data and not other information.
The flowchart to obtain measurement data is given in Figure 5-40. At first the RS-232 link is configured to match the baud rate and other parameters as being setup in the PIC microcontroller. In this case, the following configurations (shown in Table 5-1) were setup in both the PIC and PC:

| Baud-rate: 19600 | Data bits: 8 | Parity: None | Stop bits: 1 |

Table 5-1 Serial link settings between the embedded microcontroller and the PC

The program then searches for the start of data line symbol of ‘*’ in the data stream. Once that is found, the data values are taken and stored as integers. The end of line symbol ‘#’ ends the program and it return to the polling mode for further data. The stored values are manipulated to obtain the encoder information. The software interface created with the help of Visual Basic program for this task is given in Figure 5-41.
Various options are available through the interface as shown in the figure. There are provisions to obtain information regarding average velocity, measured distance and measurement duration among others. The interface also provides the option to save the preferred measured value.
5.7. **Optical mouse encoder calibration tests**

The setup for the optical mouse calibration is shown in Figure 5-42. The optical mouse sensor is held above the sample at an optimum height of 2.4 mm. Since it has been shown by Ng (2003) that significant loss of feature can occur with increasing stand-off distance, it is necessary to correctly place the mouse sensor over the wood sample.

The lead-screw driven stage is used to provide the scanning motion. An inexpensive DC motor driven stage is used for this purpose.

![Figure 5-42 Calibration setup for the optical mouse based encoder](image-url)
5.7.1. Effect of stand-off distance in measurement results

It has been reported previously that the stand-off distance of the optical mouse sensor affects the measurement of the encoder (Ng 2003). This is also evident from the data sheet of the ADNS-2051.

![Graph](image)

Figure 5-43 Measurement error at different stand-off distances (sample length of 138.2 mm)

The effect of stand-off distance on the measurement of the optical mouse encoder was measured using the setup shown in Figure 5-42. The average error count from 20 measurements at various stand-off distances has been shown in Figure 5-43. It can be observed that the optimum stand-off distance is in the region of 2.4 mm. This figure is in agreement with the aforementioned literature.
The repeatability error of the measurement of the encoder at the optimum stand-off distance has been measured and shown in Figure 5-44. The results show that the maximum measurement error at the optimum stand-off distance is around 1.7%, which indicates a very low repeatability error of the optical mouse based sensor. It is worth mentioning here that the measurement error between the stand-off distance of 2.1 mm and 2.7 mm is somewhat low, about maximum 5% compared to more than 60% at 2.9 mm. Thus, it can be concluded that the encoder can be used with reasonable repeatable accuracy when the stand-off distance is between 2.1 and 2.7 mm, with 2.4 mm being the optimum value.
5.7.2. Calibration tests on timber

The calibration results obtained through both PC-based and a microcontroller based systems are given in this sub-section.

![Calibration graph acquired through a PC-based system](image)

Figure 5-45 Calibration graph acquired through a PC-based system

The graph obtained from a PC-based data acquisition system is shown in Figure 5-45.

A light-colored piece of timber with length of 42.6 mm was measured with the help of the encoder and the figure shows the results for 20 measurement trials. The standard deviation (SD) of the measured value is calculated as 0.3691.

Due the fact that PC-based measurement schemes do not offer real-time data acquisition as a result of various running background processes, an embedded microcontroller-based system was developed to see whether the latter solution provides improvement to the acquired data or not.
The result obtained through the embedded system is shown in Figure 5-46. It can be seen that the variation in measurement result is much lower than the previous case. This is demonstrated by the fact that the standard deviation fell to only 0.2 from the previous value of 0.37. This is actually a 45% improvement in terms of reduced deviation among trials.

![Figure 5-46: Data acquired through embedded microcontroller-based system](image)

The above figure (Figure 5-47) reports the errors of 20 trials of measuring a timber sample with nominal length of 42.6 mm. These measurements are carried out using a PC-based measurement system. It can be observed from the figure that the percentage
error of measurement can be as high as 38%. The average percentage error has been calculated to 11%.

![Error Chart](image)

**Figure 5-48 Measurement error for nominal length of 42.6 mm acquired using a microcontroller-based system**

A marked improvement in the error count can be observed for the same sample from Figure 5-48, where a microcontroller based system has been used to acquire the measurement data. It can be seen that the peak percentage error has been reduced almost ten-fold to about a maximum value of 4.5%. The average error count is also significantly reduced and stands at 2.47%.

Thus it can be said that a microcontroller based system has greatly reduced repeatability error and absolute error in measurements when compared to the PC-based system.
5.8. Summary

- The system proposed in Chapter-3 to measure surface profile has been realized in this chapter.

- The system as described earlier in the thesis has been broken down into two sub-systems. An optical DVD reader-based sub-system is used to measure the height of the machined sample, while an optical mouse-based sensor is used as an encoder to provide the positional information on the point of measurement.

- A component-by-component description and design of the sub-systems have been documented.

- The calibration setup of the sub-systems along with preliminary calibration results have also been reported in this chapter.

- Initial calibration results for the DVD reader with a mirror have been reported. Calibration results involving natural timber have also been shown. As expected, the linear region of operation for the sensor has been found to be $30 \ \mu m$ for a mirror. Most importantly, it has been reported that there is a linear region of operation for the sensor when used with timber. This has been seen to be much smaller and stands at roughly $12 \ \mu m$.

- The optical mouse sensor has been calibrated using timber and has shown to provide very good repeatability and low errors when used with a microcontroller-based system as opposed to a PC-based system first developed.
Chapter - 6.

Control System Design for the Auto-focusing Mechanism

6.1. Introduction

The previous chapter has reported initial calibration results of the optical DVD reader. From these results, it can be seen that the measurement range of the sensor is understandably somewhat limited when used on timber. As discussed in chapters 3 and 4, industrial requirement of measuring cutter-mark depth stands at about 30 μm, while the sensor can provide up to about 12 μm as reported in chapter 5. Thus, it can be clearly seen that the range of measurement needs to be increased in order to successfully implement the system in a commercial woodworking environment. In order to achieve this increase in measurement range, the auto-focusing mechanism embedded inside the sensor must be used. This chapter deals with the control mechanism of this Voice Coil Motor (VCM) drive to achieve effective increase of measurement range.

6.2. System Identification

The previous chapter has in details described the VCM actuator drive system and reported calibration data for the system. In order to control the movement of this VCM, an effective control system along with actuator drive is required. To design and tune the controller, first and foremost, understanding of the characteristics of the plant (i.e. the VCM actuator) is necessary. This section of the thesis discusses how identification of the system has been carried out in order to select the appropriate controller.

The VCM system of the objective lens actuator was excited with a sinusoidal waveform of a fixed voltage by the analogue signal generator, TG120 from Thurlby Thandar Instruments. This input voltage was set to 2V peak to peak with the maximum input to
the system has been earlier identified as 6 V peak to peak. A Laser Doppler Vibrometer (LDV) VH300 from Ometron was used to measure the movement of the objective lens. A four-channel digital oscilloscope, TDS 2004B from Tektronix was used to simultaneously measure the input and output of the VCM system.

The frequency of the input at the fixed amplitude was varied from 0 Hz to 1 kHz and for each frequency, the amplitude vibration and vibration of the lens was measured. The frequency response curve of the system was drawn using the commonly used Bode plot.

If $G(j\omega)$ is the transfer function of the system in frequency domain, then,

$$G(j\omega) = |G(\omega)| e^{i\phi(\omega)} \quad (6-1)$$

where $\phi(\omega)$ is the phase and $|G(\omega)|$ is the magnitude.

The logarithmic gain of the system becomes,

$$G_{db} = 20\log_{10}|G(\omega)| \quad (6-2)$$

which is expressed in decibels (dB).

This logarithmic gain and the phase of the system were plotted and the results are shown in Figure 6-1.

From the first observation, it is obvious that the resonant frequency at which the output of the system peaks is at 48 Hz. However, this information alone is not sufficient to identify the system.
Further analysis shows that, the magnitude plot of the system has two asymptotes. The low frequency asymptote gives the DC gain of the system (Dorf and Bishop 2001). It can be observed that the high frequency asymptote drops off at -40 dB per decade and the high frequency phase asymptote is -180°. These two observations support the fact that the system has two more poles than zeros. When compared with the Bode plots of different order systems given in (Dorf and Bishop 2001), it can be seen that the transfer function of the VCM can be given by:

\[ G(s) = \frac{K}{(s\tau_1 + 1)(s\tau_2 + 1)} \]  \hspace{1cm} (6-3)

Further analysis shows that the system in equation (6-3) can be simplified to:

\[ G(s) = \frac{G_{\infty} \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  \hspace{1cm} (6-4)

Thus, this is a second order system with a damping ratio of \( \zeta \) and natural frequency of \( \omega_n \).
From Figure 6-1 it can be observed that, the two high and low frequency asymptotes meet at a frequency of 50 Hz. Thus, this can be taken as the natural frequency of the system, i.e., \( f_n = 50 \text{ Hz} \). This yield,
\[
\omega_n = 2\pi f_n = 2\pi \times 50 = 314.16 \text{ rad/s}
\]
According to Dorf and Bishop (2001), the damping ratio of \( \zeta \) can be found from the following relationship:
\[
\text{Height above DC gain} = \frac{1}{2\zeta}
\]
Thus from the bode diagram of the system in Figure 6-1,
\[
\frac{1}{2\zeta} = 8dB
\]
\[
\therefore \zeta = 0.199
\]
And the DC gain of the system is,
\[
G_{dc} = 10dB = 3.162
\]
Substituting these values in equation 4, the complete transfer function of the system is,
\[
G(s) = \frac{312.08e3}{s^2 + 125s + 98.7e3}
\]
The -3dB bandwidth of the system, shown in Figure 6-1 stands at 75 Hz. However, with the resonant frequency at 48 Hz, the maximum practical bandwidth of the system is less than 48 Hz. For industrial applications, the bandwidth of the system needs to be much higher than this, in hundreds of Hz if not thousands as discussed in chapter 4.

### 6.3. Control system design for the actuator drive

The auto-focusing of the objective lens is carried out with the help of the VCM. In order to precisely control the actuation of this VCM, an effective control scheme must be implemented.

Zhang and Cai (1997) as well as Fan et al (2001) have proposed a similar method for control, though the first authors have used the controller to control the PZT drive rather than the VCM.
Due to the constraints of high power requirements, PZT drive has not been implemented in this research work. The control loop for the servo mechanism to control the VCM is shown in the figure below (Figure 6-2).

![Figure 6-2 Control loop for the auto-focusing mechanism](image)

In the literature, Fan et al (2001) have described the mechanical system inside the pickup head as second order forced vibration system. The transfer function using Laplace transform has been given as:

\[
\frac{X(s)}{F(s)} = \frac{1}{ms^2 + cs + k}
\]  

(6-7)

where, \(k\) is the spring constant and \(c\) gives the damping coefficient of the system.

**6.3.1. Control Principle**

According to Astrom and Hagglund (1995), PID control is sufficient when the process to be controlled is of second-order. They have shown that there are no benefits gained by using a more complex controller in this case. Thus, the chosen controller for this auto-focusing system will be the PID type.

Proportional, Integral and Derivative (PID) control technique is perhaps the most widely used one in process industries as well as in research (Kristiansson and Lennartson 2006). Owing to the simplicity of implementing and tuning such a controller, it can be safely said that majority of industrial controllers are variants of a PID in one form or another.
This chapter discusses the use of this versatile control technique to effectively drive the auto-focusing mechanism of a surface profile measurement probe. It has been shown that a robustly tuned PID controller can provide the desired closed loop responses of fast settling time, reasonable overshoot, loop disturbance rejection, high system bandwidth and so on. Comparisons to performance are also drawn to controllers tuned with another method namely the most recognizable Ziegler-Nichols (ZN) method. Simulation results show marked improvement to system response parameters when a robust tuning mechanism is employed compared to the aforesaid ZN method. It can be concluded that due to the nature of the profile measurement system, a robust PID controller is the most effective control strategy for such a system.

In order to ensure smooth and efficient running of any industrial process or system within a given operating range and environment, a properly designed and tuned controller is an absolute necessity. The control system required in each case depends on several factors ranging from plant dynamics to rejection of load disturbance (Astrom and Hagglund 1995). Open-loop, feedback, robust and adaptive controllers are widely used in research and industry to control various systems (Dorf and Bishop 2001). Open-loop controllers are the simplest ones but suffer from very high uncertainty in controlled variable in the presence of disturbances. A simple feedback controller is a more practical alternative, striking a balance between complications in implementation and improvement in system response under load disturbances. Robust controllers are much more resilient to disturbance in the control loop but require higher computing power within the controller. Adaptive controllers are currently widely researched into as they offer opportunity to realize fully autonomous systems at the expense of very high requirement of machine intelligence.

The feedback controllers come into two main forms – the discontinuous and continuous modes (Johnson 2003). The focus of this project is on exploring a continuous mode controller for an auto-focusing system, thus only this controller mode will be discussed. The simplest forms of a continuous controller are the Proportional or P – controller, Integral or I – controller and the Derivative of the D – controller. In practice, in a given industrial control scenario, only one controller mode is not sufficient to control the process efficiently and within given requirements. Thus, the composite controllers of PI, PD and PID are widely used. According to Astrom and Hagglund (2004), despite
massive advances in control systems over the last 50 years, 97% of the surveyed controllers in industry are essentially PID controllers (Li et al, 2006b). This influence of PID controllers is down to their simplicity in designing, tuning and implementing in a process loop (Ang et al, 2005).

Determining that a system requires a PID controller is not merely sufficient. A proper controller tuning mechanism depending on the plant dynamics, performance requirements and tuning tools available is also required. A badly tuned controller degrades the performance of the process and ultimately contributes to wastage and loss of quality. However, choosing the right tuning technique for a particular process is far from easy. O'Dwyer (2006) has reported a total of 1,134 tuning rules for PI and PID controllers. So, one can easily see that tuning a controller to meet operating performance requirements is a daunting task.

Ever since the paper on controller tuning was published by Ziegler and Nichols (1993) in 1942, the Ziegler-Nichols (ZN) tuning method is the most widely known and used tuning technique in control engineering. Originally proposed for pneumatic actuators, this empirical technique provides very simple hands on generic method of tuning feedback controllers for many processes. Thus, for over 65 years, ZN method has been synonymous with controller tuning all over the world.

The next section of the chapter will deal with the design and tuning of a robust controller for the auto-focusing mechanism of a surface profile measurement system. Comparisons in performance of this robust controller will be made with a controller tuned using the ever popular ZN method.

Since the three-term functionality compensates for both the steady-state and transient behavior of the system, PID controllers are suitable for most control purposes (Li et al, 2006b).
Within a control loop, the deviation or error of the controlled variable from the set point is given by:

\[ e = r - b \]  

(6-8)

The error is usually expressed as percent of span for controller implementation. This is denoted as \( e_p \). This is can be given by the following equation:

\[ e_p = \frac{e}{b_{max} - b_{min}} \times 100 \]  

(6-9)

The block diagrams constituting the PID controller is given in Figure 6-4 and analytic expression for the PID controller can be given as:

\[ p = K_p e_p + K_p K_i \int_0^t e_p dt + K_p K_D \frac{de_p}{dt} + p_i(0) \]  

(6-10)

where, \( K_p \) is the proportional gain between error and controller output (% per %), \( p(0) \) is the integral term value at \( t = 0 \) (initial value), the gain \( K_i \) expresses how much controller output in percent is needed for every percent-time accumulation of error, \( K_D \) is the measure of how much percent to change the controller output for every percent-per-second rate of change of error and \( e_p \) is the error of the system obtained through the subtraction of error signal from the set point as given in equation (6.9).
Figure 6-4 Three term composite controller (Wikipedia 2007)

The controller actions are depicted in Figure 6-5. It can be seen that the three controller terms, namely, proportional, integral and differential actions are present in the final composite controller response.

Figure 6-5 Controller action for a given error profile (Johnson 2003)

A vast range of research and practical work has been done in the design and tuning of PID controllers (Li et al 2006a). One of the most popular methods of tuning a PID controller is the Ziegler-Nichols step response technique (Astrom and Hagglund 2004).
The tuning procedure and the effects on the tuning action on the system will be discussed later in this chapter.

6.3.1.1. Controller Hardware Design and Interfacing

The controller algorithm will be implemented within the IENSYS embedded microcontroller board. The core processing unit of this board is the PIC 18F4523 device from Microchip. The controller board is shown in Figure 6-6.

The PIC 18F4523 comes with a 12-bit Analog-to-Digital Converter (ADC), which is used to obtain the input to the controller from the FES signal conditioner. This FES signal is then manipulated and processed and the VCM coil driver is provided with the control signal.

However, this board does not contain a Digital-to-Analog Converter (DAC). Therefore, either an external DAC must be interfaced to this board or the Pulse Width Modulation (PWM) function on-board the PIC microcontroller can be used to provide the analog signal to the VCM driver.

Generation of analog signal from PWM signal with the help of low-pass filtering is discussed in details by Palacherla (2002). This is a quick and efficient way of generating
analog output voltage using the embedded PWM function of the microcontroller, without using an external DAC. However, due to the high positional accuracy demand of the VCM drive (in the range of 1 μm), a DAC with guaranteed output accuracy is deemed more suitable.

Thus, the MCP4921 DAC manufactured by Microchip has been used to convert the digital control signal from the IENSYS board to analog signal used for providing the drive signal for the VCM.

The schematic diagram of the connection is shown in Figure 6-7. It is seen that the DAC is sitting between the VCM drive and the microcontroller.

The 12-bit DAC comes with a Serial Peripheral Interface (SPI) connection to facilitate its connection to the microcontroller as shown in Figure 6-7.

The output of the DAC is limited from ground to the supply voltage (i.e. +5 V). Therefore, additional arrangements are required to control the VCM which requires a control voltage of -5V to +5V.

This bipolar operation of the DAC is achieved through the circuit shown in Figure 6-8 (Microchip 2004).
Figure 6-8 Circuit diagram for bipolar operation of DAC (Microchip 2004)

Here,

\[ V_{\text{OUT}} = V_{\text{ref}} G \frac{D}{2^{12}} \] (6-11)

where, \( G = \) gain select (1x or 2x), \( D = \) digital value of DAC

And,

\[ V_{\text{IN+}} = \frac{V_{\text{OUT}} R_4}{R_3 + R_4} \] (6-12)

Thus yielding,

\[ V_o = V_{\text{IN+}} (1 + \frac{R_2}{R_1}) - V_{\text{ref}} \left( \frac{R_2}{R_1} \right) \] (6-13)

Solving for the above equations the following relationships can be obtained:

\[ \frac{R_2}{R_1} = \frac{3}{5} \] (6-14)

And,

\[ \frac{R_4}{R_3} = 3 \] (6-15)

Now, considering the values of commercially available resistors, \( R_1 = 20 \, \text{k\Omega} \), \( R_2 = 12 \, \text{k\Omega} \), \( R_3 = 10 \, \text{k\Omega} \) and \( R_4 = 30 \, \text{k\Omega} \).
6.3.1.2. Controller Software Design

The aforesaid controller for the servo loop can be implemented in both analog and
digital forms. However, since the whole surface profile measurement system will be
implemented with the help of microcontroller based systems, it is easier to go for digital
implementation. The flowchart of the algorithm is given in Figure 6-9.

The error signal \( e_p \) previously discussed in equation (6.9) can be given by the
following equation:

\[
DE = \frac{DV - DSP}{DMAX - DMIN}
\]  

where, \( DV \) is the measured input, \( DSP \) is the set point, \( DMAX \) is the maximum of
range, and \( DMIN \) is the minimum of range.

And the control equations then can thus be written as:

\[
DDE = DE - DEO
\]

\[
DEO = DE
\]

\[
SUM = SUM + DE
\]

where, \( SUM \) is the running sum of errors.

\[
PI = KP \times KI \times DT \times SUM
\]

where, \( PI \) is the integral output, \( KI \) is the integral gain, \( DT \) is the time between samples,
\( KP \) is the proportional gain.

\[
PD = KP \times KD \times DDE / DT
\]

where, \( PD \) is the differential output, \( KD \) is the differential gain.

\[
P = KP \times DE + PI + PD
\]

where, \( P \) is the sum of the three controller outputs, \( KP \) is the proportional gain.

\[
POUT = P \times ROUT
\]

where, \( POUT \) is the output, \( ROUT \) is the maximum output.
6.4. Controller Tuning

Since the order and transfer function of the system has been determined, selection of the type of controller and its parameters can be taken up.

A generic simple feedback controlled loop is shown in Figure 6-10. In this case, the controller is a PID.
The structure of this PID controller can be described mathematically as in equation (5):

$$u(t) = K(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt})$$

(6-24)

where, $u$ is the control variable and $e$ is the control error ($e = y_{sp} - y$).

It can be seen from the above figure (Figure 6-10) that there are two variables $l$ and $n$ in the feedback which corresponds to load disturbance and measurement noise respectively. In practical control scenario, it is common to have substantial measurement noise. Pre-filtering techniques are usually employed to eliminate this noise from the control loop (O'Dwyer, 2006).

Load disturbance is also a source of concern when designing and tuning a controller for a given process. In case of the profile measurement system, load disturbance is unavoidable because the focusing mechanism will be subjected to surface irregularities and needs to adjust to this disturbance in a fast and efficient manner in order to minimize measurement error.

This is an important criterion that needs to be taken into account when tuning the controller for this specific application. For its relative immunity to load disturbance, a robustly tuned controller is more appropriate for the auto-focusing mechanism of this profile measurement system. This assumption is supported by the results documented in the results and discussions reported in the latter part of this chapter.
6.4.1. Ziegler-Nichols Tuning (ZN) Method

There are two ways a controller can be tuned using the ZN method. One is the process-reaction method, while the other is ultimate cycle method (Johnson 2003).

In the process-reaction method, the system is introduced a transient disturbance by a small, manual change of the controlling variable using the final control elements. The response of the controlled variable is then measured. Then, various parameters such as the lag time, process reaction time and variable change is measured as shown in the figure below (Figure 6-11).

![Figure 6-11 Process reaction curve](image)

According to this process-reaction method,

\[ L = \text{lag time in minutes} \]

\[ N = \frac{\Delta C_p}{T} \quad (6-25) \]

where, \( N = \text{reaction rate in \%/min} \), \( \Delta C_p = \text{variable change in \%} \), and \( T = \text{process reaction time in minutes} \).

The appropriate proportional gain, integration time and derivative time for the three-term PID controller then can be found out from the following equations.
Chapter – 6: Control System Design for the Auto-focusing Mechanism

\[ K_p = 1.2 \frac{\Delta P}{NL} \]  
(6-26)

\[ T_I = 2L \]  
(6-27)

\[ T_D = 0.5L \]  
(6-28)

However, this technique of open loop process response curve does not yield very good closed loop performance. Also, the parameters are all measured in minutes and this method had been proposed for pneumatic systems some 60 years back. Thus, it is very difficult to obtain the process reaction parameters from the curve with fast settling mechanisms like the one described in this paper.

A more appropriate solution is the ultimate cycle method. In this technique, all the controller gains are set to their minimum apart from the proportional gain. Then the system is excited by a transient disturbance (usually through a step input). The proportional controller is so adjusted until the closed loop system is in steady oscillation. This gain is termed as the critical gain \((K_c)\) of the system and the period of oscillation (measured in minutes) is called the critical period \((T_c)\).

The proportional gain, integration time and derivative time for the three-term PID controller then can be found out from the following equations.

\[ K_p = 0.6K_c \]  
(6-29)

\[ T_I = \frac{T_c}{2} \]  
(6-30)

\[ T_D = \frac{T_c}{8} \]  
(6-31)

The response of the closed loop system tuned using this ZN ultimate cycle method is shown and discussed in the next section.
6.4.2. Robustly Tuned PID Controller

There are several criteria that determine the performance of a controller (Kristiansson and Lennartson, 2002). These quantitative measures of the performance of the system are termed as performance indices. These indices are chosen such that emphasis is given to the important system specifications. The general form of the performance integral is,

$$ I = \int_0^T f(e(t), r(t), y(t), t) dt $$

(6-32)

where $f$ is the function of the error, input, output and time. The upper limit of the integral, $T$ is a finite time chosen in such a way that the integral approaches a steady-state value. This value is usually chosen to be the settling time.

In order to reduce the contribution of the large initial error to the value of the performance integral, as well as to emphasize errors occurring later in the response, the following ITAE (integral of time multiplied by absolute error) index has been proposed (Dorf and Bishop 2001).

$$ ITAE = \int_0^T |e(t)| dt $$

(6-33)

The following equation represents the closed loop transfer function of a feedback control system that is optimized using the ITAE criterion.

$$ T(s) = \frac{b_0}{s^n + b_{n-1}s^{n-1} + \ldots + b_1s + b_0} $$

(6-34)

The transfer function of a PID controller is as following:

$$ G_c(s) = K_1 + \frac{K_2}{s} + K_3s $$

(6-35)

The closed loop transfer function of the VCM system along with this controller $G_c(s)$ can be found to be:
\[ T_i(s) = \frac{G_c G(s)}{1 + G_c G(s)} \]  
\[ (6-36) \]

Substituting the values of \( G(s) \) and \( G_c(s) \) in equation (6-36) gives,
\[ T_i(s) = \frac{98.7e3 K_1 s^2 + 98.7e3 K_2 s + 97.7e3 K_3}{s^3 + s^2 (125 + 98.7e3 K_1) + s(98.7e3 K_1 + 98.7e3) + 98.7e3 K_2} \]  
\[ (6-37) \]

From equation (6-34), the optimum coefficients of \( T(s) \) with this controller \( G_c(s) \) based on the ITAE criterion for a step input can be derived as:
\[ s^3 + 1.75 \omega_n s + 2.15 \omega_n^2 s + \omega_n^3 \]  
\[ (6-38) \]

Thus, comparing equations (6-37) and (6-38) the optimum value of the controller coefficients \( K_1, K_2 \) and \( K_3 \) are determined based on the ITAE criterion.

Therefore the equation (6-35) becomes,
\[ G_c(s) = 8.799e3 + \frac{82.77e6}{s} + 0.355s \]  
\[ (6-39) \]

This performance index produces excellent transient response to step input, which can be seen from the results reported in the next section.

### 6.5. Control System Performance Analysis

The bode diagrams in Figure 6-12 show the uncompensated system response along with the closed loop system response with a ZN tuned controller in place. It is easily noticeable that the resonant frequency of the system has been changed and the resonant frequency of the closed loop system stands at 300 Hz. This is substantial improvement from the natural system response, which stands at 48 Hz. The -3 dB bandwidth of the closed loop system can be measured at 500 Hz, though practically due to the resonant peak, the maximum bandwidth of the system is limited to much less than 300 Hz. The value of 100 Hz can be deduced to be the practical bandwidth of the system.
However, with the implementation of an ITAE-based robust PID controller, the bandwidth of the closed loop system increases dramatically. Bode plots in Figure 6-13 show both the uncompensated and robustly controlled system responses. The robust controller yield a closed loop system bandwidth of 21 KHz, which is a marked
improvement to open loop bandwidth of 48 Hz or even to the ZN tuned controller bandwidth of 100 Hz.

![Figure 6-14](image_url)

**Figure 6-14 Closed loop response to step input with ZN tuning**

Apart from the bandwidth, the performance of a closed loop system can also be evaluated by the settling time and percentage overshoot values. The closed loop system tuned with the ZN method is shown in Figure 6-14. The settling time of the system (taking the time at which the response settles to 20% of the final value), is found to be 15 ms. The percentage overshoot of the system stands at about 60% of the final value.
Response of the closed loop system to a step input can be analyzed from Figure 6-15. The percentage overshoot of the system stands at 17%, while the settling time is reduced drastically to only 0.2 ms, which marks a reduction in settling time of almost 99%.

It can be envisioned that the auto-focusing mechanism of the optical measurement system will undergo random load disturbance due to the nature of sample under test. Thus, a good load rejection characteristic of the control system is required in order to maintain focus on the surface.

A disturbance in the closed loop was created which was 80% of the initial step input. The results of load disturbance rejection by the ZN tuned and robustly tuned loop are shown in Figure 6-16 and Figure 6-17 respectively.
Figure 6-16 Effect of load disturbance in ZN tuning

From Figure 6-16 it is apparent that, a load disturbance is introduced at time 40 ms after the VCM system has settled down. The amplitude of the disturbance is as previously mentioned, 80% of the final value. It can be observed that the system is somewhat destabilized at the introduction of the disturbance. However, for an 80% disturbance, only a 5% change in system output is observed. Thus, it can be said that the ZN tuned closed loop system offers very good noise rejection capabilities.

Figure 6-17 shows the response of the same system with a robust controller in place. It can be seen that a load disturbance of 80% of the final value has been introduced after 10 ms of the initial step input.
Despite a very high value of load disturbance, it can be seen that the output of the closed loop system does not change at all after the initial step input. Thus, it can be said that the controller has excellent robust load disturbance rejection capabilities.

The surface profile measurement scheme shown in the earlier chapters comprises a displacement measurement system. There is also an optical non-contact system providing encoder reading to the main microcontroller carrying out the profile measurements.

A pulse signal is generated whenever the encoder reading reaches a certain threshold, which in this case is set at 100 \( \mu \text{m} \). Calculations show that the required frequency response of the closed loop system needs to be at 20 kHz for measurements to take place at 2 m/sec, which close to acceptable industrial profile measurement speed (Jackson et al, 2002).
Figure 6-18 Response to square wave input at 1 kHz with ZN tuning

The closed loop system tuned with ZN method was fed with a square wave input of 1 kHz, which resembles a measurement rate of 100 mm/s. The response of the system along with the input can be observed in Figure 6-18. As shown by the frequency response curve of Figure 6-12, the ZN tuned system is not being able to provide satisfactory output at 1 kHz due to its bandwidth limitation of 100 Hz.

A better response to this 1 kHz wave can be seen from Figure 6-19, which represents a system tuned by the robust PID technique. It is seen that, though the overshoot stands at 30%, a fast settling time of 0.3 ms along with a generally acceptable response is obtained from this closed loop system.
6.6. **Summary**

- A comparative analysis of two different tuning methods for a PID controller has been discussed in this chapter of the thesis.

- It can be seen from the results that the most commonly used Ziegler-Nichols method of tuning a controller provides deficient performance for this particular system. It fails to meet the most important transient response requirements of low overshoot and fast settling time. However, a controller tuned using this technique fares reasonably well with load disturbance in the process loop.

- On the other hand, a more analytically tuned controller based on the ITAE performance criterion exhibits excellent transient response. It also shows great robustness by completely rejecting load disturbances. Though this sort of tuning requires much more complicated computational and analytical...
manipulations, the improvement in overall performance out-weighs this drawback.

- Thus, it can be concluded that a robust controller is a more suitable control solution for such an auto-focusing mechanism within this type of profile measurement system.
Chapter - 7.

Realization of the Profile Measurement System

7.1. Introduction

The previous chapters have covered the design, construction and initial calibration of the two sub-systems proposed in this thesis for a low cost solution to industrial surface profile measurement requirement for timber or other similar materials (e.g., MDF, nylon etc). It has been reported in chapter 5 that the optical DVD reader can be calibrated to obtain a FES curve for timber. However, the linear range of operation is substantially limited as expected, due to the nature of timber surface, which is not highly reflecting unlike a DVD, for which the sensor has been originally fabricated. It has also been shown that, in order to attain the required linear response, which is about 2-3 times higher than the originally achieved range, the sensor can be used in the auto-focusing mode. The details on the auto-focusing mechanism driven by a VCM drive and an appropriate controller to achieve the required response have been reported in chapters 5 and 6 respectively. This chapter will look into the integration of both the optical reader and encoder to realize the surface profile measurement system.

7.2. Hardware Issues Relating to Integration of the Sub-systems

The surface profile measurement system consists of two basic sub-systems, namely, the optical mouse based encoder and the DVD reader based surface height measurement system.

Both sensors are connected to their customized signal conditioning circuits as discussed earlier in the thesis. During the initial testing and calibration exercises, data from the two-subsystems were logged separately via dedicated microcontrollers. When the actual
surface profile measurements are carried out, it is imperative that both sets of data are measured simultaneously and in real time. For this purpose, all the routines for both sensors need to be executed in a single microcontroller. The software implementation of this is discussed in the next sub-system.

The following block diagram in Figure 7-1 depicts the proposed integration of the sub-systems on the hardware level.

![Diagram](image)

**Figure 7-1 Proposed hardware integration for a PC based system**

It can be seen that data from the two sub-systems are being fed to the main microcontroller. This microcontroller can be physically a completely separate unit or all the sub-systems can be implemented into a single microcontroller. The latter solution means that data processing of the encoder signal as well as the auto-focusing function of as well as data processing of the DVD profiler is carried out on a single chip. This provides a clutter-free compact hardware design, with lower latency. However, depending on the memory capacity and speed of the microcontroller it might not be a feasible solution to the hardware integration issue.

As shown in the above figure (Figure 7-1), the profile data is fed to a Bluetooth communication system for wirelessly transferring data from the profile measurement system to the PC for further data processing and storage. Two Bluetooth dongles (Promi SD202 from Initium) were used for this data transfer. These devices are connected to the RS-232 interface of the IENSYS board and the PC. The serial link settings of these devices were the same as reported for the IENSYS board in chapter – 5 of this thesis.
This approach is more suitable for a profile measurement system to be used for in-process measurements. In case a portable profile measurement needs to be developed, the Bluetooth interface needs to be replaced by a HD44780-based Character LCD. The schematic diagram of Figure 7-2 shows the idea for this portable system. For this purpose, HD44780U from Hitachi can be used. Appropriate software routines can be implemented to calculate and display the required surface parameters on the LCD display. However, in order to calculate certain parameters and to display them, more computing power is needed, which the current 18F series microcontroller cannot provide.

7.3. Software Aspect of the Proposed Integration

The hardware interfacing and interconnection for the integration of the two sub-systems have been discussed in the previous sub-section. This section of the thesis documents the software aspect of the integration of the optical mouse based encoder and the DVD optical probe to realize the non-contact surface profile measurement system.
7.3.1. Integrated Algorithm

The algorithm of the integrated software is shown in Figure 7-3. The first step in the algorithm is to initialize the optical mouse based encoder. The detailed software and hardware construction of this subsystem is discussed in sub-section 5.6.

![Flowchart for the integrated system](image)

When the encoder is initialized, the embedded counter counts up to the set value of $100 \mu m$ as discussed previously. Then it issues an interrupt for the DVD reader profilometer to carry out the vertical height measurement.

On receiving the interrupt, the main routine of the DVD reader first calls the sub-routine which measures the FES value, which corresponds to the vertical height of the surface. Then this value is passed on to the PID sub-routine. This sub-routine then compares this value with the set-point and provides an output in accordance to the P, I and D values.
Another sub-routine used to drive the VCM of the reader which moves the objective lens as discussed before is then called within the main program. According to the output of the PID sub-routine, the VCM driver sub-routine manoeuvres the objective lens to regain focus on the surface of the sample being measured.

Then the value of the measured profile is written to the serial link to a data logging software running on the PC. This loop is continuously carried out until the measurements come to an end.

### 7.3.2. Algorithm Timing for the DVD Probe

The detailed software algorithm for signal conditioning and data acquisition has been discussed in details in chapter 5. Also, the algorithm to integrate both the sub-systems has been discussed in this chapter. A detailed analysis of the algorithm timing using the previously proposed algorithm running on the IENSY3 board is given below. This would give a clearer picture of the bandwidth of the integrated system, which in turn will determine the speed at which measurements can be carried out.

In order to time the algorithm, a small routine was written in MikroBasic compiler. Each algorithm (e.g., ADC conversion, SPI interface for the DAC etc.) was executed in a standalone manner. At the end of each routine, a certain port was toggled (in this case PORTB). This port was then observed using an oscilloscope to determine the time required for the specific routine or algorithm to execute in the 18F4523 microcontroller.

![Figure 7-4 Timing diagram for ADC only](image-url)
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The above figure (Figure 7-5) shows the timing diagram obtained for the ADC routine of MikroBasic. It can be seen that the time required for one period is 1.7 ms, which corresponds to an execution time of 850 μs.

In a similar manner, the PID algorithm was also timed and the result from the timing exercise shown in Figure 7-5. The execution time of the code can be measured to be 1.8 ms.

![Figure 7-5 Timing diagram for only PID](image)

As discussed earlier in the thesis, an SPI interface based DAC has been used in the optical DVD probe sub-system to control the movement of the objective lens within the auto-focusing mechanism.

The combined timing of the PID algorithm along with the SPI routine is shown in Figure 7-6. This combined routine takes about 2.95 ms to execute. Considering the timing information shown in Figure 7-5 for only the PID algorithm to execute, it can be concluded that the time required for the DAC operation through the SPI interface stands at 1.15 ms.
Figure 7-6 Timing diagram for PID and SPI interface

Figure 7-7 Timing diagram with two USART data

Timing information of the profile measurement algorithm with the ADC, PID and SPI-DAC routines along with writing a set of two data at a time to the USART has been shown in Figure 7-7. It can be observed that the routines are taking up about 22.8 ms to execute. Based on the previous results, it can be seen that about 19 ms is taken only to write data to the USART. This is expected given that a string conversion is taking place inside the routine and the USART routine due to the simplicity in executing in MikroBasic has very large overhead, which takes up significant amount of time.
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Figure 7-8 Timing diagram with only one USART data

The timing exercise reported in Figure 7-7 is carried out with the view in mind that the final profile measurement data file will contain two sets of data, one the encoder information and the other the height, which is necessary for the recreation of the surface under test. However, the need for two data in a set can be eliminated based on the fact that, measurements are carried out every 100 \( \mu \text{m} \), i.e., at a set interval. Thus, only the height information will suffice to carry out the measurements and give the profile of the surface. The timing diagram of Figure 7-8 shows the time required to execute all the necessary routines along with writing only one data to the USART. As expected, the time required has been substantially reduced to 6.6 ms, which is more than 3 times reduction in execution speed.

However, this improvement is not sufficient to use it in a high speed machining environment. In comparison to the required speed of measurement at 21 kHz, the aforesaid timing can only provide measurements at 150 Hz.

This lack of measurement speed can be overcome by the use of high speed microcontroller such as the dsPIC devices from Microchip. They are capable of carrying out faster calculations and are more efficient in implementing codes than the conventional microcontrollers.

Apart from the hardware solution to the lack of measurement speed of the current setup, the software compiler can also be changed to C18 or something similar. C compilers are generally capable of creating more compact and shorter HEX files when compared to
the Basic compiler used in this project. This helps in reducing the execution time of the routines, thus enhancing the speed at which the measurement can be carried out.

7.4. System Response

The actual response of the objective lens driven by a VCM is shown in Figure 7-9, where an impulse signal has been fed to the controller and the dynamic response of the lens is observed using the vibrometer.

![Figure 7-9 System response to an impulse input to the controller](image)

The simultaneous observation of the input to the controller and the response of the lens in Figure 7-9 show that there is a noticeable delay between the input and the reaction of the system to this impulse input. This delay can be attributed to the time needed to execute various routines inside the microcontroller, which has been discussed previously. From the response curve, it can be seen that this delay is in the region of about 7 ms, which is very close to the value of 6.6 ms as obtained from the timing diagram of Figure 7-8.
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The response of the system at square wave input of 71 Hz is shown in Figure 7-10. It can be seen that the output is in agreement with the input to the controller. Thus, the system works at this rate, which is expected according to the discussions in sub-section 7.3.2.

7.5. Product Design Specifications

In the previous sections of this chapter, various electronic hardware and software issues have been discussed. This sub-section is intended to provide some of the product design specifications for the on and off-line measurement systems.

7.5.1. Off-line Measurement System

In accordance to the literature review carried out for a profile measurement system, the following factors are considered for an off-line system.

Speed of Measurement: The speed of measurement is one of the most important parameters while designing a profile measurement system. As discussed in chapter - 4 of the thesis, the maximum speed with which the optical encoder can provide measurements stands at 473 mm/s. However, in order to achieve repeatable and consistent measurements, the maximum speed of measurement will be limited to 400 mm/s. This speed is also within the working range of a robustly tuned auto-focusing probe as shown in chapter – 6. Also, in order to ensure that the measurements are not
affected by rapid acceleration across the measured sample, an accelerometer will be attached to the housing of the profile measurement system. The accelerometer will ensure that if the acceleration experienced by the profile measurement system is more than 0.15g, the operator will be asked to re-measure the surface profile.

**Elimination of Measurement Noise due to Vibration:** Due to the nature of operation, vibration to the sample under test affects the surface profile measurements by the focusing profiler. In order to avoid this error due to vibration, the common mode rejection method explained in chapter - 4 will be incorporated in the overall design of the system.

**Weight and Size of the System:** The weight and size of the system is important for designing a hand-held offline profile measurement system. The maximum weight of the system needs to be limited to 800 g. This weight is in line with leading high performance ergonomic mice available in the market. Also, the size of the enclosure must be such that it fits comfortably in the hand of the operator. Thus, the overall dimension of the system needs to be 11 cm x 6 cm. The enclosure of the system needs to be rugged enough to withstand continuous handling in harsh industrial environments. Thus metallic supports must be used in the structure of the enclosure to increase the rigidity of the overall system.

**Operating Environment:** The operating environment for the surface profile measurement system is deemed to contain significant amount of dust. In order to ensure proper functioning of the device, the optical lens of both the DVD focusing probe and the optical encoder must be kept dust-free. A post processing operation to clear the dust from the machined surface is required for accurate profile measurement results.

**Target Cost:** Currently available surface profile measurement systems are usually expensive. Some of the well known systems can cost up to £80k. One of the main objectives of this research work is to develop a cost effective solution to measure machined timber surface. The target cost of the developed system thus needs to be effectively controlled. The intended cost is £500 for a hand-held profile measurement device with a LCD panel to display measured data and provide simple surface characterization parameter (e.g., $R_{\text{sm}}$ value).
Safety Considerations: Both the DVD reader and optical mouse sensor are low-power devices. Thus, laser radiation from the sensors is minimal and not harmful to the operator. However, it must be mentioned in the operator’s manual as well as on the casing of the system not to look directly into the laser probe to avoid any damage to the eyes.

7.5.2. On-line Measurement System

The design specifications for the off-line measurement system are documented in the last sub-section. The specifications for implementing the profile measurement system within a small-scale Mechatronic planer are given below.

Speed of Measurement: As in off-line measurement system, the speed of measurement is also important to ensure the accuracy and repeatability of the surface profile measurement results. In previous calculations presented in chapter – 4, it can be seen that the optical mouse encoder imposes limit on the speed with which surface profile measurements can be carried out. Although the bandwidth of the DVD profiler is also quite small, with the help of the control strategy discussed in chapter – 6, the speed of measurement can be increased significantly. As the machined samples are fed to the surface monitoring system at a constant speed, the optical encoder can be removed from the system, leaving only the DVD profiler probe to obtain vertical height information. Therefore, measurements can be carried out at 1 m/s with the help of the profile measurement system embedded in the small-scale planer.

Elimination of Measurement Noise due to Vibration: As discussed in the previous sub-section, noise introduced in the surface profile data can be eliminated with the help of common mode rejection ratio.

Weight and Size of the System: In the on-line measurement system, the sensor will be installed within the planer for post process inspection of machined surface. Therefore, the weight and size of the system is not as important as the off-line measurement system. The size and weight requirements described beforehand will suffice for on-line measurements as well.
Operating Environment: The optical lenses of the surface profile measurement system need to be kept dust-free in order to accurately measure surface profiles. However, the small-scale planer has a dust extraction system which readily removes the generated dust during the planing process from the surface of the machined sample. Therefore, the profile measurement system will work satisfactorily within the planer.

Target Cost: The on-line version of the profile measurement system also needs to be cost-effective. However, it is perceived that in this mode, more information needs to be made available to the machine controller to ensure high quality surface finish. Therefore, higher hardware costs will be encountered during the implementation of the system when compared to the off-line system. The total target cost of the system thus stands at £700. This increase in cost includes the need to incorporate a PC to the overall design to carry out more demanding data processing tasks for the planer's controller.

Safety Considerations: Due to the low wattage of the optical devices, laser radiation hazard associated with this system is minimal. However, proper shielding of cables and connectors are required to embed the system to an industrial planer. This protection will help reduce Electromagnetic interference of the electronics as well as physically protect the wires and connectors from the industrial environment.
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<table>
<thead>
<tr>
<th></th>
<th>On-line System</th>
<th>Off-line System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of measurement</td>
<td>1 m/s</td>
<td>400 m/s</td>
</tr>
<tr>
<td>Vibration suppression</td>
<td>Common Mode Method</td>
<td>Common Mode Method</td>
</tr>
<tr>
<td>Weight and size</td>
<td>N/A (typically similar to off-line method)</td>
<td>800 g, 11 cm x 6 cm, metal enforced enclosure</td>
</tr>
<tr>
<td>Operating environment</td>
<td>Extractor installed in the planer to remove dust</td>
<td>Operator needs to ensure surface is dust free</td>
</tr>
<tr>
<td>Target cost</td>
<td>£700</td>
<td>£500</td>
</tr>
<tr>
<td>Safety considerations</td>
<td>Avoid prolonged exposure to laser, appropriate cable shielding</td>
<td>Avoid prolonged exposure to laser</td>
</tr>
</tbody>
</table>

Table 7-1 Summary of the product design specifications for both on and off-line systems

The table above (Table 7-1) summarizes the discussed product design specifications for both the on and off line systems.
7.6. Integration into the Active Vibration Controlled Woodworking Machine

The surface profile measurement system can be integrated as a feedback loop for a smart planing system designed within the Mechatronics Research Centre at Loughborough University (Hynek et al., 2004). The system is shown in Figure 7-11. The smart planing system consists of a base frame on which the feed table and spindle system are mounted. The smart spindle unit is the main part of the test rig. Four piezoelectric actuators are mounted on the front bearing. Two opposing actuators for each axis have been chosen in order to achieve a “push-pull” operation. Applying appropriate voltage levels to the piezoelectric actuators controls the movement of the spindle. The smart spindle unit is based on mechatronics control approach which comprises appropriate sensors, signal conditioning circuits, driving amplifiers and control computer.

Figure 7-11 Smart active planer (Hynek et al., 2004)
A detailed view of the spindle unit is given in Figure 7-12. The spindle unit is equipped with two non-contact eddy current sensors to measure the XY displacement of the spindle. These signals are then converted into digital signals via the multifunction I/O card in the control PC. The smart spindle unit is also equipped with an incremental encoder in order to measure the angular position of the spindle. These two measures (XY displacement and the angular position of the spindle) are used to assess the surface profile in real-time. The Matlab xPC Target prototyping environment is used to carry out this real-time control application.

A monitoring system has been proposed to detect the spindle vibrations and spindle speed in-process and feed the control algorithm with information about the machined surface quality (Elmas et al, 2007). This new proposed smart planing system will be able to adapt to the spindle displacement in real-time to the current surface waviness. As a result of this machining process, the disturbances and the machining variability will be reduced and a consistent and improved surface quality can be achieved. This scheme is shown in Figure 7-13.
Figure 7-13 Active vibration control strategy with a feedback system (Elmas et al., 2007)

Apart from the aforesaid method of monitoring the surface finish by Elmas et al. (2007), the non-contact optical surface measurement system can be used successfully to provide the machine controller with the surface profile data. In this set up shown in Figure 7-14, the near real time surface profile measurement data (X and Y) can be fed to the machine controller through a RS-232 Bluetooth interface as discussed before.

Figure 7-14 Proposed feedback system with the optical profiler for the smart planer
This is a more direct approach of assessing the surface profile of the machined sample and will enable the controller to sense the surface finish more accurately. Thus, the inconsistency of the cutter marks can be better sensed by the machine, enabling it to take corrective actions to greatly improve the surface finish.

7.7. Summary

- Various practical aspects of the non-contact surface profile measurement system have been discussed in this chapter.

- The hardware interfacing has been shown for both the portable handheld design as well as for the in-process profile measurement system.

- It has been proposed that the profile measurement system be connected to wireless transceivers to connect to a PC or workstation for online measurements. While, a LCD display based system is more appropriate in displaying various surface parameters for a handheld device.

- The software aspect of integrating the two sub-systems of the optical encoder and the DVD profiler has been shown.

- The timing diagrams for the software have been discussed and the limitation imposed by the lack of speed of the microcontroller pointed out in this chapter.

- Product design specifications are included in the chapter for both on-line and off-line measurement schemes.

- Finally, integration of the system into a smart planer has been discussed. It has been proposed that the optical profiler can be an alternative to methods used by other researchers to provide feedback to the machine controller for improving the surface finish quality and realize a fully autonomous planer.
Chapter - 8.

Final Testing and Measurement Results

8.1. Introduction

The design and realization of optical non-contact novel surface profile measurement system based on the DVD reader has been discussed in the previous chapters of this thesis. It has been observed that the probe can be calibrated successfully on various materials e.g. different colored timber and nylon. It has also been documented that the VCM of the DVD reader can be driven to provide an auto-focusing action, thus increasing the range of surface profile measurements significantly. A suitable controller has also been designed and tested to implement this auto-focusing scheme of the VCM drive. This chapter will look into various advanced aspects of sensor calibration, which have not been addressed in chapter 5. These include the investigation of the effect of gain adjustment of the instrumentation amplifier on the calibration curve, repeatability of the FES curve for a given material and the effect of tilting the sensor on the calibration curve. The latter part of the chapter looks into surface profile measurements carried out with the help of the DVD profilometer and comparison of these surface traces to two different benchmark traces.

8.2. Final FES Calibration and Analyses

As mentioned earlier, various aspects of calibrating the sensor has been looked into in this section of the thesis. Basic calibration curves involving various materials have already been reported in chapter 5. These analyses will focus mainly on the practical issues of the calibration curve, namely, the repeatability of the FES curve for a given material, effect of gain change on the calibration and the effect of sensor tilt on the calibration curve.
8.2.1. Repeatability Analysis of FES Curves

A series of 10 calibrations curves obtained through 10 trials have been reported in Figure 8-1. The series 1 to 10 corresponds to the 10 trials in all the figures presented here. It can be observed that the focal length (x-axis value) of the sensor on this particular piece of sample (i.e., black nylon) varies significantly. Apart from that, the FES output also varies from trial to trial.

![Figure 8-1 Non-repeatable nature of the FES curve](image)

This is due to the imbalance created at the input of the instrumentation amplifier as discussed in sub-section 5.2.1.2 and shown in Figure 5-2. This non-repeatability is not acceptable for a closed loop system where the FES signal will be used as the feedback signal to drive the VCM and ultimately maintain focus of the laser beam on the surface of the sample under measurement. With the varying of the FES signal with each trial, the controller parameters will have to change and uncertainty of the measurements carried out by the system cannot be eliminated.

Thus, a consistent, repeatable FES curve is needed in order to realize this auto-focusing surface profile measurement system. The scheme shown in Figure 5-3 has therefore been employed successfully to ensure the repeatability of the FES curve for a given material.
Figure 8-2 Repeatability of FES curve on black nylon

Similar sort of calibration on a black nylon sample has been carried out with the aforesaid improvement scheme in place. The results from this calibration practice have been reported in Figure 8-3. It can be seen from the 10 trials that the linear region of the s-curve is highly repeatable, while there are some focal length and FES output deviation on either side of the linear range. Since, the focusing mechanism is designed in such a way that it operates only in the linear range, this deviation between trials do not affect the measurements.

Figure 8-3 Repeatability of FES curve on white nylon
However, calibration curves with higher repeatability were obtained when the same trials were carried out on a white nylon sample. Both the amplitude of the FES curve and the focal length of the probe showed excellent repeatability across the 10 trials.

![Figure 8-4 Repeatability of FES curve on hardwood](image)

This is also true for the calibration curves for a dark sample of timber reported in Figure 8-4. It can be observed that the FES amplitude and the focal distance of the probe are both highly repeatable throughout the 10 trials.

![Figure 8-5 Standard deviation among 10 trials of each sample](image)

The standard deviation of the trials were calculated for each sample and shown in Figure 8-5. It can be observed that the black nylon sample has the highest standard
deviation, which in turn means more error into the final measurements. However, the deviation is substantially small, with the highest one standing at only 1.2%.

From the results reported in the above figures, it can be concluded that the signal conditioning improvements proposed in chapter 5 have been effective in providing highly consistent s-curves for various materials. Also, it can be seen that the sensor shows better repeatability on white nylon sample and the hardwood. This might well be due to the poor light reflectance nature of the black nylon sample. However, it might also be down to the individual sample, which might have grainy features or roughness, thus making the reflection of light off the surface inconsistent. Further studies on other black samples are required to satisfactorily come to a conclusion.

8.2.2. Effect of Gain Variation

As reported in the data sheet for the Hitachi HOP-1000 DVD reader, the power of the LED is limited to 0.5 mW. However, in order to ensure the consistency of measurements and avoiding overdriving the probe, an effective power management scheme must be put in place as reported by Fan et al, (2000). This ensures that the laser diode is driven at an optimal power and the power is kept at a constant negating the effect of heating, which in turn gives rise to inaccuracy in measurements.

![Figure 8-6 Effect of gain variation on black nylon sample](image)
It can be envisioned that the more light is incident on the surface the more reflection can be obtained back off the surface for the four-quadrant photodiodes. This would mean that reflection-wise non-ideal surfaces can be more effectively measured using the DVD probe. This technique will be immensely useful in measuring dark timber samples or black nylon samples similar to the one reported in this thesis.

Thus, ideally, the laser diode needs to be driven at a higher power to provide this higher illumination of the surface. But, as mentioned earlier, there are some constraints on the power that the laser diode can be driven with. So, the illumination of the surface is more or less constant with the power controlled laser diode and cannot be adjusted greatly for various materials.

In order to overcome this limitation, tests were carried out to determine whether the changing of the gain of the amplifier shown in Figure 5-3 can provide with a better measurement range for non-ideal surfaces. The rationale behind this idea was that, by increasing the gain of the amplifiers, the signal conditioning system can be made more sensitive to even smaller changes in reflection, which in turn could give similar effect as increasing the power of the laser diode.

![Figure 8-7 Effect of gain variation on white nylon](image)
Two sets of tests on black and white nylon samples were carried out and the results are reported in Figure 8-6 and Figure 8-7 respectively. In both cases, FES curves were obtained for five different gain settings of the amplifier.

The results show that the focal distance of the probe doesn't change significantly with the change of amplifier gain. When gain 1 and gain 5 are compared in Figure 8-6, a fourfold change in gain has resulted in a focal distance change of about 2 μm. A gain change of about 4 times has changed the Thus, it can be concluded that the focusing range of the optical DVD reader cannot be altered by increasing or decreasing the gain of the instrumentation amplifier.

8.2.3. Effect of Tilt

In this sub-section, how the FES curves for various materials are affected by tilting the sensor at certain angles is reported. In a real industrial scenario, due to the handling of operators, the profile measurement sensor is prone to being tilted. Thus, it is imperative that the effect of tilting be investigated.

In order to carry out the tilt angle experiments, the following setup as in Figure 8-8 was used. A universal tilting stage was used to provide the tilt at various angles.
The samples were glued to the stage in order to keep them rigidly fixed during the course of the experiments. The samples were tilted at 5 degree intervals.

### 8.2.3.1. Black Nylon Sample

The figure given below (Figure 8-9) shows the response of the DVD probe for 10 trials while the sample under test is tilted at an angle of 5 degree.
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Figure 8-9 FES curves for a tilt angle of 5° on black nylon

It can be observed from the curves that the peak of the FES output varies significantly; however, one of the linear regions of the curve shows good repeatability. Thus, even at an angle of 5°, the auto-focusing system can be successfully employed to carry out the profile measurement using the values of this region.

Figure 8-10 FES curves for a tilt angle of 10° on black nylon

However, when the sample is tilted by an angle of 10°, the repeatability and consistency of the FES curve reduces. This phenomenon can be clearly observed from Figure 8-10. Whilst the amplitude of the FES output is fairly consistent in the linear region of the
curve, the focal distance corresponding to the FES changes among trials. But this shift in the focal distance is only about 3 to 4 \( \mu m \), which practically will not introduce too much error into the measurements.

![FES curves for a tilt angle of 15° on black nylon](image)

**Figure 8-11 FES curves for a tilt angle of 15° on black nylon**

A similar group of 10 FES curves are shown in Figure 8-11, which represents the results when the sample is tilted at an angle of 15°. It can again be observed that some of the trials offer high degree of repeatability in terms of FES output and focal distance but some differ quite significantly from others. Therefore, at this angle, the profile measured might to some degree offer correct measurements. It is worth mentioning here that one of the linear regions does offer higher repeatability but the FES curve is not linear. So, this region cannot be used for focusing the probe.

It was observed during the experimentations that there are no FES output from the sensor when the black nylon sample is tilted more than 15°. Thus, FES curves beyond 15° tilt are not reported in here.

The reason for losing focus for a tilt of more than 15° might be twofold. The light reflected back off the surface due to the wide incidence angle will not return in a quantity sufficient for the photodiodes. Also, with the tilting of the sample, the standoff distance increases, which in turn means that again, enough reflection is not obtained for the photodiodes to provide the FES signal.
Figure 8-12 Summary of the tilting effect of a black nylon sample

A summary of the mid point of the FES curve or the focal point has been given in the above figure (Figure 8-12). The variations are clearly observable from the bar graphs. However, these variations are somewhat less than the white nylon sample and timber sample as seen from the results presented in the next sub-sections.

8.2.3.2. White Nylon Sample

The FES response curves obtained by tilting a white nylon sample at 5° are shown in Figure 8-13.
The curves show that the linear region of the FES curves is quite consistent and repeatable despite the tilt. However, two of the curves are not repeatable. Despite this inconsistency, effective measurements can be carried out at this level of tilt.

Further tilting of samples at 10° and 15° shown in Figure 8-14 and Figure 8-15 respectively reveals the inconsistency and loss of repeatability with the increase of tilt angle.

Also, the white nylon has been subjected to further tilting at an angle of 20° and the FES curves obtained is shown in Figure 8-16. It is clear from the figure that the FES curves have lost the repeatability with this higher degree of tilting. It was observed that no FES curves can be obtained after a tilting angle of 25°.
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Figure 8-14 FES curves for a tilt angle of 10° on white nylon

The focusing point or the null point on the FES curves for every trial has been reported in Figure 8-17. The variations of the focal point for each trial can be seen from the figure, especially for higher degree of tilt.

Figure 8-15 15 FES curves for a tilt angle of 15° on white nylon
8.2.3.3. Light-colored Timber Sample

More tests were carried out on light-colored timber sample to determine the effect of tilting the sample on the FES curves.
Chapter 8: Final Testing and Measurement Results

Figure 8-18 FES curves for a tilt angle of $5^\circ$ on timber

The first set of results shown in Figure 8-18 gives the FES curves obtained by tilting the timber sample by $5^\circ$. It can be observed that the repeatability of the FES curves is very poor and varies significantly from trial to trial. Thus, an effective auto-focusing system cannot be implemented at this tilting angle and surface profile measurements cannot be carried out.

Figure 8-19 FES curves for a tilt angle of $10^\circ$ on timber

The timber sample was tilted further and the FES curves obtained at $10^\circ$ tilt is shown in Figure 8-19. It can be seen that there are no linear FES response of the probe at this angle, making any profile measurements impossible. All the tilt results are summarized.
in Figure 8-20, taking the mid point of the linear region of FES curves as the plotted point for each instance.

From the measurements presented in this sub-section, it can be seen that when the samples are tilted at various angles, the response of the sensor varies significantly. It can be seen that with a black nylon sample, satisfactory FES curves can be obtained when the sample is even tilted by 10°. In comparison to that, white nylon sample loses the repeatability of the FES curves when the tilt is at 10°.

The optical probe provides the worst performance for the timber sample. Even at a tilt of 5°, the repeatability of the FES curves is non-existent.

![Figure 8-20 Summary of the tilting effect of a light-colored timber sample](image)

Figure 8-20 Summary of the tilting effect of a light-colored timber sample

As pointed out earlier, lack of reflection of the light off the surfaces and increase of stand-off distance of the probe contributes to the loss of focusing of the probe. With the results obtained through this set of experiments, it can be said that, as expected, the sensor needs to be held parallel to the surface. However, a tilt of 10° for black nylon and 5° for white nylon is acceptable to produce reasonable surface measurements. Nevertheless, in order to successfully maintain focus on a timber surface, any sort of tilting must be avoided.
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8.3. Surface Profile Measurements

In this section of the thesis surface profile measurements carried out on various machined samples will be presented. The samples used consist of black nylon, white nylon, dark colored timber and light colored timber. The choice of material reflects the wide range of surfaces with different reflectance properties that can be measured using the DVD profiler albeit with varying level of accuracy.

8.3.1. Sample Benchmarks

In order to determine the accuracy of surface measurement results provided by the DVD reader based profile measurement system, the samples must be compared to a reference or benchmark. Therefore, the samples used in producing surface traces were first measured using the Talysurf CLI 2000 (pictured in Figure 8-21), manufactured by Taylor Hobson Precision Ltd.

Figure 8-21 Talysurf CLI 2000 by Taylor Hobson Precision Ltd
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The Talysurf mainly houses three probes which are a Chromatic Length Aberration (CLA) or white light gauge, a laser gauge and a mechanical stylus or also known as the inductive gauge.

This measurement system is regularly calibrated and certified to UKAS standards (certificate number 210305), following NPL's guidelines. Thus, this creates a credible benchmark which can be traced back to NPL standards.

All the samples were traced using the inductive gauge, while the nylon samples were measured using the white light interferometer and the timber samples with the laser probe. This was done in accordance to the recommendations provided in the operating manual of the Talysurf. It was also observed during the experimental work that due to excess roughness of the timber surface, the CLA probe was frequently going out of focus. This problem was overcome with the use of the laser gauge which has a much larger focusing range and thus more suitable for measuring rougher surfaces like the timber.

The specifications of all three probes are given below in Table 8-1:

<table>
<thead>
<tr>
<th>Spot size/Tip diameter</th>
<th>Laser gauge</th>
<th>CLA gauge</th>
<th>Inductive gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30µm - 150µm</td>
<td>8µm</td>
<td>4µm</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>1µm</td>
<td>0.02nm</td>
<td>10nm</td>
</tr>
<tr>
<td>Repeatability</td>
<td>N/A</td>
<td>2nm</td>
<td>6nm</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>1µm</td>
<td>1µm</td>
<td>2µm</td>
</tr>
<tr>
<td>Measurement speed</td>
<td>1mm/s</td>
<td>1mm/s</td>
<td>2mm/s</td>
</tr>
<tr>
<td>Stylus force</td>
<td>N/A</td>
<td>N/A</td>
<td>100mg (at 0 gauge reading)</td>
</tr>
</tbody>
</table>

Table 8-1 Specifications of the Talysurf gauges

From the above data, it can be seen that the inductive gauge has the finest measurement footprint in terms of having the smallest spot size. It can be seen later that due to this, the gauge picks up more surface roughness in the traces. However, as the focus of this
research work is to determine the waviness pattern, this roughness is filtered out. This data filtering was carried out as discussed by Yang et al, (2006).

8.3.1.1. Effect of Sampling Rate

As pointed out above, the horizontal resolution of the Laser or CLA gauge is 1 \( \mu m \), while for the inductive gauge it is 2 \( \mu m \). This means that a measurement can be taken every 1 or 2 \( \mu m \) depending on the gauge used. This is substantially higher than the sampling rate of 127 \( \mu m \) when the measurements are obtained using the DVD profiler. This limitation was imposed on the DVD profiler due to the lack of resolution of the stage used for carrying out the measurements. Thus in order to harmonize the results and create effective benchmarks; the sampling frequency of the Talysurf was also changed to 127 \( \mu m \).

8.3.2. White Nylon Defect

The first sample measured was a white nylon machined with a defect. The 3-D plot of the machined area of the sample obtained with the help of Talysurf is shown in Figure 8-22.

![Figure 8-22 3-D plot of white nylon sample with defects](image)

The defects created on the machined sample are shown in the figure. The nature of the defect and detailed analysis of this surface forming is beyond the scope of this thesis and therefore has not been reported here.
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Figure 8-23 Comparison of unfiltered surface profile of a white nylon sample with defects using Talysurf white light and inductive gauges

The figure shown above (Figure 8-23) shows the correlation between the sample traces of the defective white nylon sample obtained by the use of CLA and the inductive gauge. It can be seen that the two traces are identical and has a correlation coefficient of 0.9974.

The 2-D surface profile plot generated in Figure 8-24 shows clearly the defect generated on the surface with the small scale planer discussed in chapter 7. This plot has been obtained with the help of the CLA gauge.

An FFT analysis of the surface plot reveals that the dominant wavelength present in the waveform is of 10 mm. This is consistent with the analysis presented by Elmas et al, (2007) that for such a defect the dominant wavelength appears to be four times the nominal wave pitch, which in this case is 2.5 mm.
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Figure 8-24 Defective white nylon surface profile trace and its FFT obtained using the CLA gauge

Figure 8-25 Defective white nylon surface profile trace and FFT obtained using the inductive gauge
The surface trace and its FFT analysis obtained using the inductive gauge of the Talysurf has been shown in Figure 8-25. It can be seen that same sort of phenomenon occurs at the FFT as in the CLA gauge results. The dominant wavelength appears at the 10 mm mark with the defects clearly appearing around the 40 and 60 mm mark on the profile plot.

![Defective white nylon surface profile trace and its FFT obtained using the DVD profiler](image)

Figure 8-26 Defective white nylon surface profile trace and its FFT obtained using the DVD profiler

The surface profile trace of the white nylon sample with defects obtained using the optical DVD profilometer is shown in Figure 8-26. This sample trace as well as all the others with this probe is obtained with a horizontal spacing of 127 μm. From the surface trace it can be seen that the defect generated on the surface can be clearly observed, while the FFT analysis reveals that the dominant wavelength is present at approximately 11 mm.
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Figure 8-27 Defective white nylon surface profile traces using all three probes

All the three traces are reported together in Figure 8-27. It can be seen that the general shape of the profile obtained using the DVD profiler matches very well with the other two methods. However, the surface height is shallower in some parts of the trace, most notably around the defect regions. The difference in surface height between the benchmark and DVD profiler stands at about 10μm in this region.

But in the rest of the profile the optical DVD profiler follows the benchmark traces very closely. The correlation coefficient between the DVD profiler and the CLA gauge was calculated and stands at 0.9204, while the correlation coefficient between the inductive gauge and the DVD profiler has been calculated to be 0.9194. Therefore, the DVD profiler was able to measure the surface profile of this sample with over 91% accuracy.

The mean width of profile elements or mean width of surface irregularities (Rsm) is a standard quantitative measure of the waviness patterns of a machined surface (Leach and Harris, 2004). This parameter is also highly suitable to quantitatively describe surfaces like the planed timber and similar materials reported here, as the waviness
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Figure 8-29 Comparison of unfiltered surface profile of a white nylon sample with 2mm wave pitch using Talysurf white light and inductive gauges

The filtered and polynomial fitted 2-D surface profile trace of the sample along with its FFT is reported in Figure 8-30 and Figure 8-31. The first trace is obtained using the CLA gauge mounted on the Talysurf, while the latter figure shows the profile as traced by the inductive gauge.

From the profile trace it can be seen that the regularly spaced cutter marks of 2mm is present. The FFT of this trace shows that the dominant wavelength stands at roughly 2.5 mm, which correlates closely to the nominal value mentioned above.

However, the FFT of surface trace obtained though the inductive gauge shows that the dominant wavelength present in the surface is in the order of roughly 2.3 mm (Figure 8-31). Thus, it can be said that the measurements carried out by the inductive gauge is more accurate in picking up the right wavelength present in this surface trace.
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Figure 8-30 2.5 mm pitched white nylon surface profile trace and its FFT obtained by CLA gauge

Figure 8-31 2.5 mm pitched white nylon surface profile trace and its FFT obtained by stylus
The above figure (Figure 8-32) reports the surface trace of the 2mm pitched white nylon sample along with its Fourier analysis obtained using the DVD profiler. The whole of surface trace does not very clearly show that the wave pitch stands at about 2 mm. But the marked area of the figure does show that the wave pitch is of that order.

The FFT analysis of the surface does show that the dominant wavelength present in the trace is about 2.6 mm, which is very close to the value obtained with the CLA gauge. It can be seen from the 3-D plot of the surface (Figure 8-28) that the edges of the sample are higher than the middle part. Since the measurements were started from one of the edge, the surface trace is not very consistent due to this tilt as discussed in the previous section of this thesis.
All the three traces for the white nylon sample are shown together in Figure 8-33. It can be observed that as stated before, there are some anomalies in the trace obtained through the DVD profiler when compared to the benchmarks. However, in general, the shape and pitch width of the trace correlates well with the other two.

The correlation coefficient between the traces obtained by the CLA gauge and the DVD profiler is 0.3473, while it is 0.3396 between the inductive gauge and the DVD profiler. The correlation coefficient is low compared to the one reported for the white nylon sample with defects. From Figure 8-33, it can be seen that the trace obtained from the DVD profiler corresponds well with the benchmarks in the region of 10 to 22.5 mm. This visual observation can be backed up with correlation coefficients, which come out to be 0.7376 and 0.7626 when compared to the inductive and CLA gauge respectively. This marks a significant improvement over the results discussed earlier. However, the coefficients are much higher in the 15 to 20 mm region. They are 0.8763 and 0.8162 for the CLA and inductive gauge respectively.
The $R_{sm}$ value for the benchmarks has been calculated and has been found out to be 2 mm. This compares very well with the $R_{sm}$ value of 2.01 mm as calculated for the trace obtained by the help of the DVD profilometer.

Despite the similarities in the pitch length and in general pitch shapes, there are some differences in the surface height measured by the DVD profiler and the Talysurf. More calibration exercises must be carried out to rectify the calibration error and exactly match the surface height of this sample with the benchmark.

8.3.4. Hardwood with 4.5 mm Pitch

A dark-colored hardwood sample was measured using the three probes presented in this chapter. The nominal wave pitch of this machined sample was 4.5 mm without any defect or deformation.

![Figure 8-34 3-D plot of hardwood sample with 4.5 mm pitch](image)

The 3-D image of the machined surface can be seen in Figure 8-34. From this figure it can be observed that regularly spaced cutter marks are present in this sample.

The benchmarking of the sample was done with the laser gauge and the inductive gauge as shown in the plot in Figure 8-35. The two sample traces are plotted unfiltered.
Figure 8-35 Comparison of unfiltered surface profile of a hardwood sample with 4.5 mm wave pitch using Talysurf white light and inductive gauges

From this plot in Figure 8-35, the correlation coefficient between the two traces have been calculated and found to be 0.8928. This is significantly lower than the white nylon samples reported earlier. It has been discussed in this thesis that the light reflection from the wood surface is highly affected by the inconsistency and different grain sizes of the wood sample. This fact is epitomized here with the difference in surface height and shape in the traces. Especially, the two traces have significant differences in the 10 to 15 mm region.

As mentioned earlier, the wave pitch of the machined sample is 4.5 mm, determined using the machining parameters discussed earlier in the thesis.
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4.5 mm pitch

Figure 8-36 Surface profile and FFT of 4.5 mm pitch hardwood sample using laser gauge

4.5 mm pitch

Figure 8-37 Surface profile and FFT of 4.5 mm pitch hardwood sample using inductive gauge
The first benchmark of the surface profile of the hardwood as presented in Figure 8-36 shows that the consecutive peaks of the cutter marks are spaced roughly at 4.5 mm, supporting the fact that it is a 4.5 mm pitched sample. However, the FFT analysis provided alongside the profile graph shows the dominant wavelength at about 5 mm.

The surface scan results obtained with the help of the mechanical stylus is presented in Figure 8-37 and shows that the two consecutive peaks are approximately 4.5 mm apart. Again, the FFT analysis of the surface shows that the dominant wavelength present in the profile trace is 5 mm and not 4.5 mm.

![Graph showing surface profile and FFT of 4.5 mm pitch hardwood sample using DVD profiler](image)

**Figure 8-38** Surface profile and FFT of 4.5 mm pitch hardwood sample using DVD profiler

A similar trend is observed with the surface profile traces obtained by using the DVD profiler. In Figure 8-38, the profile graph shows waviness with a pitch length of roughly 4.5 mm. As, in the previous two traces, the FFT analysis shows that the dominant wavelength is at 5 mm and not 4.5 mm. This result corresponds exactly with the benchmark values.
The surface profile plots obtained with the help of all three methods are presented in Figure 8-39. As in the previous samples, correlation coefficients between the benchmarks and the DVD profiler have been calculated. The correlation coefficient between the DVD profiler and the laser gauge is 0.4995, while it is 0.4401 between the inductive gauge and the DVD profiler.

Again, visual observation of the sample traces reveals that the correlation between the DVD profiler and the benchmarks are much better in the region of 0 to 20 mm. The coefficient of correlation for this region has been found out to be 0.7525 and 0.7977 when the DVD profiler trace is compared to the traces obtained through the inductive gauges and laser respectively. Further analysis shows that the correlation coefficient is highest in the region of 10 to 20 mm. The correlation coefficient in this region is 0.7787 and 0.8746 when the DVD profiler is compared to the inductive gauge and the laser gauge respectively.
The $R_{sm}$ value calculated for the benchmarks show that it is 4.6 mm, very close to the machined pitch width of 4.5 mm. The sample trace from DVD profiler shows an $R_{sm}$ value of 4.9 mm, which marks a deviation of 8.9% from the benchmark value.

As pointed out in the analysis of this nylon sample, it is observed that there are some deviations on the pitch shape of the DVD profiler when compared to the benchmark traces created using the Talysurf. These anomalies can be down to the fact that the stages used to provide the scanning motion for the two samples are not the same, thus their calibrations do not match. Hence, the exact locations of measurement of the DVD profiler and the Talysurf probes do not coincide, giving rise to the mismatch in the x-axis of the sample trace. This phenomenon can be observed from the shifting of the curves. Also, some of the height of peaks of the DVD profilometer does not match with the benchmarks, which is possibly due to the tilt in the sample. However, more calibration exercises with samples without any tilts are required to validate this.

### 8.3.5. Light-colored Timber with 2 mm Pitch

This sub-section reports measurement carried out on a light-colored timber sample using the Talysurf probes as well as the DVD profiler. The 3-D axonometric view of the machined timber is shown in Figure 8-40.

![3-D view of a light-colored timber with 2mm pitch length](image)

From the above figure (Figure 8-40), it can be seen that the machined sample has a regular waviness pattern on the surface albeit with some deviation. Apart from that,
substantial roughness can be observed on the machined surface, which is consistent with fibrous material like timber.

Figure 8-41 Comparison of unfiltered surface profile of a light-colored timber sample with 2mm wave pitch using Talysurf laser and inductive gauges

Unfiltered profile plots of the surface obtained through both the laser and inductive probes have been reported in Figure 8-41. Substantial differences in peak height (particularly at 2.5 mm, 7 mm, 15 mm, 20 mm and 24 mm mark) and shape can be observed between the two traces. This visual observation of significant difference between the two probes is backed up by the low correlation coefficient of 0.7806.

The surface profile trace obtained using the laser probe has been reported in Figure 8-42 along with the FFT analysis of the trace. From the profile trace, it can be seen that the waviness pattern with a regularly spaced pitch of 2 mm is present. The corresponding FFT also shows that the dominant wavelength present in the trace is of about 2.1 mm which closely resembles the actual pitch length value of 2 mm.
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Figure 8-42 2 mm pitched light-colored timber sample and its FFT obtained using laser gauge

Figure 8-43 2 mm pitched light-colored timber sample and its FFT obtained using inductive gauge
Similar surface trace is reported in Figure 8-43, obtained using the inductive gauge of the Talysurf. The spacing between the two consecutive peaks is seen to be about 2 mm. The FFT analysis like the laser probe also shows that the dominant wavelength present in the trace is of the magnitude of about 2.1 mm. Therefore, it can be said that this is the actual length of the waviness of this machined sample.

![Graph showing 2 mm pitch and dominant wavelength](image)

Figure 8-44 2 mm pitched light-colored timber sample trace and its FFT obtained using DVD profiler

The surface profile of the 2mm light-colored timber sample is shown in Figure 8-44 along with the FFT of the trace. The profile graph shows that the measurements are greatly influenced by the roughness present in the sample. However, when the FFT analysis is looked into, the dominant wavelength is found at 2.8 mm, which is somewhat higher than the as the benchmark traces discussed earlier.

All the surface traces are plotted together in Figure 8-45. As mentioned just now, due to the roughness of the timber sample, the surface trace obtained with the help of the DVD profiler is different than the ones obtained through the Talysurf measurements. It can be
observed from Figure 8-45 that is some places; the DVD profiler follows the profile of the machined sample with great accuracy, as epitomized by the trace between 5 and 10 mm. In other places, there appears to have been shifts in the curve as well as excessive response of the DVD probe due to small change in surface height or roughness.

Figure 8-45 Surface profile trace of a light-colored timber sample obtained using all three probes

The coefficient of correlation was calculated as in with previous samples. The value of the coefficient has been found out to be 0.3769 when the DVD profiler is compared to the inductive gauge and 0.4025 when compared to the laser gauge of the Talysurf. However, this coefficient is significantly higher in the region between 0 to 7.5 mm, where it is 0.7692 and 0.8417 when the DVD profiler is compared to the inductive gauge and the laser gauge respectively. Similar analysis on the other end of the sample shows that the correlation coefficient is about 0.6420 when the DVD profiler is compared to the inductive gauge and 0.8497 when the trace results are compared with the laser probe.

The $R_{\text{sm}}$ values obtained from the benchmark samples and the DVD profiler are 2.03 mm and 2.07 mm respectively.
It can be seen from the traces presented here that the FFT analysis results are significantly different when the DVD profiler is compared to either benchmarks. However, the mean width of profile elements or the spacing parameter $R_{sm}$ is similar in both cases and the DVD profiler's $R_{sm}$ value differs from the benchmark value by a mere 2%.

The 3-D plot of the sample as reported in Figure 8-40 shows that there is considerable roughness on the surface. This sort of roughness feature is quite common in materials like the timber. As a result of this sort of surface irregularity, unexpected light scattering takes place. Thus, there is a significant loss of reflected light back to the photo detectors. So, errors creep in to the profile height measured by the sensor.

Another source of error is the calibration curve itself. As pointed out in chapter – 5, the calibration curves are obtained through experiments for a particular sample. Substantial calibration exercises have been carried out for each sample (10 per sample) and the average is used in the auto-focusing algorithm. But, due to the rough and fibrous nature of timber surface, deviations in the FES curves can be easily expected. A slight deviation between the average FES curve and the actual one can hinder the focusing action. Due to this, errors have also been introduced to the measurement results.

### 8.3.6. Black Nylon Defect

A black nylon sample with defects is shown in the following figure (Figure 8-46). The defects on the machined surface are pointed out. It can be seen that the defects are much shallower in depth when compared to the ones seen for the white nylon sample in Figure 8-22.
The surface is formed with a small scale planer as discussed earlier with similar sort of defect as the white nylon sample.

![3-D image of black nylon sample with defects](image.png)

**Figure 8-46** 3-D image of black nylon sample with defects

The correlation coefficient of the unfiltered profiles is calculated from the CLA and inductive gauge traces shown in Figure 8-47. This coefficient is 0.9883. Thus, the two benchmarks excellently agree with each other.

![Comparison of unfiltered surface profile of a black nylon sample with defects using Talyurf white light and inductive gauges](image2.png)

**Figure 8-47** Comparison of unfiltered surface profile of a black nylon sample with defects using Talyurf white light and inductive gauges
The 2-D surface profile curve of this sample is shown in Figure 8-48 was obtained with the help of the CLA or the white light gauge mounted on the Talysurf profilometer. It can be observed that the defect on the surface occurs after three successive peaks on the surface, which is consistent with the discussions provided in the literature published by Elmas et al, (2007). The FFT of the waveform shows that the dominant wavelength occurs four times of the nominal wavelength, which also matches the above literature.

Figure 8-48 Defective black nylon surface trace and its FFT obtained using CLA gauge
Figure 8-49 Defective black nylon surface trace and its FFT obtained using inductive gauge

The surface is also measured using the inductive gauge and the result is shown in Figure 8-49. This profile measurement correlates very well with the aforesaid CLA gauge. The FFT analysis also shows similar trend as discussed above.
The surface of the black nylon with defects is again measured with the DVD profiler and the surface trace is reported in Figure 8-50. The surface profile measurement shows that the DVD profiler is not very accurate in picking up the surface waviness features of the black nylon sample. Nonetheless, some of the defects are recognizable as shown in the figure.

The FFT analysis of the profile reveals a much better picture of the surface. The dominant wavelength appears at about 10.1 mm, while for the mechanical stylus and the CLA gauge, it stood at 9 mm. This gives a deviation of 12%.
Figure 8-51 Defective black nylon surface traces using all three probes

The profile of the black nylon sample measured using all three probes are shown in the figure above (Figure 8-51). As pointed out in the analysis just preceding the figure, there is significant deviation in the measurement of the surface profile of this sample using the DVD profiler when compared to the other probes. This deviation is evident from the traces shown in Figure 8-51. The correlation coefficient between the DVD profiler and the inductive gauge is 0.1249 and between the DVD gauge and the CLA gauge is 0.1465. However, better correlation among the measurements can be seen in the region between 40 mm to 60 mm of the sample. The correlation coefficient in this region is 0.3299 and 0.2615 when the DVD profiler trace is compared to the traces obtained from the CLA gauge and the inductive gauge respectively.

The mean spacing parameter $R_{sm}$ was also calculated for this sample and the value obtained for the Talysurf benchmark was 6.66 mm. The $R_{sm}$ value of the surface profile obtained with the help of the DVD profiler is 6.08 mm. This corresponds to a difference of 8.7%.
From the results presented here, it is clearly seen that the surface profile of the black nylon sample cannot be clearly observed when measured with the DVD profilometer. It has been discussed previously that due to the dark color of the sample, large amount of light absorption takes place when compared to lighter colored material having higher reflectance property. Therefore, though the probe can be initially calibrated on this type of surface, the final measurement results do not compare well with the benchmarks.

Nevertheless, it is interesting to observe that the FFT analysis clearly shows that the main frequency components are present in the surface trace. The height of the surface plot is heavily dependent on the right quantity of reflected light on the four-quadrant receiver. Thus, it is natural that with low quantity of reflected light back on the receiver, the surface heights will not be measured correctly by the probe. However, the FFT analysis is a normalized method of obtaining the wavelength components in a given waveform and is less affected by the amplitude of the signal. Since the FFT analysis of the plot obtained with the DVD profiler corresponds closely to the Talysurf benchmarks, it may well be the case that, with the increase in power of the laser diode inside the DVD reader, the surface profile of dark colored samples can be measured correctly with this probe. But more research needs to be carried out to confirm this assumption.

8.3.7. Summary of Results

The results obtained from the analysis of the surface traces are summarized in Table 8-2.
<table>
<thead>
<tr>
<th>Samples</th>
<th>Correlation Coefficient</th>
<th>FFT Analysis (Dominant wavelength)</th>
<th>R$_{sm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>White nylon (defect)</td>
<td>With CLA gauge: 0.92</td>
<td>All probes: 11 mm</td>
<td>CLA &amp; inductive gauge: 12.55 mm</td>
</tr>
<tr>
<td></td>
<td>With inductive gauge: 0.92</td>
<td></td>
<td>DVD profiler: 12.75 mm</td>
</tr>
<tr>
<td>White nylon (2mm pitch)</td>
<td>With CLA gauge: 0.35 (0.74 for 10-22.5 mm region)</td>
<td>CLA gauge: 2.5 mm</td>
<td>CLA &amp; inductive gauge: 2.00 mm</td>
</tr>
<tr>
<td></td>
<td>With inductive gauge: 0.34 (0.76 for 10-22.5 mm region)</td>
<td>Inductive gauge: 2.3 mm</td>
<td>DVD profiler: 2.01 mm</td>
</tr>
<tr>
<td>Light colored timber (2mm pitch)</td>
<td>With inductive gauge: 0.38 (0.77 for 0-7.5 mm region)</td>
<td>Laser gauge: 2.1 mm</td>
<td>DVD profiler: 2.8 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inductive gauge: 2.1 mm</td>
<td>Laser &amp; inductive gauge: 2.03 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DVD profiler: 2.07 mm</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Surface Material</th>
<th>Measurements with Laser Gauge</th>
<th>Measurements with Inductive Gauge</th>
<th>Measurements with CLA Gauge</th>
<th>Measurements with DVD Profiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardwood (4.5 mm pitch)</td>
<td>0.5 (0.80 for 0-20 mm region)</td>
<td>0.44 (0.75 for 0-20 mm region)</td>
<td>0.15 (0.33 for 40-60 mm region)</td>
<td>0.13 (0.26 for 40-60 mm region)</td>
</tr>
<tr>
<td>Black nylon (defect)</td>
<td>All gauges: 5 mm</td>
<td>Inductive gauge: 9 mm</td>
<td>CLA gauge: 9 mm</td>
<td>DVD profiler: 6.66 mm</td>
</tr>
<tr>
<td></td>
<td>Laser &amp; inductive gauge: 4.5 mm</td>
<td>DVD profiler: 10.1 mm</td>
<td>DVD profiler: 4.9 mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 8-2 Summary of the analytical results obtained from all the surface traces

These results are summarized in the bar diagrams presented below. The correlation coefficients of the full sample lengths are presented in Figure 8-52, while the results of the best matched sections on the samples are shown in Figure 8-53.

The dominant wavelengths obtained though the FFT analyses on the sample traces are given in Figure 8-54. Comparison of the $R_{sm}$ values is summarized in Figure 8-55.
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Figure 8-52 Comparison of correlation coefficients for the full length of the samples

Figure 8-53 Comparison of correlation coefficients for the best matched areas of the samples

Figure 8-54 Comparison of dominant wavelength present in the FFT analysis of the samples
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![Bar Chart](image)

**Figure 8-55** Comparison of $R_{sm}$ values of the samples

The variance of the dominant wavelength obtained from the FFT analyses between the benchmark and the DVD profiler has been reported in Figure 8-56. It can be observed that, as pointed out before, the values match exactly for hardwood and the white nylon sample with defect. An almost zero variation can be observed for the white nylon sample with 2mm, while higher variations can be seen for light colored timber and the black nylon sample.

![Line Chart](image)

**Figure 8-56** Variance of dominant wavelength between the benchmarks and DVD profiler

The variance of the $R_{sm}$ values between the benchmarks and the DVD profiler is reported in Figure 8-57. As in other results documented earlier, the black nylon sample has the largest deviation from the benchmark results, while the others exhibit very small
variances (between 0 and 4%). However, all the variations are less than 10%, which is quite close to the actual values.

![Graph showing variance of Rs value between benchmarks and DVD profiler](image)

Figure 8-57 Variance of $R_{\text{sm}}$ value between the benchmarks and DVD profiler

### 8.3.8. Sources of Error

It can be observed from the previous table that some of the measurements of the samples do not correlate well with the benchmarks. The likely reasons for these errors in the results obtained by the DVD profiler are as follows—

- The stage of the Talysurf profiler used to obtain the benchmarks and the stage used with the DVD profiler do not have same calibrations. So, there will be some discrepancy between the displacement information on the x-axis. For instance, a 100 $\mu$m displacement on the Talysurf stage will not exactly correspond to a 100 $\mu$m displacement on the DVD profiler stage. Thus, the profile measured by the two systems will not be the same. This results to poor correlation value between the two.

- Also, it is almost impossible to align the two areas of measurement by the Talysurf and the developed profiler. A small mismatch of the starting point of the surface scans results in difference between the measured profile and the benchmarks.
- The DVD profiler has to be calibrated for a certain material to successfully carry out the surface profile measurements. In order to focus the probe on the surface of the measured sample, this calibration curve needs to be correct for measured point. However, due to various limitations, only 10 characteristics curves were obtained from one sample and an average was used to carry out the surface profile measurements. Due to the non uniform anatomical nature of the samples, especially the timber ones, some of the points did not correspond to the obtained characteristics curve. Thus, the focusing mechanism can obtain a wrong focal point on the sample surface, introducing error in measurements.

- It has been shown at the beginning of the chapter that the measurements obtained through the DVD profiler probe are susceptible to tilt on the measured surface. Therefore, some of the measurement values do not compare well to the benchmarks due to the tilt observed from the 3-D profile obtained with the Talysurf.

- It is a well established fact that timber surfaces have anatomical irregularities contributing to deep valleys on the surface. When the light from the DVD profiler strikes a deep valley, the photo detectors do not get the reflection back of the surface and the profiler loses focus on the surface under test. This also contributes to the errors in measurement.

- Some parts of the dark timber sample can absorb the laser of the DVD probe. This creates an effect like the black nylon sample and gives rise to errors in surface profile measurements of that type of samples.

8.4. Summary

- The effect of changing the gain of the FES signal conditioning amplifiers on the stand-off distance has been investigated in this chapter. It was seen that, with the alteration of this gain, the stand-off distance doesn’t change significantly. The
only probable way to change the stand-off distance is to increase the power of the laser diode inside the probe. This couldn’t be done due to the lack of available resources about the power control system of the probe.

- The effect of tilt on the FES curves for various materials was looked into and reported in this chapter. The results show that consistent FES linear regions can be obtained for a black nylon sample even though the sample is tilted by $15^\circ$. No FES regions can be obtained when the sensor is tilted by $10^\circ$ for a white nylon sample and $5^\circ$ for a timber sample. Thus, it was observed that the measurement results can be significantly affected by the tilt in the sample or if the sensor is held an angle.

- The surface profile measurement results were also reported in this chapter. Various samples were measured and compared to the benchmark traces obtained through the contact and non-contact probes of the calibrated Talysurf profiler.

- A white nylon sample with defects was measured with the highest accuracy by the DVD profiler, with over 90% correlation with the benchmark traces.

- The surface traces obtained for the white nylon sample with 2mm pitch, light colored timber also with 2mm pitch and dark colored timber with 4.5 mm pitch all showed some excellent correlation as well as some deviation from the benchmarks. In general, the FFT analysis as well as the $R_{sm}$ values of the traces correlated well with the Talysurf traces.

- The surface trace of the black nylon sample did not correlate well with the benchmarks, with the lowest correlation values among all the samples. However, the FFT analysis of the DVD profiler trace matched well with the benchmarks. The $R_{sm}$ value was also less than 10% higher than the one obtained from the Talysurf traces.

- It was concluded that the power of the laser diode needs to be increased to increase the amount of light returned to the photo detectors for measuring the
black nylon's surface profile with more success. This will help in achieving better correlation with the benchmark traces.

- Also, it was discussed that due to the mismatch of the calibration of the stages used for providing scanning motion on the Talysurf and the DVD profiler, the correlation coefficient is lower in some part of the sample traces.
Chapter - 9.

Conclusions and Further Work

9.1. Conclusions

The research work presented in this thesis involves the design and development of a profile measurement system employed in surface finish measurement of softer materials e.g. timber and nylon. The main aim of this work has been to develop a novel, cost-effective non-contact surface profile measurement system to accurately measure the cutter marks formed on surfaces planed by a small scale mechatronic planer.

There are various techniques already available in industry and research labs to measure surface finish quality of machined surfaces. However, as pointed out in the literature review, most of the systems are prohibitively expensive, bulky, difficult to set up, complicated to use and most important of all, only suitable for metallic surfaces. Thus, there is a great demand for cost-effective, reliable, portable and easy-to-use surface profile measurement systems within the woodworking industry.

Keeping this in mind, the developed surface profile measurement system has been designed with the help of off-the-shelf components; an optical mouse sensor and a DVD reader head. This has ensured that the system is both low-cost and portable, meeting the two most important criterions for such a system. Within this measurement system, the mouse sensor essentially works as an optical encoder, while the vertical profile height measurement is achieved through the focusing mechanism of the DVD reader.

From the experimental results, it can be seen that the DVD profiler can be calibrated for various materials, having different textures and surface colors. However, as with other focusing probes, tilting the sensor greatly affected its calibration curves. Most notably, with a tilt angle of 5°, the probe could not be calibrated on timber samples. But the
effect of tilting was less observable on nylon sample. Nevertheless, a tilt of more than 10° made it impossible to obtain repeatable calibration curves even on nypons. Thus, this probe is unsuitable for samples having tilts of more than 10° on the machined surface.

Before the samples were measured with the DVD profiler, they were first measured with the help of two different probes mounted on a commercial Talysurf profiler, calibrated to NPL standards. This helped in creating benchmark traces, against which the surface profile plots obtained through the DVD profiler were compared. For non-contact measurements of nylon samples, a CLA gauge was used, while a laser gauge was used for timber surfaces. All the samples were then measured with a mechanical stylus probe, which is also referred to as the inductive gauge. While the contact and non-contact methods correlated highly (about 99%) when nylon samples were measured, measurement of timber surface showed that the two probes generated quite different surface profiles of the same sample. In the case of the timber sample with highly visible surface roughness, the correlation between the two methods was only 78%. This highlights the difficulty of obtaining true surface profile traces from optical non-contact methods for porous and rough materials like timber.

Due to the effect of surface data filtering and mismatch in the x-coordinate of the plot, merely measuring correlation between the benchmark surface profile and the DVD profiler plots can be a misleading way of validating the experimental results. Thus, besides calculating the correlation between the traces, more advanced surface characterization techniques have been employed while analyzing the surface data. FFT analysis has been carried out on all the surface traces, which helps to determine dominant wavelength present in the traces. From this, an idea of the wave pitch present in the surface data can be obtained. Also, the value of mean spacing of profile elements ($R_{\text{sm}}$) was calculated for all the samples.

The actual profile measurement results showed some good encouragements. A correlation of over 90% could be seen between the traces obtained from the Talysurf and the DVD profiler for a white nylon sample with defects. FFT analysis and $R_{\text{sm}}$
values from the aforesaid two methods were also is very good agreement with each other.

However, poor correlation between the traces was observed for the sample of the same material with a 2 mm pitch width. This was due to the effect of tilt on the sample surface as discussed in the previous chapter. Again, the FFT analysis and the mean spacing parameter were in good agreement with the benchmark.

Timber samples with pitch width of 2 mm and 4.5 mm were also measured with the help of the DVD profiler and the measurements provided mixed correlations. It was seen that the correlation coefficient almost reached 90% for some parts of the sample, while in other areas it was only about 30%. As pointed out earlier, it is very difficult to align the points on the x-axis of various curves properly due to the difference in stages providing the scanning motion. Also, due to the nature of timber surfaces, unexpected anomalies in surface measurements can easily creep in. As observed for the white nylon sample, the FFT analysis and mean spacing parameter compared well with the benchmark traces.

The black nylon sample with defects provided the worst correlation among all the samples, which stood at only about 25%. It has been discussed in the previous chapter that due to the high light absorption nature of the material, the profile heights of the machined surface did not match well with the benchmarks. But the FFT analysis clearly showed that the dominant wavelength was at four times the fundamental wavelength, as expected. Also, $R_{sm}$ was quite close to the benchmark. Nevertheless, it is quite clear that more research needs to be done to overcome this problem when measuring the surface profile of dark materials.

The main aim of the research presented in this thesis has been to develop a low-cost, reliable, easy to use and customized surface profile measurement system to be employed within the woodworking industry to measure planed surfaces. The sample traces used in the analysis have all been formed by a small scale planer used in woodworking industry, which addresses the aim of using the profile measurement system in woodworking.
The cost saving achieved through the use of off the shelf elements have been substantial. This profile measurement system can be developed from scratch for less than £500, while a commercially available profiler costs 30 times more.

It has been discussed earlier that there are two different ways of implementing the surface profile measurement system; a portable handheld device or part of an in-process measurement scheme as a feedback to the machine controller.

The software timing issues discussed in chapter 7 clearly shows that the microcontroller used in the current setup is not capable of executing all the algorithms fast enough for in-process implementation of the system. However, the speed requirement for a portable system is somewhat less demanding. So, this system can only be used to in a hand-held configuration using the current setup.

The reliability and repeatability issues of the profile measurement system have not been fully addressed in the thesis. But the calibration curves obtained for various materials show that excellent repeatability can be achieve with the focusing probe.

It can be concluded that the surface profile measurement system proposed, designed, fabricated and tested during the course of this research work can be potentially developed into a fully-fledged cost-effective measurement system for the woodworking or similar industry.

9.1.1. Knowledge Contribution
The following are the contributions of the research work presented in this thesis to current knowledge –

- **Sensor system** – The DVD pickup based metrology is not exactly a novel approach, as, various other researchers have carried out similar work. However, the approach to signal processing and data acquisition differs from the previous techniques employed. This improvement enables better noise rejection of the system leading to greater measurement accuracy and repeatability.
• **Auto-focusing mechanism** – A robust PID controller based auto-focusing mechanism has been developed and implemented within the profile measurement system. Performance analysis of this controller has also been carried out in chapter 6. It is worth mentioning here that, detailed performance analysis of such controllers in a similar profile measurement scheme has not been carried out in the past.

• **Displacement sensing** – In order to obtain the sensor displacement across the tested surface, precision micro-stage has been used in the past. This approach is suitable for specimens of a length in the range of millimeters but will fail to satisfy the requirements of the industry, where, the length of the surface under test will be in the range of meters or close to that. Thus a novel PC mouse sensor based displacement tracking device has been proposed. This would eliminate the need for a micro-stage, thus significantly reducing the development cost of the sensor, whilst, substantially increasing the range of measurement.

• **Industrial integration** – All the surface profile measurement systems built with the DVD optical reader head are essentially suitable for laboratory based metrology. The focus of such measurement scheme is to obtain ultra-precision measurement of highly consistent surfaces. This approach is somewhat unsuitable for an industrial environment, where robustness, speed, small footprint of sensor coupled with acceptable measurement resolution is of more importance than precision measurement. Also, the sensor system needs to be integrated into the process machineries to realize the desired monitoring system for finished products. This aspect is addressed by proposing integration of the sensor system into high-speed woodworking machines currently being developed at the Mechatronics Research Center.

• **Embedded approach to surface profile measurement** – Most of the surface profiling systems developed in various research institutions and laboratories are PC-based and thus, inflexible. In order to achieve the required level of industrial integration, the system needs to be fully integrated with the existing machining setup. This aspect of the system has been addressed by the use of embedded
microcontroller and other interfacing circuits. This has eliminated the need for expensive data acquisition cards extensively used in other researches. This leads to better reliability (in terms of dedicated hardware) and high cost saving (£10 pounds in contrast to about £170 for a data acquisition card from National Instruments).

- **Application** – Most of the pickup based sensors have been applied to find out the surface profile of 'ideal' surfaces. These include – mirrors, thin films of Silicon, commercially available CDs etc. The main focus of this research was to examine 'real' engineering applications of the proposed system. The surfaces tested include timber and nylon samples and the effects of surface textures on the measurement results have been analyzed and discussed in the thesis. It has been seen that a black nylon sample cannot be accurately measured with the existing setup.

- **Surface characterization** – Almost all the surface profile measurements carried out previously looked only into matching the obtained surface traces with the benchmarks or prior knowledge about the surface. For instance, Fan et al, (2000) measured the surface profile of a CD and compared the pit width with a known value. In the analysis presented in this thesis, correlation coefficients of the traces have been calculated as well as FFT analysis has been carried out for every sample. Also, the mean spacing parameter has been calculated. This provides a much better-rounded feel to the measurement results and how it compares to the benchmarks.
9.2. Further Work

In order to realize a reliable, robust and highly accurate surface profile measurement system which can be fully employed in industry, more research work needs to be done.

Firstly, the measurements reported here were carried out in static conditions. Thus, the next step would be to calibrate the system for dynamic measurements. However, as pointed out earlier in the thesis, the current microcontroller used for controlling the focusing mechanism is unable to provide the required processing speed for in-process measurements. Therefore, DSP-based microcontroller needs to be used to carry out the focusing action.

Secondly, as more processing power can be made available with the use of DSP-based embedded system, other control algorithms need to be implemented and tested. In this thesis, only a robust PID controller has been tested, which shows significant immunity to disturbance in the loop when compared to traditional PID. For this profile measurement system, adaptive control techniques need to be looked into. This control technique might be more suitable for the focusing mechanism given the uncertainty involved with the measurement process.

Thirdly, the possibility of increasing the power of the laser diode needs to be researched into. This would be immensely helpful in accurately measuring the surface profile of darker materials, something which the current setup is unable to carry out. Also, an automatic power control system can be designed, which would eliminate the need to manually adjusting the power of the diode.

Fourthly, the gain control mechanism of the FES signal conditioning sub-system can be changed in such a way that automatic gain control (AGC) can be achieved. This would make sure that the sub-system is always tuned at the optimal gain for any given material and no tedious manual adjustments are needed when different samples are measured.

Fifthly, the light dispersion phenomenon of various samples needs to be closely looked into. Especially, how the laser light is reflected off the surface of a timber needs to be observed and analyzed, including the effect of grain sizes on the reflection pattern. This
would provide a thorough and robust explanation of the errors observed in the measurements of timber samples. Also, repeatability analysis must be carried out on the measurement results obtained from the system.

And finally, the surface profile measurement system needs to be rigorously tested in a real wood machining environment to fully determine its suitability for the intended purpose.
References


Appendices
Appendix – 1: Hitachi HOP-1000 Data Sheet
### トランスミッター信号（T.F.E.

- **視点変更**
  - **視点**
    - **Level**
      - **無偏正**
        - **水平**
          - **5.5 ± 0.05V**
        - **垂直**
          - **5.5 ± 0.05V**
      - **偏正**
        - **水平**
          - **5.5 ± 0.05V**
        - **垂直**
          - **5.5 ± 0.05V**
    - **差分**
      - **水平**
        - **5.5 ± 0.05V**
      - **垂直**
        - **5.5 ± 0.05V**
  - **ポリューチン**
    - **ポリューチン**
      - **水平**
        - **5.5 ± 0.05V**
      - **垂直**
        - **5.5 ± 0.05V**

### フォーカスエラー信号（F.E.

- **波形確認**
  - **波形**
    - **5.5 ± 0.05V**
    - **5.5 ± 0.05V**

### フォーカスエラー信号（F.E.

- **波形確認**
  - **波形**
    - **5.5 ± 0.05V**
    - **5.5 ± 0.05V**
<table>
<thead>
<tr>
<th>Operation</th>
<th>Action</th>
<th>Property 1</th>
<th>Property 2</th>
<th>Notes</th>
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<tr>
<td>Idle</td>
<td>Stop</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Run</td>
<td>Start</td>
<td>N/A</td>
<td>N/A</td>
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<td>Stop</td>
<td>Stop</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
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Notes:
- N/A: Not applicable.
- Start: Commence running.
- Stop: Cease operation.
- Idle: Not in use.
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<th></th>
<th>10 mA</th>
<th>45 mA</th>
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<td><strong>Test Voltage</strong></td>
<td>2.8 V</td>
<td>3.3 V</td>
</tr>
<tr>
<td><strong><a href="mailto:Current@2.8V">Current@2.8V</a></strong></td>
<td>5 mA</td>
<td>10 mA</td>
</tr>
<tr>
<td><strong>Operating Voltage</strong></td>
<td>10 V</td>
<td>15 V</td>
</tr>
<tr>
<td><strong>Operating Current</strong></td>
<td>2 mA</td>
<td>5 mA</td>
</tr>
<tr>
<td><strong>Maximum Current</strong></td>
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<td>50 mA</td>
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<td><strong>Maximum Power</strong></td>
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<td><strong>Operating Voltage</strong></td>
<td>10 V</td>
<td>15 V</td>
</tr>
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<td><strong>Operating Current</strong></td>
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<td>5 mA</td>
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<tr>
<td><strong>Maximum Current</strong></td>
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<td>50 mA</td>
</tr>
<tr>
<td><strong>Maximum Power</strong></td>
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</tr>
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</table>

**Specifications:**
- Test Voltage: 2.8 V, 3.3 V
- Current@2.8V: 5 mA, 10 mA
- Operating Voltage: 10 V, 15 V
- Operating Current: 2 mA, 5 mA
- Maximum Current: 20 mA, 50 mA
- Maximum Power: 10 mW, 25 mW

**Notes:**
- For more details, refer to the manufacturer's instructions.
### STANDARD PERFORMANCE

#### 4. 性能规格

#### 4.1 光学性能

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<th>参数</th>
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<td><strong>Focus length (mm)</strong></td>
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<td><strong>Numerical aperture (NA)</strong></td>
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<td><strong>Working distance (mm)</strong></td>
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#### 4.2 光电性能

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<td><strong>Emission light power P1</strong> (mW)</td>
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<tr>
<td><strong>Wavelength (nm)</strong></td>
<td>650 ~ 1650</td>
<td>790 ± 20</td>
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</table>

*Typical*

*Maximum at 25°C*
3. 性能評価条件

STANDARD CONDITIONS OF EVALUATION

(1) 手順上端
Test posture: Optimal axis of objective should be right to gravity and projected point from
the objective should be upward.

(2) 環境
Environment: Temperature

温度 50 ± 5°C

Humidity

湿度 45 〜 75%RH

Note: Temperature range 15 〜 35°C, humidity range 45 〜 75%RH.

If there are no doubt about judgment.

(3) 評価ディスク
Evaluation disc: Use the disc that we admit for evaluation.

C.D.: UCD-1628 (Made by TEAC CORPORATION)

商品が評価として認められたディスクを使用する。

Use the disc that we admit for evaluation

(4) 評価装置
Evaluation equipment: Use Hitachi standard measuring equipment (Fig. 4, 5)

レーザ指向器を用いた測定装置を用いる。

Laser target circuit shown in Fig. 3

(5) 評価用調光器
Jitter meter: M0J-031C (Made by MEGURO ELECTRIC CO.)

CD: M0J-031C (Made by MEGURO ELECTRIC CO.)

Features: 0.1 μm above

Pointly made "Jitter":

(6) 評価用転送速度
Evaluation: Use standard speed

Disc speed: normal speed.
2. 一般仕様

GENERAL SPECIFICATIONS

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*Fig. 2*
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<tr>
<td>DC 感度</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
</tr>
<tr>
<td>DC 衡体</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
</tr>
<tr>
<td>DC 産業</td>
<td>400 ± 20%</td>
<td>400 ± 20%</td>
<td>400 ± 20%</td>
<td>400 ± 20%</td>
<td>400 ± 20%</td>
<td>400 ± 20%</td>
<td>400 ± 20%</td>
</tr>
<tr>
<td>DC 感度</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
</tr>
<tr>
<td>DC 産業</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
</tr>
<tr>
<td>DC 感度</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
</tr>
<tr>
<td>DC 産業</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
<td>600 ± 20%</td>
</tr>
<tr>
<td>DC 感度</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
<td>0.9 ± 0.4</td>
</tr>
</tbody>
</table>
Appendix – 2: MCP-4921 DAC Data Sheet

Microchip

MCP4921/4922

12-Bit DAC with SPI™ Interface

Features

- 12-Bit Resolution
- ±0.2 LSB DNL (typ)
- ±2 LSB INL (typ)
- Single or Dual Channel
- Rail-to-Rail Output
- SPI™ Interface with 20 MHz Clock Support
- Simultaneous Latching of the Dual DACs w/LOAC
- Fast Settling Time of 4.6 μs
- Selectable Unity or 2x Gain Output
- 450 kHz MΩpolar Mode
- External VREF Input
- 2.7V to 5.5V Single-Supply Operation
- Extended Temperature Range: -40°C to +125°C

Applications

- Selective or Offset Trimming
- Sensor Calibration
- Digitally-Controlled Multiplier/Divider
- Portable Instrumentation (Battery-Powered)
- Motor Feedback Loop Control

Description

The Microchip Technology Inc. MCP492X are 2.7-5.5 V, low-power, low DNL, 12-bit Digital-to-Analog Converters (DACs) with optional 2x buffered output and SPI™ Interface.

The MCP492X are DACs that provide high accuracy and low noise performance for industrial applications where calibration or compensation of signals (such as temperature, pressure, and humidity) are required.

The MCP492X are available in the extended temperature range and PDIP, SOIC, MSOP and TSSOP packages.

The MCP492X devices utilize a resistive string architecture, with its inherent advantages of low DNL error, low ratio metric temperature coefficient and fast settling time. These devices are specified over the extended temperature range. The MCP492X include dual-buffered inputs, allowing simultaneous updates using the LOAC pin. These devices also incorporate a Power-On Reset (POR) circuit to ensure reliable power-up.

Package Types

8-Pin PDIP, SOIC, NSOP

14-Pin PDIP, SOIC, TSSOP
Appendix – 3: 18F4523 Data Sheet

Peripheral Highlights:
- 12-bit, up to 13-channel Analog-to-Digital Converter module (A/D):
  - Auto-acquisition capability
  - Conversion available during Sleep
- Dual analog comparators with input multiplexing
- High-current sink/source 25 mA/25 mA
- Three programmable external interrupts
- Four input change interrupts
- Up to 2 Capture/Compare/PWM (CCP) modules, one with Auto-Shutdown (28-pin devices)
- Enhanced Capture/Compare/PWM (ECCP) module (40/44-pin devices only):
  - One, two or four PWM outputs
  - Selectable polarity
  - Programmable dead time
  - Auto-shutdown and auto-restart
- Master Synchronous Serial Port (MSSP) module supporting 3-wire SPI (all 4 modes) and 12 C"
- Master and Slave modes
- Enhanced USART module:
  - Supports RS-485, RS-232 and UART
  - RS-232 operation using Phaselock Loop (available for crystal and internal oscillators)

Flexible Oscillator Structure:
- Four Crystal modes, up to 25 MHz
- 4x Phase Lock Loop (available for crystal and internal oscillators)
- Two External RC modes, up to 4 MHz
- Two External Clock modes, up to 25 MHz
- Internal oscillator block:
  - 8 user-selectable frequencies, from 51 kHz to 8 MHz
  - Provides a complete range of clock speeds from 31 kHz to 32 MHz when used with PLL
  - User-selectable to compensate for frequency drift
- Secondary oscillator using Timer1 @ 32 kHz
- Fail-Safe Clock Monitor:
  - Allows for safe shutdown if external clock stops

Special Microcontroller Features:
- C compiler optimized architecture
- Optional extended instruction set designed to optimize re-entrant code
- 100,000 erase/write cycle Enhanced Flash program memory typical
- 1,000,000 erase/write cycle Data EEPROM memory typical
- Flash/Deadline EEPROM Retention: 100 years typical
- Self-programmable under software control
- Priority levels for interrupts
- 8 x 8 Single-Cycle Hardware Multiplier
- Extended Watchdog Timer (WDT):
  - Programmable period from 4 ms to 131 s
  - Single-Slope In-Circuit Serial Programming™ (ICSP™) via two pins
  - In-Circuit Debug (ICD) via two pins
- Operating voltage range: 2.0V to 5.5V
- Programmable 16-level High/Low-Voltage Detection (HLVD) module
- Supports interrupt on High/Low-Voltage Detection
- Programmable Brownout Reset (BOR):
  - With software enable option

<table>
<thead>
<tr>
<th>Device</th>
<th>Program Memory (bytes)</th>
<th>Data Memory (bytes)</th>
<th>I/O</th>
<th>CCP</th>
<th>ECCP</th>
<th>MSSP</th>
<th>Comp.</th>
<th>Timers</th>
<th>Bypass</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIC18F2423</td>
<td>16K</td>
<td>1828</td>
<td>128</td>
<td>210</td>
<td>210</td>
<td>1</td>
<td>2</td>
<td>1/3</td>
<td></td>
</tr>
<tr>
<td>PIC18F2523</td>
<td>32K</td>
<td>1830</td>
<td>256</td>
<td>10</td>
<td>210</td>
<td>1</td>
<td>2</td>
<td>1/3</td>
<td></td>
</tr>
<tr>
<td>PIC18F4423</td>
<td>16K</td>
<td>1828</td>
<td>128</td>
<td>210</td>
<td>210</td>
<td>1</td>
<td>2</td>
<td>1/3</td>
<td></td>
</tr>
<tr>
<td>PIC18F4523</td>
<td>32K</td>
<td>1830</td>
<td>256</td>
<td>10</td>
<td>210</td>
<td>1</td>
<td>2</td>
<td>1/3</td>
<td></td>
</tr>
</tbody>
</table>

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Appendix – 4: ADNS-2051 Data Sheet

ADNS-2051
Optical Mouse Sensor

Data Sheet

Description
The ADNS-2051 is a low cost optical sensor used to implement a non-mechanical tracking engine for computer mice.

It is based on optical navigation technology, which measures changes in position by optically acquiring sequential surface images (frames) and mathematically determining the direction and magnitude of movement.

The sensor is housed in a 16-pin staggered dual inline package (DIP) that is designed for use with the HDNS-2100 Lens and HDNS-2200 Clip and HLMP-ED80-XX000 (639 nm LED Illuminator source). There are no moving parts and precision optical alignment is not required, facilitating high volume assembly.

The output format is two channel quadrature (X and Y direction) which emulates encoder photo-transistors. The current X and Y information are available in registers accessed via a serial port.

Default resolution is specified as 400 counts per inch (cpi), with rates of motion up to 14 inches per second (ips).

Resolution can also be programmed to 800 cpi.

The part is programmed via a two wire serial port, through registers.

Theory of Operation
The ADNS-2051 is based on Optical Navigation Technology. It contains an Image Acquisition System (IAS), a Digital Signal Processor (DSP), a two-channel quadrature output, and a two wire serial port.

The IAS acquires microscopic surface images via the lens and illumination system provided by the HDNS-2100, 2200, and HLMP-ED80-XX000 LED. These images are processed by the DSP to determine the direction and distance of motion. The DSP generates the \( \Delta x \) and \( \Delta y \) relative displacement values that are converted into two channel quadrature signals.

Features
- Precise optical navigation technology
- No mechanical moving parts
- Complete 2D motion sensor
- Serial interface and/or quadrature interface
- Smooth surface navigation
- Programmable frame speed up to 2300 frames per second (fps)
- Accurate motion up to 14 ips
- 800 cpi resolution
- High reliability
- High speed motion detector
- No precision optical alignment
- Wave solderable
- Single 5.0 volt power supply
- Shutdown pin for USB suspend mode operation
- Power conservation mode during times of no movement
- On-chip LED drive with regulated current
- Serial port registers
  - Programming
  - Data transfer
- 16-pin staggered dual inline package (DIP)

Applications
- Mice for desktop PCs, workstations, and portable PCs
- Trackballs
- Integrated input devices
## Recommended Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>$T_o$</td>
<td>0</td>
<td>49</td>
<td></td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Power Supply Voltage</td>
<td>$V_{CC}$</td>
<td>4.25</td>
<td>5.0</td>
<td>5.5</td>
<td>volts</td>
<td>Register values retained for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>voltage transients below 4.25 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>but greater than 4 V.</td>
</tr>
<tr>
<td>Power Supply Rise Time</td>
<td>$V_{RS}$</td>
<td>100</td>
<td></td>
<td></td>
<td>ms</td>
<td>Peak to peak within 0-100 kΩ.</td>
</tr>
<tr>
<td>Supply Noise</td>
<td>$V_n$</td>
<td>190</td>
<td>190</td>
<td></td>
<td>mV</td>
<td></td>
</tr>
<tr>
<td>Clock Frequency</td>
<td>$f_{CLK}$</td>
<td>17.4</td>
<td>18.0</td>
<td>18.7</td>
<td>MHz</td>
<td>Set by ceramic resonator.</td>
</tr>
<tr>
<td>Serial Port Clock Frequency</td>
<td>$f_{SCLK}$</td>
<td>17.4</td>
<td>18.0</td>
<td>18.7</td>
<td>MHz</td>
<td></td>
</tr>
<tr>
<td>Resonator Impedance</td>
<td>$X_{RES}$</td>
<td>55</td>
<td>55</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance from Lens Reference</td>
<td>$Z$</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
<td>mm</td>
<td>Results in ±0.2 mm DOF. (See Figure 12.)</td>
</tr>
<tr>
<td>Plane to Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>$S$</td>
<td>0</td>
<td>14</td>
<td></td>
<td>m/sec</td>
<td>$@$ frame rate = 1500/second.</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$A$</td>
<td>0.15</td>
<td>0.15</td>
<td>0.25</td>
<td>g</td>
<td>$@$ frame rate = 1500/second.</td>
</tr>
<tr>
<td>Light Level onto IC</td>
<td>$I_{IRR}$</td>
<td>0.09</td>
<td>25,000</td>
<td></td>
<td>mW/m²</td>
<td>$\lambda$ = 639 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>30,000</td>
<td></td>
<td></td>
<td>$\lambda$ = 875 nm</td>
</tr>
<tr>
<td>SDIO Read Hold Time</td>
<td>$t_{HOLD}$</td>
<td>100</td>
<td></td>
<td></td>
<td>µs</td>
<td>Hold time for valid data. (Refer to Figure 28.)</td>
</tr>
<tr>
<td>SDIO Serial Write-Write Time</td>
<td>$t_{WW}$</td>
<td>100</td>
<td></td>
<td></td>
<td>µs</td>
<td>Time between two write commands. (Refer to Figure 31.)</td>
</tr>
<tr>
<td>SDIO Serial Write-Read Time</td>
<td>$t_{WR}$</td>
<td>100</td>
<td></td>
<td></td>
<td>µs</td>
<td>Time between write and read operation. (Refer to Figure 32.)</td>
</tr>
<tr>
<td>SDIO Serial Read-Write Time</td>
<td>$t_{RW}$</td>
<td>120</td>
<td></td>
<td></td>
<td>ns</td>
<td>Time between read and write operation. (Refer to Figure 33.)</td>
</tr>
<tr>
<td>SDIO Serial Read-Read Time</td>
<td>$t_{RR}$</td>
<td>120</td>
<td></td>
<td></td>
<td>ns</td>
<td>Time between two read commands. (Refer to Figure 33.)</td>
</tr>
<tr>
<td>Data Delay after PD ↓</td>
<td>$t_{D}$</td>
<td>3.2</td>
<td></td>
<td></td>
<td>ms</td>
<td>After $t_{COMPUT}$, all registers contain data from first image after PD↓. Note that an additional 75 frames for AGC (shutter) stabilization may be required if excessive movement occurred while PD was high. (Refer to Figure 12.)</td>
</tr>
<tr>
<td>SDIO Write Setup Time</td>
<td>$t_{SETUP}$</td>
<td>60</td>
<td></td>
<td></td>
<td>ns</td>
<td>Data valid time before the rising of SCLK. (Refer to Figure 26.)</td>
</tr>
<tr>
<td>PD Pulse Width (to power down the chip)</td>
<td>$t_{PW}$</td>
<td>700</td>
<td></td>
<td></td>
<td>µs</td>
<td>Pulse width to initiate the power down cycle @ 1500 fps. (Refer to Figure 12 and Figure 14.)</td>
</tr>
<tr>
<td>PD Pulse Width (to reset the serial port)</td>
<td>$t_{RP}$</td>
<td>190</td>
<td></td>
<td></td>
<td>µs</td>
<td>Pulse width to reset the serial port @ 1500 fps (but may also initiate a power down cycle. Normal PD recovery sequence to be followed. (Refer to Figure 15.)</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>$FR$</td>
<td>1500</td>
<td></td>
<td></td>
<td>Frames/s</td>
<td>See Frame Period register section.</td>
</tr>
<tr>
<td>Bin Resistor</td>
<td>$R_{I}$</td>
<td>15 K</td>
<td>15 K</td>
<td>37 K</td>
<td>Ω</td>
<td>Refer to Figure 8.</td>
</tr>
</tbody>
</table>
### DC Electrical Specifications

Electrical Characteristics over recommended operating conditions. Typical values at 25°C, VDD = 5.0V, 18 MHz.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Supply Current (mouse moving)</td>
<td>Idd, AVG</td>
<td>15</td>
<td>25</td>
<td>mA</td>
<td>No load on XA, XB, YA, YB, SCLK, SDIO, excluding LED current.</td>
<td></td>
</tr>
<tr>
<td>Peak Supply Current (mouse moving)</td>
<td>Ipp, MAX</td>
<td>20</td>
<td>mA</td>
<td>No load on XA, XB, YA, YB, SCLK, SDIO, excluding LED current.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC Supply Current (mouse not moving)</td>
<td>Idd</td>
<td>12</td>
<td>25</td>
<td>mA</td>
<td>No load on XA, XB, YA, YB, SCLK, SDIO, excluding LED current.</td>
<td></td>
</tr>
<tr>
<td>DC Supply Current (power down)</td>
<td>Itoff</td>
<td>170</td>
<td>240</td>
<td>µA</td>
<td>PD = high, SCLK, SDIO = GND or VDD, VDD # 4.25V to 5.25V.</td>
<td></td>
</tr>
<tr>
<td>SCLK, SDIO, PD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Refer to Figure 11.</td>
</tr>
<tr>
<td>Input Low Voltage</td>
<td>VIL</td>
<td>0.8</td>
<td>V</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>Input High Voltage</td>
<td>VIH</td>
<td>0.6 * VDD</td>
<td>V</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>Output Low Voltage</td>
<td>VOL</td>
<td>0.7</td>
<td>V</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>Output High Voltage</td>
<td>VOH</td>
<td>0.6 * VDD</td>
<td>V</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>Output Low Voltage (XA, XB, YA, YB)</td>
<td>VCL</td>
<td>0.4</td>
<td>V</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>Output High Voltage (XA, XB, YA, YB)</td>
<td>VOH</td>
<td>0.6 * VDD</td>
<td>V</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>Output Low Voltage (XY LED)</td>
<td>VCL</td>
<td>1.1</td>
<td>V</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>XY LED Current (typical)</td>
<td>ILED</td>
<td>15</td>
<td>µA</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>XY LED Current (fault mode)</td>
<td>ILED</td>
<td>500</td>
<td>µA</td>
<td></td>
<td>Refer to Figure 11. See table below.</td>
<td></td>
</tr>
<tr>
<td>REF_A (normal model)</td>
<td>VREF_A</td>
<td>3.3</td>
<td>V</td>
<td></td>
<td>1.5 KΩ to 3V or GND, PD = low.</td>
<td></td>
</tr>
<tr>
<td>REF_A (power down model)</td>
<td>VREF_A</td>
<td>3.3</td>
<td>V</td>
<td></td>
<td>1.5 KΩ to 3V or GND, PD = high.</td>
<td></td>
</tr>
</tbody>
</table>

**Typical LED Current Table**

<table>
<thead>
<tr>
<th>LED Current (typical)</th>
<th>mA</th>
<th>10</th>
<th>15</th>
<th>18</th>
<th>22</th>
<th>27</th>
<th>33</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED Current (typical)</td>
<td>mA</td>
<td>42</td>
<td>35</td>
<td>20</td>
<td>25</td>
<td>20</td>
<td>10</td>
<td>17</td>
</tr>
</tbody>
</table>
Synchronous Serial Port

The synchronous serial port is used to set and read parameters in the ADNS-2051, and can be used to read out the motion information instead of the quadrature data pins.

The port is a two wire, half duplex port. The host microcontroller always initiates communication; the ADNS-2051 never initiates data transfers.

SCLK: The serial port clock. It is always generated by the master (the micro-controller).

SDO: The data line.

PD: A third line is sometimes involved. PD (Power Down) is usually used to place the ADNS-2051 in a low power mode to meet USB suspend specification. PD can also be used to force re-synchronization between the micro-controller and the ADNS-2051 in case of an error.

Write Operation

Write operations, where data is going from the microcontroller to the ADNS-2051, is always initiated by the micro-controller and consists of two bytes. The first byte contains the address (seven bits) and has a '1' as its MSB to indicate data direction. The second byte contains the data. The transfer is synchronized by SCLK. The micro-controller changes SDO on falling edges of SCLK. The ADNS-2051 reads SDO on rising edges of SCLK.

Write Operation Diagram

Figure 26. SDO setup and hold times SCLK pulse width
Read Operation

A read operation, which means that data is going from the ADNS-2051 to the micro-controller, is always initiated by the micro-controller and consists of two bytes. The first byte contains the address, which is written by the micro-controller, and has a "0" as its MSB to indicate data direction. The second byte contains the data and is driven by the ADNS-2051. The transfer is synchronized by SCLK. SDIO is changed on falling edges of SCLK and read on every rising edge of SCLK. The micro-controller must go to a high Z state after the last address data bit. The ADNS-2051 will go to the high Z state after the last data bit (see detail "A" in Figure 28). One other thing to note during a read operation is that SCLK will need to be delayed after the last address data bit to ensure that the ADNS-2051 has at least 100 µs to prepare the requested data. This is shown in the timing diagrams below.

![Figure 27. Read operation](image)

**Figure 27. Read operation**

**DETAIL "A"**

- MICROCONTROLLER TO ADNS-2051
- SDIO HANDOFF

![Figure 28. Microcontroller to ADNS-2051 SDIO handoff](image)

**Figure 28. Microcontroller to ADNS-2051 SDIO handoff**

**DETAIL "B"**

- ADNS-2051 TO MICROCONTROLLER
- SDIO HANDOFF

![Figure 29. ADNS-2051 to microcontroller SDIO handoff](image)

**Figure 29. ADNS-2051 to microcontroller SDIO handoff**

**Note:**

The 120 ns high state of SCLK is the minimum data hold time of the ADNS-2051. Since the falling edge of SCLK is actually the start of the next read or write command, the ADNS-2051 will hold the state of D0 on the SDIO line until the falling edge of SCLK. In both write and read operations, SCLK is driven by the micro-controller.

Serial port communications is not allowed while PD (power down) is high. See "Error Detection and Recovery" regarding re-synchronizing via PD.
Appendix – 5: INA-118P Data Sheet

**INA118**

**Precision, Low Power INSTRUMENTATION AMPLIFIER**

**FEATURES**
- **LOW OFFSET VOLTAGE:** 50μV max
- **LOW DRIFT:** 0.5μV/°C max
- **LOW INPUT BIAS CURRENT:** 5nA max
- **HIGH CMR:** 110dB min
- **INPUTS PROTECTED TO ±40V**
- **WIDE SUPPLY RANGE:** ±1.35 to ±18V
- **LOW QUIESCENT CURRENT:** 350μA
- **8-PIN PLASTIC DIP, SO-8**

**APPLICATIONS**
- **BRIDGE AMPLIFIER**
- **THERMOCOUPLE AMPLIFIER**
- **RTD SENSOR AMPLIFIER**
- **MEDICAL INSTRUMENTATION**
- **DATA ACQUISITION**

**DESCRIPTION**

The INA118 is a low power, general purpose instrumentation amplifier offering excellent accuracy, low drift, high CMR, and versatility. The small size makes it ideal for a wide range of applications. Current-feedback input circuitry provides wide bandwidth even at high gain (78kHz at G = 100).

A single external resistor sets any gain from 1 to 10,000. Internal input protection can withstand up to ±40V without damage. The INA118 is laser-trimmed for very low offset voltage (50μV), drift (0.5μV/°C) and high common-mode rejection (110dB at G = 1000). It operates with power supplies as low as ±1.35V, and quiescent current is only 350μA—ideal for battery operated systems.

The INA118 is available in 8-pin plastic DIP, and SO-8 surface-mount packages, specified for the –40°C to +85°C temperature range.
SPECIFICATIONS
ELECTRICAL
At T_A = +25°C, V_R = +15V, R_S = 10kΩ unless otherwise noted.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>CONDITIONS</th>
<th>841/180, UD</th>
<th>841/180, UB</th>
<th>IN811SP, U</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT</td>
<td>Offset Voltage, RTI</td>
<td>±0.5V</td>
<td>±0.3V</td>
<td>±0.25V</td>
</tr>
<tr>
<td>Current vs Temperature</td>
<td>T_A = +70°C</td>
<td>±2.5mA</td>
<td>±2mA</td>
<td>±1.5mA</td>
</tr>
<tr>
<td>Voltage vs Power Supply</td>
<td>V_T = ±25V</td>
<td>±0.25V</td>
<td>±0.2V</td>
<td>±0.15V</td>
</tr>
<tr>
<td>Low-Ripple Current, Differential</td>
<td>±1mA</td>
<td>±0.5mA</td>
<td>±0.3mA</td>
<td>±0.2mA</td>
</tr>
<tr>
<td>Common-Mode Voltage Range</td>
<td>±10V</td>
<td>±5V</td>
<td>±3V</td>
<td>±1.5V</td>
</tr>
<tr>
<td>Safe Input Voltage Common-Mode Rejection</td>
<td>V_IN (max) = +15V</td>
<td>±5V</td>
<td>±2.5V</td>
<td>±1V</td>
</tr>
<tr>
<td>SAT. CURRENT</td>
<td>vs Temperature</td>
<td>±1mA</td>
<td>±0.5mA</td>
<td>±0.2mA</td>
</tr>
<tr>
<td>OFFSET CURRENT</td>
<td>vs Temperature</td>
<td>±1mA</td>
<td>±0.5mA</td>
<td>±0.2mA</td>
</tr>
<tr>
<td>MORE VOLTAGE, RTI</td>
<td>±10%</td>
<td>±5%</td>
<td>±2.5%</td>
<td></td>
</tr>
<tr>
<td>Offset Voltage</td>
<td>±10%</td>
<td>±5%</td>
<td>±2.5%</td>
<td></td>
</tr>
<tr>
<td>Leakage Current</td>
<td>±0.05mA</td>
<td>±0.025mA</td>
<td>±0.0125mA</td>
<td></td>
</tr>
<tr>
<td>Noise Voltage, RTI</td>
<td>±20nV</td>
<td>±10nV</td>
<td>±5nV</td>
<td></td>
</tr>
<tr>
<td>COMMON-INPUT VOLTAGE</td>
<td>±50V</td>
<td>±25V</td>
<td>±12.5V</td>
<td></td>
</tr>
<tr>
<td>COMMON-INPUT BIAS</td>
<td>±0.5mA</td>
<td>±0.25mA</td>
<td>±0.125mA</td>
<td></td>
</tr>
<tr>
<td>COMMON-INPUT CURRENT</td>
<td>±1mA</td>
<td>±0.5mA</td>
<td>±0.2mA</td>
<td></td>
</tr>
<tr>
<td>GAIN</td>
<td>Gain Equation</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Range of Gain</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Gain Error</td>
<td>±0.01%</td>
<td>±0.005%</td>
<td>±0.0025%</td>
<td></td>
</tr>
<tr>
<td>Gain vs Temperature</td>
<td>±0.02%</td>
<td>±0.01%</td>
<td>±0.005%</td>
<td></td>
</tr>
<tr>
<td>Noise Voltage</td>
<td>±20nV</td>
<td>±10nV</td>
<td>±5nV</td>
<td></td>
</tr>
<tr>
<td>LOAD CAPACITANCE STABILITY</td>
<td>±10%</td>
<td>±5%</td>
<td>±2.5%</td>
<td></td>
</tr>
<tr>
<td>Short-Circuit Current</td>
<td>±0.5mA</td>
<td>±0.25mA</td>
<td>±0.125mA</td>
<td></td>
</tr>
<tr>
<td>FREQUENCY RESPONSE</td>
<td>Bandwidth, HZ</td>
<td>1000</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Near Frequency</td>
<td>±5%</td>
<td>±2.5%</td>
<td>±1.25%</td>
<td></td>
</tr>
<tr>
<td>Slew Rate</td>
<td>±0.5V/µs</td>
<td>±0.25V/µs</td>
<td>±0.125V/µs</td>
<td></td>
</tr>
<tr>
<td>Settling Time, 0.1%</td>
<td>±10µs</td>
<td>±5µs</td>
<td>±2.5µs</td>
<td></td>
</tr>
<tr>
<td>Output Overload Recovery</td>
<td>50% Overload</td>
<td>10ms</td>
<td>5ms</td>
<td>2.5ms</td>
</tr>
<tr>
<td>POWER SUPPLY</td>
<td>Voltage Range</td>
<td>±1.25V</td>
<td>±0.625V</td>
<td>±0.3125V</td>
</tr>
<tr>
<td>Overshoot Recovery</td>
<td>50% Overshoot</td>
<td>20ns</td>
<td>10ns</td>
<td>5ns</td>
</tr>
<tr>
<td>TEMPERATURE RANGE</td>
<td>Specification</td>
<td>±40°C</td>
<td>±25°C</td>
<td>±15°C</td>
</tr>
<tr>
<td>Operating</td>
<td>±40°C</td>
<td>±25°C</td>
<td>±15°C</td>
<td></td>
</tr>
</tbody>
</table>

* Specification same as INA118P, UB.

NOTE: (1) Temperature coefficient of the "µV/K" term in the gain equation is limited. See text for discussion of how power supply and single power supply operation.
Appendix  –  6:  Talysurf CLI2000
Specifications and Calibration Certificate

Flexible gauging system
dedicated to 3D topography

The Talysurf CLI 2000 offers the capability to measure and analyse surfaces in three dimensions using either contact or non contact gauging technology. The system provides powerful measurement and analysis capability in 3D and 2D and yet it is easy to use.

Large Capacity...
With a 200mm x 200mm x 200mm measuring envelope and a load capacity of 20kgs the system will accommodate a wide range of components.

Multiple gauging...
Optimum versatility is built into the system. Talysurf CLI 2000 supports the inductive Form Talysurf gauge, a 10mm laser triangulation gauge and a range of chromatic length aberration gauges.

Automated scanning...
The system provides automated movement of the X, Y and Z slides up to a maximum speed of 20mm/sec. This allows for fast-automated measurement sequences on components.

Powerful analysis software
Talymap software is flexible and can be used for simple checks, process control or research level analysis. Standard functions include:
- Leveling of measured surface data
- 2D profile extraction from 3D surface
- Form and defect removal
- Volume and area measurements
- Step height and distance
- Zoom function in 2D and 3D

Positional control
Batch mode programming measures multiple parts automatically and efficiently while freeing the operator to perform other tasks.

Automatic analysis...
For uniformity of results and maximum throughput, "templates" can be used to automate and speed the analysis process.

Practical 3D analysis...
Talysurf CLI 2000 makes the third dimension of surface metrology easily accessible and readily understood using parameters that are recognized by all manufacturers.

Taylor Hobson Precision, 2 New Star Road, Leicester LE4 9JG, England
Tel: +44 0116 276 3771  Fax: +44 0116 246 9979  e-mail: sales@taylor-hobson.com
www.taylor-hobson.com
# Specifications

## Measuring Capacity

<table>
<thead>
<tr>
<th></th>
<th>Max width (Y-axis)</th>
<th>Max length (X-axis)</th>
<th>Max height (Z-axis)</th>
<th>Max weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200mm (8in)</td>
<td>200mm (8in)</td>
<td>200mm (8in)</td>
<td>20 kg (44lbs)</td>
</tr>
</tbody>
</table>

## Weights and Dimensions

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measuring</td>
<td>Maximum</td>
<td>Maximum</td>
<td>Maximum</td>
</tr>
<tr>
<td></td>
<td>capacity</td>
<td>width</td>
<td>height</td>
<td>weight</td>
</tr>
<tr>
<td></td>
<td>Main instrument: overall weight</td>
<td>280 kg (616lbs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overall length</td>
<td>800mm (32in)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overall width</td>
<td>600mm (24in)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overall height</td>
<td>800mm (32in)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Slide Straightness (1 profile)

<table>
<thead>
<tr>
<th></th>
<th>Profile (L)</th>
<th>Corrected</th>
<th>Peak to Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50mm</td>
<td>+/-0.3µm</td>
<td>+/-/0.4µm</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>+/-0.7µm</td>
<td>+/-/1.2µm</td>
</tr>
<tr>
<td></td>
<td>150mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Slide Flatness

<table>
<thead>
<tr>
<th></th>
<th>Area (L x L)</th>
<th>Corrected</th>
<th>Peak to Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50mm</td>
<td>+/-0.5µm</td>
<td>+/-/0.7µm</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>+/-/1µm</td>
<td>+/-/2µm</td>
</tr>
<tr>
<td></td>
<td>150mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Slide resolution (data spacing)

<table>
<thead>
<tr>
<th></th>
<th>X-axis</th>
<th>0.5µm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y-axis</td>
<td>0.5µm</td>
</tr>
<tr>
<td></td>
<td>Z-axis</td>
<td>0.5µm</td>
</tr>
</tbody>
</table>

## Laser Gauges

<table>
<thead>
<tr>
<th>Type</th>
<th>Range</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>10mm Laser triangulation</td>
<td>10mm</td>
<td>1.0µm</td>
</tr>
</tbody>
</table>

## Chromatic Length Aberration

<table>
<thead>
<tr>
<th>Type</th>
<th>Range</th>
<th>Vertical Resolution</th>
<th>Lateral resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mm CLA gauge</td>
<td>3mm</td>
<td>100µm</td>
<td>5µm</td>
</tr>
<tr>
<td>300µm CLA BE gauge</td>
<td>300µm</td>
<td>10µm</td>
<td>2µm</td>
</tr>
<tr>
<td>300µm CLA HE gauge</td>
<td>300µm</td>
<td>10µm</td>
<td>1µm</td>
</tr>
</tbody>
</table>

## Inductive Gauge

<table>
<thead>
<tr>
<th>Type</th>
<th>Range</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form Talysurf with 2µm radius diamond stylus</td>
<td>2.5mm</td>
<td>50nm</td>
</tr>
<tr>
<td>500µm</td>
<td>10nm</td>
<td></td>
</tr>
<tr>
<td>100µm</td>
<td>2nm</td>
<td></td>
</tr>
</tbody>
</table>

---

**Note:** The above quoted individual data is for measuring devices as supplied. Users should note that new products may be available on request and product specifications are subject to change without notice. Taylor Hobson reserves the right to amend their specifications at any time.

Taylor Hobson precision, 2 New Star Road, Leicester LE4 9UJ, England
Tel +44 0116 276 3771  Fax: +44 0116 246 0579  e-mail: sales@taylor-hobson.com
www.taylor-hobson.com
Service Department Calibration Certificate

Customer: Loughborough University
Contact: Jagpal Singh
Contract Visit: Once Yearly
Last Visit: 1/1/88

This instrument has been serviced as per schedule no 1/1/88 on the date specified (see note).
The following aspects only of the above instrument performance were calibrated at the date noted using UKAS traceable standards for Roughness, Magnification, Roundness, Straightness (Delete as applicable).

<table>
<thead>
<tr>
<th>Code No. of Standard</th>
<th>Serial No. of Standard</th>
<th>Reading Prior to Service</th>
<th>Reading after Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge Blocks</td>
<td>GT 3039</td>
<td>0.2mm, 2mm, 6mm</td>
<td>200um, 1.988um, 599um</td>
</tr>
<tr>
<td>RL Standard</td>
<td>4.315</td>
<td>Std 5.95</td>
<td>5.85, 5.91, 5.9um</td>
</tr>
<tr>
<td>Calibrating Flat</td>
<td>S/N 004</td>
<td>2.10 x 2.10mm</td>
<td>0.8um, 0.4um</td>
</tr>
</tbody>
</table>

All checks carried out at ambient temperature between 19°C and 21°C.

Signed: Date 11-6-08
Position: Technical Service Eng

For and on behalf of
TAYLOR HOBSON LIMITED

For and on behalf of
TAYLOR HOBSON LTD

TAYLOR HOBSON LTD RECOMMENDS THAT THE INSTRUMENT CALIBRATION IS CHECKED AT FREQUENT INTERVALS AGAINST THE STANDARDS PROVIDED. TO MAINTAIN FULL TRACEABILITY THE STANDARDS SHOULD HAVE A NATIONAL MEASUREMENT ACCREDITATION SERVICE CERTIFICATE. THIS CAN BE OBTAINED THROUGH THE U.K.A.S. LABORATORY (APPROVAL NO. 0026) AT TAYLOR HOBSON LTD.
Appendix – 7: List of Publications

Conference


Journal

Appendix – 8: Analysis of Profile Measurement Techniques Employed to Surfaces Planed by an Active Machining System


The paper is currently under review.
Analysis of Profile Measurement Techniques Employed to Surfaces Planed by an Active Machining System

S Elmas, N Islam, M R Jackson, R M Parkin

Mechatronics Research Group, Loughborough University, Loughborough, UK

Abstract

The importance of a reliable and robust surface profile measurement system in the inspection of surface finish is beyond any doubt. For years, visual inspection has been employed in the industries to determine the quality of surface finish. Since, in most cases, it fails to ensure a consistent minimum standard of finish quality, mechanical stylus based measurement systems have successfully taken over from human inspection. However, in recent years, the trend is to explore other techniques for conducting the surface profile measurements. Non-contact optical methods have emerged as one of the leading candidates. One of most important aspect of using non-contact methods is avoiding damage to the machined surface for softer materials. In this paper, analysis of surfaces machined with an active mechatronic planer has been discussed. Mainly two kinds of materials have been used for the planing operation, one is made up of nylon and the other is hard wood. The surface profile of machined specimens is measured with the help of light-sectioning method, conventional mechanical stylus and a novel two-image photometric stereo method. An industry-standard Talysurf CLI system was used to provide the benchmark, traceable to NPL standards, for the measurements. Suitability of different measurement techniques have been discussed based on the results obtained.
Keywords: active machining system, non-contact surface profile measurements, light sectioning method, mechanical stylus, two-image photometric stereo method, Talysurf.

1. Introduction

Wood machining is an essential part of the furniture and wooden product manufacturing industry. This speeds up the whole process as well as maintaining the quality of product finish [1]. Machining of wood consists of various processes such as sawing, rough planing, planing, molding, sanding and so on. Among all these, two widely employed processes in wood machining industry are planing and molding [2]. In order to carry out these machining operations, rotary machining technique has been used in industry for over two centuries [3]. It is a very well established fact that the rotary machining operation is able to provide the woodworking industry with the required surface finish of products coupled with the desired speed, lower labour cost and thus, cost-effectiveness. In the current ultra competitive business environment these are the required attributes for a manufacturing establishment to survive and prosper.

During the process of planing, the cutter heads contain straight cutters on all the four faces [4]. The rotary wood machining process is similar in nature to the up-cut milling of metals [5]. Although, the milling operation is similar to the one of metal working, there are some significant differences between the two processes. The primary one is the cutting speed. Whilst cutting speed for metal lies in the region of 0.5 to 1.5 m/s, the wood machining speed is in the region of 30 to 80 m/s. Also, the feed speed of the woodworking process is higher, at around 0.08 to 1.6 m/s [6].
Due to kinematics of the machining process, planed and moulded surfaces appear to have a series of waves whose peaks are perpendicular to the passage of the product through the machine [6]. However, these cutter-marks or waviness as termed in the woodworking industry are actually not defects, if the their heights and widths are small and uniform [7].

In order to ensure that this waviness is consistent and of acceptable patterns, a range of contact and non-contact accurate measurement techniques have been deployed over the years. Despite advances in other technologies, mechanical stylus based contact measurement remains the most widely used surface measurement system. This is essentially a slow and often destructive method of obtaining surface profile but has wide acceptability due to very well-established standards [8]. Advancements towards ever increasing levels of automation, higher speed of processes and the advent of various soft materials have caused this contact method to become inadequate in certain situations. As a result, non-contact methods are proving to be the way forward for measurement applications involving timber and similar softer materials.

A brief literature review of the surface planing technique has been presented in this paper, along with some of the surface profile measurement techniques. In the latter part of the paper, a comparative analysis of surface profile measurements is carried out using four different measurement techniques.
2. Timber Surface Forming

The dynamic behaviour of wood machining process has a negative impact on the surface quality of machined timber. The dynamic behaviour is due to the factors such as workpiece properties, cutting tool condition, engineering quality of the machine, cutterhead vibrations, spindle imbalance. These variations are reflected to the machined surface, which can reach unacceptable quality levels. In molding and planing which are commonly used within the woodworking industry, surface defects, torn and raised grain result in high production costs [1]. This rotary machining process is similar to milling of metals in up-cutting mode. The principle of the rotary machining process is such that a timber is fed towards a rotating cutterhead containing a certain number of cutting knives. This process is illustrated in figure 1.

![Figure 9-1 Rotary machining principle](image)

The machined surface has a series of waves due to the kinematics of the rotary machining process. The surface waves, also called cutmarks, are generally accepted as unavoidable, therefore machined surfaces are not ideally smooth and flat. The length of the cutmark \( p \), also called pitch, is usually taken as a measure of surface quality. A good surface finish should follow a uniform pattern. The length of the cutmarks \( p \) is dependent on workpiece feed speed \( v_f \), cutterhead rotational speed \( v_c \) and the number of
finishing cutting knives \( N \). This relationship can be expressed by the following equation:

\[
P = \frac{v_f}{v_c \cdot N}
\]  

(1)

It is often assumed, for simplicity, that the shape of the cuttermarks is circular and that the surface can be considered as a series of intersecting circular arcs. The waviness height \( h \) of the simplified surface can then be expressed by the following equation:

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

(2)

where \( R \) is the cutterhead radius. These equations (1) and (2) are well established and widely used. Although the modern planing machines provide a good surface quality, the undesired variations within the machining process do not guarantee a consistent surface quality. The presence of the vibrations during the machining process has an adverse effect on the surface quality. Vibrations mainly occur between the relative movements of the cutterhead and the workpiece. Relatively small surface wave height values ranging from 2 – 20 \( \mu \text{m} \) make the waviness highly susceptible to relative vibrations between cutting knives and the workpiece normal to the machined surface. This displacement can be caused by either structural vibration or by cutterhead inaccuracies. The effects of these disturbances are summarized in [3, 9].

In order to produce some specimens for the surface profile measurement systems a mechatronics approach based small scale planer is used (Fig 2). One of the advantages of the small scale planer is the ability to produce various surface qualities to order which means that the limitations as well as the quality of the measurement systems can
be assessed and compared. Thus the reliability of the surface profile measurement systems can be compared more precisely.

![Piezoelectric actuator and Eddy current sensor](image)

Figure 9-2 Smart planing system

The small scale planer consists of a base frame, on which the feed table and spindle system are mounted (Fig. 2) [10]. The smart spindle unit is the main part of the test rig. Four piezoelectric actuators are mounted on the front bearing. Piezoelectric stack type actuators have been selected to control the movement of the front bearing, because they are able to provide high force, fast response and a controllable displacement in micrometer range. Two opposing actuators for each axis have been chosen in order to achieve a "push-pull" operation. This approach was also adopted by other researchers [9, 11]. Applying appropriate voltage levels to the piezoelectric actuators controls the movement of the spindle in the plane perpendicular to the spindle’s rotational axis. These capabilities of the smart spindle unit allow a higher degree of freedom in terms control over machining process. The smart spindle unit is a novel mechatronics control approach which comprises appropriate sensors, signal conditioning circuits, driving amplifiers and control computer in order to implement the controlled cutterhead
movement. The system diagram of the test rig, shown in Fig. 2, shows all key components of the instrumentation.

Two widely used techniques within woodworking domain, single-knife finish and multi-knife finish are produced with the small scale planer to assess the measurement techniques whereas the latter one has been produced with a controlled generated disturbance the so called 1/rev vibration. A more detailed description of the various surface defects can be found in [3, 4]. The defect is machined on a black plastic sample in order to reduce the effect of workpiece properties such as roughness. This defect as well as the single knife finish specimens are then measured with all four measurement devices for comparison. The measurement techniques are introduced in section 3.

3. Surface Profile Measurement Systems

The profile measurement systems currently being used in industry to obtain surface characteristics can be divided into two main groups – contact and non-contact methods.

a. Contact Method

The most common method of obtaining surface profile data is to pass a mechanical stylus probe across the surface and trace the movement of the probe to obtain surface profile information [12]. This is essentially a contact method for obtaining the surface data. These measurements are usually carried out in the micrometer range for most industrial applications. However, techniques to use mechanical profilometers in finer nanometre range have been explored in publications by Garratt and Nettleton [13], Whitehouse et al [14] and in a more recent research by Groeger et al [15].
nanometre range measurements have found applications in wide ranging fields of manufacturing laser optics, electro optic devices, semi-conductors, computer memory devices etc. [15].

The contact based measurement system suffers from various drawbacks. One of the main drawbacks associated with this technique is the loading effect of the stylus tip on the surface under test. This can lead to the deformation of the surface, especially for softer surfaces like wood, nylon etc. Also, the speed of measurement is somewhat slow, thus making this technique unsuitable for on-line measurements [7].

b. Non-contact Methods

Most of the methods used for non-contact measurements are optical method. These include optical profilometers (mostly laser based), microscopes, image analyzers, imaging spectrographs, interferometers, fibre-optic transducers, white-light speckles, laser scattering, optical light sectioning systems, etc. According to research published in [7], the optical methods can be classified into three categories according to their principle of operation –

- Triangulation sensing
- Shadow analysis
- Light sectioning

Equipment using triangulation sensors or auto-focusing 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. A laser displacement sensor (LDS) based surface profile measurement system has been proposed in [16] as well as in [17] and [18]. This method uses the aforesaid triangulation measurement approach. Laser light emitted by a semiconductor laser diode passes through a transmitter lens and is focused on the target surface. The reflected light is focused on a position-sensitive detector (PSD) after passing through a receiver lens. The detector uses the distribution of the entire beam spot entering the light-receiving element to determine the beam spot centre of gravity and identifies it as the target position. Of the LDS's distance to the measured surface changes, the position of the reflected spot on the detector changes proportionally. This process can be correlated to the smoothness of the measured surface.

Another method of evaluating the surface smoothness is the shadow sectioning method. Sandak and Tanaka [19] as well as Yang et al [20] have used this technique to evaluate machined wood surface. Light emitted with a fixed small angle to the surface plane by a projector is directed onto the measured surface. A curtain installed in the light path close to the surface creates a shadow on the measured surface. The shape of the border between bright and dark is a profile section of the surface. A camera installed over the surface captures an image of the border and a digital signal processor using image analysis techniques digitizes the profile section. In general, the shadow analysis method cannot measure surface heights.

Researchers in [21, 22] have proposed sensors based on light sectioning principle to measure the surface profile of fabric and width of steel plates respectively. In a more recent and relevant research [7], this light sectioning method has been used to determine
the surface profile of wood. This method requires oblique illumination and a laser light stripe is projected from the side of the sample on to the surface to produce light section. The light section is actually a wavy line produced by the projected light due to the waviness of the surface under test. Also, there is a triangular relationship between the height of the cutter mark wave \( H \), and the height of its corresponding wave \( L \) in the light section. This can be given by equation (3).

\[
H = L \tan \theta
\]

where, \( \theta \) is the angle of incidence of the projected light with respect to the surface.

Thus, by measuring the wavy line, i.e. the light section, the widths and heights of cutter mark waves on the surface can be calculated.

A more robust extension of the light-sectioning concept is the two-image photometric stereo method. This has been discussed in detail in [23]. In this method, two suitable identical light sources are located opposite to each other and along the direction of the cutter-mark of the machined material. Two images using a high resolution camera are then taken, with only light source 1 turned on and only light source 2 turned on respectively. The radiance of the surfaces can be measured using the camera in the form of pixel intensities in the images. This pixel intensity can in turn be used to obtain the surface gradient of the machined surface. A novel algorithm is then used to obtain the surface shape in two-dimension. The details of this technique are beyond the scope of this paper and will be reported in future publications.
4. Experimental work

This section of the paper gives a brief overview of the measurement setups and equipments used for the surface profile measurements. The following sub-sections look into the Talysurf measurement system from Taylor Hobson Ltd., mechanical stylus instrument, light-sectioning method and the photometric stereo method.

a. Talysurf CL1

The Talysurf (figure 3) is the most widely used surface metrology equipment in industry [24]. This equipment comes with various instruments including both contact and non-contact probes. However, the results produced in this paper are all obtained by the laser-based instrument mounted on the machine. The Talysurf system is calibrated with standardised artefacts and the calibrations can be traced back to the NPL standards (UKAS certificate number 29248).
Figure 9-3 Talysurf optical profilometer (Taylor Hobson 2007)

The system consists of a precision X-Y translation table to hold the sample underneath the probes and provide the scanning motion. The stand-off distance (Z-direction) of the Talysurf can be adjusted to achieve focusing of the probe. The Talymap software from Taylor Hobson is used for data acquisition and processing. A typical generated surface from Talymap is shown in figure 4.

Figure 9-4 3D mapping of a measured surface generated by Talymap software
b. **Light-sectioning Method**

The measurement setup for light-sectioning method is shown in figure 5. A light source projects a light stripe on to the surface of the machined material from the side of the sample. This projected light creates a light section on the sample according to the shape of the surface. The light section is captured by the camera and then the image is processed off-line by MATLAB image processing toolbox. A light-sectioned image taken by the camera is also shown in figure 5.

![Measurement setup for light-sectioning method and the image obtained through the camera](image)

Figure 9-5 Measurement setup for light-sectioning method and the image obtained through the camera [7]

c. **Two-image Photometric Stereo Method**

This method was first proposed and demonstrated by Yang [23] as part of the Wood Surface Measurement System (WSMS). The experimental setup is illustrated in figure 6. The light sources consist of a laser, a collimator and a beam expander. A camera takes image of the timber surface with light source 1 turned on. Then another image in taken by switching off the first light source and turning on light source 2.
Surface profile of the machined timber is obtained by comparing and transforming the surface shape function to a 2-D profile. This two-image photometric stereo method will be referred to as WSMS in this paper. The actual test rig is shown in figure 7.
5. Results and Discussions

This section of the paper reports surface profile measurement results obtained by the four different methods. Two samples are used to make a comparative study of the aforesaid methods. The first sample is a machined timber of 2 mm pitch length, while the second one is a black nylon with surface defect.

a. Wood Sample with 2 mm Pitch Length

Surface profile of the machined timber with 2 mm pitch and the corresponding Fast Fourier Transform (FFT) results of the surface are shown in this sub-section. As discussed by Harris [25], the FFT analysis clearly reveals the wavelength components that make up a given waveform. It should be pointed out that the unit for the frequency is determined as \(1/(\text{unit length})\) i.e. \(1/mm\), which can be perceived as the number of cuttermarks per unit length. This is a very useful technique of determining the fundamental pitch length present in the measurement data.
Figure 9-8 Surface profile and FFT analysis of machined timber obtained using light-sectioning method

Figure 8 depicts the surface profile obtained with the use of light-sectioning method. From the normalized profile measurement data it is evident that there are periodic cutter-marks on the timber surface. When the FFT analysis of the surface profile is carried out, it can be seen that the main wavelength component is 1.8 mm. This value is somewhat close to the fundamental wavelength of 2.0 mm in this specimen. Due to the scattering effects of the laser beams on the edges of the specimen, the measurement accuracy decreases which can also be observed in figure 8 at the beginning of the measurement (i.e. from 0 to 5 mm) where a more noisy behavior of the waviness is apparent. Since the machined surface is not ideally flat, the laser scattering would be present to a certain degree depending on the tilting effect of the machined surface. This measurement technique also requires a precise setting of the laser beam by considering the incident angle for every measurement which also affects the overall scatter.
characteristics of the laser beam. For example if the incident angle is too low (i.e. $<1^\circ$) then the scattering of the laser beam increases if it is $>5^\circ$ the measurement precision decreases. Furthermore the inspection area is limited to the laser beam length of up to 50mm. This measurement technique also needs to be performed under exclusion of the ambient light which can affect the measurement quality.

![Graph of laser beam characteristics](image)

Figure 9-9 Surface profile and FFT analysis of machined timber obtained using mechanical stylus

Figure 9 shows the surface profile as traced by a mechanical stylus. It can be seen that the regular pitch marks of 2 mm are clearly visible from the surface trace of the stylus. From the FFT, it can be observed that the fundamental wavelength present in the surface profile is in fact 2 mm. Thus, the measurement closely corresponds to the actual surface. It should be pointed out the amount of surface roughness measured within the waviness depends on the stylus tip radius as this can show integrating behavior [3, 4].
Surface profile measurement data of the sample using Talysurf is shown in figure 10. This measurement serves as the benchmark for all the other systems as this measurement can be traced back to NPL standards.

![Surface profile and FFT analysis of timber measured using Talysurf](image)

Figure 9-10 Surface profile and FFT analysis of timber measured using Talysurf

From the figure 10 it can be seen that the cuttermarks on the timber surface is evident with the periodic waveform. However, in contrast to other systems discussed in this paper, the surface appears to have very high frequency components on top of the machined waviness pattern.

This fact can be clearly seen from the presence of harmonics within the lower wavelength components than other methods. Because of the fact that the Talysurf has a very high resolution of measurement (1 μm), apart from the waviness pattern on wood,
it also measures the constituent grains of the timber. Thus, the measurement appears more ‘noisy’ due to the additionally measured roughness of the surface.

Figure 9-11 Surface profile and FFT analysis of machined timber obtained using WSMS

The surface profile of the machined timber as obtained by the use of WSMS is shown in figure 11. From the actual profile graph, it can be seen that the system is able to detect the periodic nature of surface waviness. The FFT analysis reveals that the dominant wavelength present in the measured data is approximately 2 mm. Thus, the measurement obtained from the WSMS for a machined timber with 2 mm pitch length agrees very closely to the actual surface finish. As all four measurements candidates show the capability of measuring the surface profile of the machined timber at 2 mm pitch, the measurement difficulty level has been raised by the next specimen. This is a special case of a multi-knife finish where all the cutting knives do not follow a common cutting path, hence producing a waviness defect. This type of defect with 6 μm peak to peak vibration amplitude is indeed difficult to generate on timber surfaces due
to the inhomogeneous nature of timber, therefore a black plastic sample defect has been machined with the smart planing system [3]. For the non contact measurement systems is this type of defect indeed difficult to detect firstly due to the very low waviness heights variation and secondly due to the black color of the sample which absorb the light thus adding uncertainty in the accuracy of profile detection. In other words this defect is to show the limitations of the surface profile measurement candidates.

b. Nylon Sample with Defects

The surface profile of a black nylon sample with defects was measured using the aforesaid techniques. During the measurement exercises, it was found out that the light sectioning method was unable to detect the surface profile of the nylon sample. This was due to the fact that, the projected laser light was fully absorbed by the black-colored sample. Thus, no light pattern formed on the surface and as a result, the camera wasn't able to capture any meaningful image. Therefore, in this sub-section only results obtained from the Talysurf, WSMS and mechanical stylus have been reported.
The surface defects can be observed from figure 12 and a detailed analysis of defect forming found in literature [3]. The FFT analysis clearly shows that the dominant wavelength can be observed at the approximately 8 mm, which is four times the fundamental wavelength of 2 mm. This is in perfect agreement with the defect analysis presented in the aforesaid paper [3].
A surface trace obtained by the use of a mechanical stylus has been reported in figure 13. The general shape of the curve is similar to the one reported in figure 12. The FFT analysis also reveals the trend of obtaining the dominant wavelength at 8 mm, four times the fundamental machined wavelength of 2 mm.

Surface profile measurement results obtained from the WSMS system is shown in figure 14. From the profile graph it can be easily seen that the shape of the plot corresponds very closely to the ones obtained through Talysurf and mechanical stylus.
The FFT analysis however is not conclusive in comparison to the first two methods. However the WSMS is still capable of measuring the shape of the surface defect. When figure 14 is compared with the 2 mm pitch in figure 11 it can clearly be seen that the surface profile of surface defect is very different.

c. **Comparison of the Techniques**

The previous sub-sections reported the surface profile measurement results obtained using four different profiling techniques.

The Talysurf has been used in this paper as the benchmark for the samples, as its measurements are traceable to UKAS standards. It was found out that the fine measurements carried out by the Talysurf on timber surface not only picked up the
waviness but also the surface roughness. Thus, in order to recover the exact waviness pattern from the measurement data, some filtering is required. In order to carry out the measurements, around 20 minutes was required for each sample of 50 mm length. Thus, it is a very slow process and not suitable for online inspection of wood machining process where high throughput rates up to 40 m/min are required.

The light sectioning method could not be used to measure the black nylon sample with defect. However, the 2 mm regular pitch length could be satisfactorily measured using this method. The main drawback of the system has been the tedious setup of the incident angle and the extensive filtering for surface profile extraction from the images. Nevertheless this technique can potentially be employed for offline surface analysis purposes; since it is relatively straightforward configuration allows a quick experimental set up of the components. Moreover for higher pitch values i.e. >2 mm the precision of the measurement increases significantly. However this method is not suitable to measure high quality surfaces where the pitch is lower than 1.5 mm [23].

The measurement results obtained through mechanical stylus instrument has closely resembled that of Talysurf. But this method is inherently slow and destructive for softer materials like wood and nylon. Also, the loading of the stylus tip affects the measurement data. Furthermore this technique is also not suitable for in-process inspection of timber surfaces where high throughput rates are required, since the stylus tip tends to jump at high measuring speed. This effect also called “bouncing” where the stylus tip looses contact with the machined surface has been reported in various related publications [4, 26, 27].
The WSMS system has been successfully used to carry out both the regular machined surface as well as the surface with defect. Data acquisition with the system took only a few seconds and the analysis of the captured image to obtain the 2-D profile only about a minute. Thus, it was the fastest among the four methods of surface profile measurement. Also with the help of this system, a machined area of the sample was measured, thus providing an averaged profile of that area with a higher overall accuracy. Whereas all other measurement devices are capable of only measuring a line trace on the machined surface at a time. In order to obtain the true profile of the surface, multiple traces were taken in the area under investigation and an averaging was taken place. According to the detailed analysis in [23], this line tracing and subsequent averaging could give erroneous profile measurement, if not done properly. Thus, the method of taking the area measurement of WSMS is more suitable for such surface profile measurements. Furthermore this method is more promising in terms of in-process measurement application.

**6. Conclusions:**

The research work presented in this paper compares and contrasts four different surface profile measurement systems. With the help of these systems two sample - one timber and a nylon one were traced. It is seen from the measurement data that the Talysurf provided very good representation of the surfaces. Thus, this was used as the benchmark to compare the other systems.

Among the two optical non-contact methods, light-sectioning was not able to measure the surface profile of black nylon. However, it was able to provide satisfactory trace of
the machined timber surface. The mechanical stylus was able to provide good surface profile measurement results with both nylon and timber. But the use of such an instrument is not recommended for surfaces such as wood and nylon due to the destructive nature of measurement.

The WSMS system was able to provide very fast measurements with highly satisfactory profile measurement results. The measurements very closely correspond to the ones obtained with the help of Talysurf. From the results presented in this paper, it is evident that the WSMS is the most suitable system for measuring machined timber and nylon in terms of speed, non-destructiveness, accuracy and cost effectiveness.

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8. References


