Precision surface measurement

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Surface size, geometry and texture are some of the most influential subjects in the fields of precision and ultra-precision engineering, defining the functional interface through which emerging products operate. Next-generation products demand super-smooth surfaces, freeform geometries or even deterministically introduced microstructures to provide functional performance. Technological progress using these surfaces types is possible only if the associated manufacturing processes are rigorously controlled and the surfaces are measurable. Metrology for advanced surfaces is not established. The current state of the art is challenged in respect to (i) surface characteristics, extremity of size, ultra precision, quality, geometric complexity, or combinations of these aspects, and (ii) measurement technology for the manufacturing environment, in particular, online, non-contact, high speed, ease of use, small footprint and robustness. This study addresses the challenges in this subject area and discusses some fundamentals and principles derived from interdisciplinary research. The combination of these aspects is enabling the creation of manufacturing-environment-based measurement technology. This is expected to facilitate advanced surface manufacture over a wide range of sectors, including large science programmes and high-technology engineering.

Keywords: precision measurement; optical interferometry; surfaces

1. Introduction

Precision engineering is a multi-disciplinary scientific field that is always seeking ‘the next decimal place’. Surface measurement is one of the important subjects in precision engineering and it has steadily progressed alongside evolutionary precision technologies throughout past decades. Surface geometry and topography have significantly influenced many key areas such as pure and applied sciences, engineering and bioengineering. Examples include surfaces used in optics in high-power laser-energy systems, optics in earth/space-based large telescopes, interfaces in fluid dynamics (energy-efficient jet engines, aircraft fuselages and wings), long-life human-joint implants, microelectronics and microelectromechanical machines/nanoelectromechanical machines in nanotechnology applications.

Surface geometry and topography are vital for the key components of science and engineering applications. Differing from conventional surfaces, the surfaces for high added value products may have complex freeforms (non-rotational and
non-translational symmetric) up to 1–2 m in size with one part in $10^8$ surface topography; some have very accurate surfaces but small size, and work in extreme environmental conditions; some have deterministic structures; others result from the merging of dimensional geometry with surface texture [1].

These examples confront the state-of-the-art in surface measurement science in terms of: (i) surface characteristics, extremity of size, ultra precision, quality, geometry complexity, or combinations of these aspects, and (ii) measurement technology for the manufacturing environment, in particular, online, non-contact, high speed, ease of use, small footprint and robustness. Developing the measurement capability necessary to perform quantitative measurements on the surfaces types listed earlier, with the required assessment conditions and speed, is very challenging.

(a) Manufacturing challenges

The continuing evolution of high-precision manufacture is placing evermore need to perform surface measurement in the manufacturing environment. Example areas include the following.

— Advanced and emerging products from many sectors have large-scale (up to metres) ultra-precision (nanometre tolerance) components with complex surfaces. For example, micro moulding (e.g. aspheric lenses) produces a large amount of small components. These manufactured products need individual sample measurement without removal from the machine tool/production line. Batch sampling is not sufficient to provide consistency and quality, so high-speed, automated measurement is critical.

— Online measurement either for the form of a freeform surface for key science objects, such as telescope mirror segments (surface roughness less than 5 nm r.m.s., form accuracy less than 25 nm r.m.s. over 1–2 m size) [2] and nanostructures on large-scale substrates (e.g. photovoltaic panels, reel to reel thin film) [3], with the speed necessary for affordable manufacture does not exist. For such a high level of surface accuracy, offline measurement using state-of-the-art laboratory instruments is not applicable. If an expensive trial-and-error approach is used, measurement can take up a substantial fraction of the cycle time for precision surface fabrication, as high as 90 per cent in the final stages of finishing a large optical surface segment for instance [4]; it is more difficult for large substrate manufacture, which requires quality control simultaneously with continuous production processes [5].

— The assessment of geometry and surface topography of small objects, for example, inertial-confinement fusion shells in high-power laser fusion systems, especially in terms of the required measurement speed, is currently lacking. It has been verified that surface imperfections of these shells grow and can lead to an asymmetric implosion or even shell break-up and, as such, the measurement the topography of every target shell is extremely important for a successful fusion reaction. Currently, atomic force microscopy (AFM)-based offline measurement takes 2.5 h to measure a 2 mm diameter shell. This evaluation method constitutes a qualitative
description and does not provide any information for the control of the manufacturing process [6].

— Currently, quantitative surface metrology techniques provide the basis for inspection of the majority of micro and nanoscale surface topography present on large area substrates. They have demonstrated capability to measure surfaces at the sub-micro/nanoscale. However, almost without exception, these measurement techniques are confined to laboratory environments. Integration of measurement systems within the manufacturing process provides a particular challenge with regard to online, non-contact, high speed, ease of use, small footprint and robustness [7].

— There are clear technology gaps to be bridged for the evolution of laboratory-based measurement systems into the application within the manufacturing environment to provide inline/on-process measurement: (i) capability of achieving the required measurement resolution in the vertical and lateral scales, (ii) tolerance in terms of performance owing to the manufacturing environment, (iii) a fast measurement response without undue pressure on production time, and (iv) demonstrable measurement traceability and uncertainty [8].

(b) State of the art

Measurement of geometrical surfaces is mature for ‘planar’ (Euclidean) surfaces, i.e. to say for surfaces that can be defined by a single height value for each point in a plane [1]. Mature laboratory-based instruments adopt a wide range of principles [9]. Stylus profilometry provides the current state of the art in terms of vertical range (12.5 mm) versus resolution (2 nm), but is very slow [10]. The lateral resolution is dependent on reducing the stylus radius, which also increases the likelihood of scratching, making the metrology destructive in many cases. Low-force-stylus-based methods aim to expand the potential of contact measurement to delicate, micro-featured surfaces as well as increasing measurement speed [11,12]. Scanning probe microscopy techniques, particularly AFM, provide the ultimate in terms of lateral resolution. These techniques are notoriously difficult to apply and are severely limited in terms of speed/range/tip wear [13].

Optical techniques cover a large number of differing techniques, many of which are very well established in high-precision manufacturing because of their sensitivity, non-destructive nature and relative speed [14]. Optical methods are most likely to provide the best avenue to meet metrology requirements for precision surface manufacture. In many cases, it is not possible to use contact-based metrology without damaging the surface. For those types of manufacturing processes that require metrology in batches, the inherent speed of the majority of optical methods is essential. Certainly, the most prevalent optical technology for surface metrology is the scanning white-light interferometer (SWLI). Commercially available instrumentation based on SWLI can provide areal topographic information with nanometre uncertainty over 200 µm vertical range. Larger vertical ranges may be traded for higher measurement uncertainty. Measurement times are several tens of seconds depending on the vertical range to be covered.
While SWLI is currently the *de facto* technique for optical interrogation of many advanced surfaces, it is often found to be somewhat slow, especially over large vertical ranges. Some recent commercial advances have increased the speed of data acquisition and objective scanning [15], and also some work is being carried out in order to increase the data efficiency of SWLI [16]. Nevertheless, SWLI techniques are always limited by the need to physically move the objective lens (or sample) through the vertical measurement range.

SWLI is, of course, not only the established technique for surface metrology, but it is also one of the most flexible. Many other techniques however play an important role in specific areas. A phase-shifting interferometer (PSI) provides the ultimate in terms of vertical resolution, but is limited to smooth surfaces having no discontinuities larger than half the source light wavelength [17]. This may be extended by the use of synthetic wavelengths, but generally the extended vertical range is at the cost of vertical resolution [18]. Frequency stability of the light sources becomes increasingly problematic as more wavelengths are added [19]. Fringe projection techniques are being applied to determine local slope of surfaces down to the nanoscale, but these are limited to fringe ambiguity problems in the same way as PSI, while at the same time being less traceable [20].

Some single-point measurement methods have good potential for online applications by virtue of small probe footprints and the ability to mount them remotely using fibre links in some cases. Instruments based on confocal techniques such as focus follow [21] and chromatic aberration probing [22] are attractive for their long depth of focus. They do not reach the same levels of resolution or traceability as interferometry however, and the former requires mechanical movement within the probe head. Synthetic wavelength techniques can provide single-point probes with enhanced traceability and no mechanical movement, but the same limitations are present as for their bulk optic counterparts [23].

The instruments above cover surface measurement from nano to microscale, but almost all operate in a laboratory environment. They are powerful in their ability to derive surface geometry at various scales, but the measurement speed, physical footprint and system complexity are the primary factors in limiting potential for manufacturing environment applications.

In this paper, systemic building blocks, based on some fundamental techniques from multi-disciplinary fields, are discussed. New optical principles, *wavelength/frequency-scanning techniques*, derived from the fundamentals are presented. The aim for this investigation was to create next-generation ultra-precision/nanoscale surface instrumentation to retrieve information on the topography and geometry of precision surfaces in a very fast, accurate and robust way with a potential for providing online capable measurement and facilitating manufacturing environment applications.

### 2. Fundaments and principles

This section outlines these basic fundaments and principles that have been investigated to seek new methods which could be used to build the next-generation surface measurement systems.
**Multi-wavelength scanning interferometry (tech I)**

This method uses a tunable laser to create a series of interferograms from an interferometer. A tunable laser is able to provide a range of wavelengths, \( \lambda \), of quasi-monochromatic light. In reality, the mode spacing of the laser cavity means that these tuned wavelengths are approximately discrete, the laser ‘hops’ to specific wavelength values over the tuning range \( I(\lambda_j) : j = 1, 2, \ldots, J \). As such, a Michelson interferometer sourced by a tunable laser will have an output intensity function

\[
I(\lambda_j) = I_r(\lambda_j) + I_m(\lambda_j) + 2\sqrt{I_r(\lambda_j)I_m(\lambda_j)}|g(\tau)|\cos \theta(\lambda_j),
\]

neglecting for the moment any spatial relationship for clarity. \( I_r \) and \( I_m \) are the reference and measurement arm intensities, respectively. \( g(\tau) \) is the complex degree of coherence and depends on the overall time delay, \( \tau \), between the two arms. This is a complex quantity having a phase, \( \phi \), that represents the phase difference between the interfering light.

In a high-quality, tunable laser source having a line width of a few megahertz, the coherence length is several metres at least. This is much longer than the phase differences to be investigated in optical surface metrology, and as such, it may be assumed that \( |g(\tau)| = 1 \) for all \( \tau \) over the range of interest. If \( I_{DC} = I_r(\lambda_j) + I_m(\lambda_j) \) is a DC term formed by the addition of the intensities returning from each interferometer arm and \( I_{AC} = 2\sqrt{I_r(\lambda_j)I_m(\lambda_j)} \) is an AC component describing the amplitude of the modulated fringe intensity, equation (2.1) can be rewritten in a simplified form,

\[
I(\lambda_j) = I_{DC}(\lambda_j) + I_{AC}(\lambda_j) \cos \theta(\lambda_j).
\]

The intensity varies with wavelength owing to the output spectrum of the laser and any wavelength-dependent absorption or reflection from components in each arm. If the laser remains quasi-monochromatic throughout the tuning range, it is reasonable to assume that the magnitude of the complex degree of coherence is constant and unity. The phase however is dependent on the wavelength as

\[
\theta(\lambda_j) = \frac{4\pi(h + \xi)}{\lambda_j},
\]

where \( \xi \) is a phase offset relating to the reflection and transmission properties in the interferometer arms, as well as their lengths relative to each other. \( h \) is the optical path difference due to sample surface height (in a surface measurement application). The phase offset quantity \( \xi \) may be viewed as constant offset, assuming it is constant across the field of view. Generally, it is preferable to keep \( \xi \) as close to zero as possible for most wavelength scanning applications, thus avoiding a constant phase ramp in the result. Equation (2.3) is sometimes simplified further by introducing a fringe frequency term, \( K_j = 4\pi/\lambda_j \).

**Self-calibration interferometry (tech II)**

Self-calibration techniques using common path (or near common path) interferometry and active stabilization techniques can reduce sensitivity to disturbance. This can allow the subsequent reduction of complexity and mass...
of an instrument, as well as increasing the range of environments in which it may be expected to perform acceptably.

The output of any interferometer is subject to a time-varying phase term \( \epsilon(t) \), which is due to environmental disturbance altering either the physical path length or the refractive index of the transmission medium (usually air),

\[
I(\lambda, t) = I_{DC}(\lambda, t) + I_{AC}(\lambda, t) \cos[\theta(\lambda) + \epsilon(t)].
\] (2.4)

This time-varying error term may be tracked by a reference interferometer assuming that any interrogation technique has sufficient bandwidth. If this reference interferometer has a common path with the measurement interferometer, then the tracked phase is the error term, \( \epsilon(t) \), that is present in both interferometers. This error term may then either be removed at the signal-processing stage, or used as the feedback parameter in a control loop. In the latter case, the phase must be physically altered and this may be performed by, for instance, a piezo-mounted mirror or an electro-optic phase modulator (EOPM) placed in one arm.

(c) Wavelength dispersive multiplexing (tech III)

A dispersive optical element can be used to cause the spatial separation of wavelengths emitted from an interferometer. In this case, it is possible to interrogate a specific point on a surface with a specific wavelength. Assuming a one-to-one mapping of wavelength to a surface position, which may be ensured by the careful choice of a dispersive element, the equation for the interferometer output may be rewritten as

\[
I_{x}(\lambda_j) = I_{DCx_j}(\lambda_j) + I_{ACx_j}(\lambda_j) \cos[K_j h(x_j)], \quad \text{where} \quad x = f(\lambda)
\] (2.5)

and \( f \) is some function describing the position-to-wavelength response of the dispersive probe in use and its specific parameters. The surface height, \( h \), is now that height interrogated at some position along a profile, \( x \), as dictated by the current tuned wavelength. Here, the phase offset, \( \xi \), is assumed to be zero across the field of view.

The scanning range is dependent on the type of dispersive element as well as its parameters. One effective method is to use a blazed grating in order to angularly disperse the light. The light spot on the grating is positioned at the rear focal point of a lens so that the light exiting the lens is collimated and vertically incident on the sample. After reflection, the light travels back along the same path, as shown in figure 1. From the grating equation

\[
d(\sin \alpha + \sin \beta) = m\lambda,
\] (2.6)

where \( d \) is the grating pitch, \( \alpha \) and \( \beta \) are the incidence and diffracted angles, respectively, \( m \) is the diffraction order and \( \lambda \) is the wavelength.

The small angle scan range of the system, \( S \), is dependent on the effective focal length of the lens, \( f \), and the wavelength-tuning range, \( \Delta \lambda = \lambda_{\text{max}} - \lambda_{\text{min}} \). Other factors are the grating pitch, \( d \), and the angle of incidence, \( \alpha \). The equations describing operation in the first order are

\[
S = f \cdot \frac{\lambda_{\text{max}} - \lambda_{\text{min}}}{d \cos \beta}
\] (2.7)
Figure 1. Wavelength scanning using blazed diffraction grating. GRIN, graded index; MFI, multiplexed fibre interferometer; OSA, optical spectrum analyser.

and

$$\beta = \sin^{-1}\left(\frac{m\lambda}{d} - \sin \alpha\right). \quad (2.8)$$

If $\beta$ is kept small, the physical translation of the spot on the measurand surface will change, to a good approximation, linearly with wavelength. Although the effective focal length, grating pitch and wavelength range are fixed quantities in any system, it is possible to adjust the angle of incidence, $\alpha$, in order to change the scan range.

(d) Wavelength absolute measurement (tech IV)

Source wavelength scanning can be applied to a Michelson interferometer for purposes of determining the absolute optical path length difference between the two arms. First, it is often convenient to rewrite the interferometer equation (2.2) in terms of a discrete angular wavenumber, $k_m = 2\pi/\lambda_j$, with $m = 1, 2 \ldots M$. This leads to

$$I(k_m) = I'_\text{DC}(k_m) + I'_\text{AC}(k_m) \cos \theta(k_m). \quad (2.9)$$

Looking at equation (2.9), it can be seen that wavenumber scanning will result in phase cycling if the interferometer is not perfectly matched. The frequency of the phase cycling is determined by the sample height, $h$, and the phase offset, $\xi$. If the phase offset is zero and constant across the field of view, the sample height may then be determined by

$$h = \frac{\Delta \theta}{2(k_M - k_0)}, \quad (2.10)$$

for $M$ discrete wavenumber steps. One requirement is that the phase must not change by more than $\pi$ radians between each wavenumber step or aliasing will occur.

If the wavenumber is scanned and an interferogram recorded at each of the discrete scanned wavenumber values, the optical path difference and thus surface height may be determined.
(e) ‘Lab-on-a-chip’ microsystems (tech V)

‘Lab-on-a-chip’ microsystems permit the integration of several sequential experimental steps into a single automated process to perform more analysis over a unit time at a lower cost per analysis. They offer several advantages over conventional analytical techniques such as large autonomy owing to elimination and simplification of external instruments, minimal sample requirements, rapid analysis time, ease-of-use, minimized exposure to hazardous materials, reduced waste generation and also much lower cost. Progress in integrated optics technology, including critically, increased automation in device construction, will allow the design and building of more complex and efficient ‘Lab-on-a-chip’ microsystems at a reduced cost.

The ‘Lab-on-a-chip’ concept is being applied to the multi-disciplinary fields of chemistry, biology, optics and microelectronics. It concerns the miniaturization and the integration of complex systems on a small substrate of silicon, glass or plastic. The latest technology allows the passive assembly of single-mode optical components made from different material systems by way of location and alignment artefacts created by technologies such as deep etching.

3. Online/inline precision surface measurement systems

With the application of the techniques described in the previous section, it is possible to generate a set of new surface measurement instrumentation to provide capability that previously was only possible offline. In the first stages of exploration, an attempt was made to find a measurement system, which could be evolutionary, by combining a mechanical stylus system and a PSI to achieve appropriate properties in terms of speed, robustness, stability and miniaturization. Figure 2 shows such a philosophical structure. The subsections below are examples of optical interferometry systems derived from combinations of the techniques described in §2.

(a) Fibre surface profiling interferometer (tech I–III)

For single-point scanning, the idea is analogous to a traditional contact stylus, but realized in the optical domain in order to achieve a fast scan rate. The optical stylus technique can be combined with an optical fibre to produce a compact probe that is suitable for use online. By using an optical fibre, the probe can be mounted remotely from the interrogation apparatus that contains the bulk of the optics and electronics. Figure 3 illustrates the setup of the optical stylus probe, shown in the dashed outlined box (bottom right) [24].

Light from the optical fibre is collimated into free space by the graded index (GRIN) lens. It is then incident on a reflective grating and the first-order diffracted beam is then focused by an object-space telecentric scanning lens onto the surface. Reflected light then returns from the surface and re-enters the fibre in the reverse manner. It is apparent that by changing the wavelength of the source light, the angle at which the first-order diffracted beam leaves the grating may also be altered. The result is lateral displacement of the focused beam upon the measured surface. As such, it is possible to move the beam over the surface in one axial direction simply by altering the wavelength of the source light. In
this sense, the beam is swept across the surface in the same manner as a contact stylus might be.

The self-calibration method is adopted for phase retrieval with high fidelity. The phase value of the interferogram is determined by two interfering wavefronts. One wavefront is a known reference, and the other is retro-reflected from the measured surface. The resulting phase map, along with knowledge of the illuminating wavelength, reveals a representation of the surface topology.

The general relationship between the phase and the output intensity, $I$, of the interferometer is a series as developed from equation (2.5),

$$I_{x_1}(\lambda_1), I_{x_2}(\lambda_2), \ldots, I_{x_j}(\lambda_j), \ldots, I_{x_J}(\lambda_J), \quad 1 \leq j \leq J; \quad 0 \leq x_j \leq S, \quad (3.1)$$

$x_j$ are the discrete wavelength steps taken that have an equivalent interval over a range $S$. The surface height at each point is then

$$h_{x_j} = \frac{\theta_{x_j} \lambda_j}{4\pi}, \quad (3.2)$$

assuming that the phase offset, $\xi$, is constant at zero across the field of view.

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The ability to use fibre interferometry provides the major advantage of being able to mount a compact probe head remotely from the rest of the instrumentation. However, implementing optical fibre interferometers creates in itself a particular set of challenges. It is well documented that fibre interferometers suffer from major instabilities brought about by environmental effects [25]. Temperature variations and vibration cause deformation and stresses in the fibre core, resulting in changes in the optical path length. Path length changes on a macrolevel result in an additive error to the phase to be measured; those on a microlevel contribute thermodynamic phase noise to the output [26]. Random polarization state evolution is also another problem that can cause difficulty for acquiring stable measurement [27]. Mitigating the effects of all these disturbances is essential, if any meaningful surface height information is to be obtained from the acquired phase data.
Optical path length change imposes itself directly on the measurement result, distorting the data. The severity of the path length change scales with the length of fibre. With approximately 20 m of fibre, as found in the current experimental setup, temperature drift alone can result in a few micrometres of path change within a few seconds, completely obliterating any measurement at the nanometre scale. In order to successfully make any measurement at this scale, it is necessary to provide some way of stabilizing the fibre interferometer.

Therefore, a self-calibration method is necessary by using two multiplexed interferometers having different source wavelengths. One is a measurement interferometer sourced by the tunable laser that provides the optical stylus. The second interferometer is termed the tracking interferometer and is sourced by a fixed wavelength distributed Bragg reflector laser diode that provides a stable single mode, long coherence length source with a wavelength of 1500 nm. The tracking interferometer follows any path changes occurring due to environmental disturbance in either of the optical fibre paths [28].

An EOPM is used as the path length actuator to provide closed-loop stabilization. EOPMs take advantage of the Pockels effect that is present to a relatively large degree in certain crystal types, in this case, lithium niobate. By applying an electric field across the active crystal axis, the refractive index and thus the optical path length may be altered over that region. Key advantages are much better linearity than piezoelectric elements, negligible settling times and a hugely increased frequency response.

The scan range of this fibre interferometer depends on the parameters of the dispersive element. The blazed grating is used in this system, with an angle of incidence $\alpha = 26^\circ$ and a scan range $1560 \leq \lambda \leq 1575$ nm. The effective focal length of the scanning lens is 35.98 mm, providing a 3.2 mm lateral scan range. The calculated scan profiles for various angles of incidence are shown in figure 4.

The lateral resolution of the optical probe is determined by the spot size of the beam focused on the measured surface. The light output from a single-mode fibre forms a good approximation of a Gaussian beam. It is thus reasonable to state that the limit for the complete resolution of two points on the surface is the intersection of the central peak of one beam spot to the $1/e^2$ intensity point of an adjacent spot. The LSM-03 objective lens produces a $1/e^2$ spot size of approximately 25 µm under ideal conditions; this yields a total of 255 resolvable points on the surface with the current setup. The maximum scan range, limited...
by the aperture of the objective lens, is 9.4 mm, thus yielding a maximum of 752 resolvable points. For major changes in scan width and resolution, a lens with a different focal length would be required.

An alternative method for carrying out the scanning is a frequency-based spatial scanning method using acousto-optic deflectors (AODs), as illustrated in figure 5 [29]. The scanning light beam is implemented by changing the frequency of the drive signal applied to the AOD.

This system is different from the wavelength-based spatial scanning method. In the frequency-scanning method, a tunable laser is replaced by a monochromatic He–Ne laser source with a single wavelength $\lambda'_m$. The optical dispersive probe in the previous instrument is replaced by an AOD device. The single wavelength $\lambda'_m$, which drives the measurement interferometer, is operated at a wavelength different from that of the laser diode $\lambda_r$.

In this measurement principle, the zero diffraction order of $\lambda_{0r}$ and the first diffraction order of $\lambda'_{m1}$ pass through the AOD simultaneously, which leads to a near common path optical structure. In order to eliminate the frequency shift of an AOD system, an AOD is used in both the measurement and reference arms to compensate for this frequency shift. The symmetrical structure of the optical path can also decrease the system error introduced by the optical aberration from the matched objective lenses. The AOD can change the angle of deflection of the laser beam, which is linearly proportional to the acoustic frequency applied. The diffracted light beam on the AOD is positioned at the focus point of the lens so that the light through the lens is vertically incident on the sample and reflected back along the same path. The scanning range of the surface, $S$, can be deduced as

$$S = f \cdot \lambda'_m \cdot \frac{\Delta F}{v_a},$$

(3.3)

where $f$ is the focal length of the objective lens, $v_a$ is the acoustic velocity in the AOD and $\Delta F$ is the range of frequency scanning.
This technique is able to provide an optical fibre linked, remote mountable probe that can provide surface profile information while also maintaining a degree of isolation from environmental perturbations. Both these factors are critical for effective online measurement at nanometre resolutions. The method has potential for very high scan rates (several kilohertz) owing to the lack of any mechanical movement.

(b) Chip optical interferometry (tech I and II and III and V or tech I and II and IV and V)

A chip optical interferometer is a truly miniaturized measurement system (figure 6). Semiconductor fabrication technologies can produce an integrated-optic interferometer, which may be much more compact than bulk optic or fibre-based apparatus. The chip device includes a tunable laser, laser diode, optical isolator, directional coupler, thin-film filter (TTF) and photodetectors on a single optical chip to realize metrology properties similar to the fibre system, as shown in figure 3.

The approach for this chip device uses a planar silica motherboard for the passive waveguide circuitry (the optical analogue of the printed circuit board), onto which are assembled silicon daughterboards containing each individual module in order to create the complete device.

The tunable laser is the crucial component for a chip interferometry system. It basically consists of two main parts, a gain block and a tuning element. The gain block is a reflective semiconductor optical amplifier (RSOA) using multiple quantum wells in the active layer structure. It has been designed to provide gain over a broad spectral bandwidth. The device is in a reflective configuration with mode expanders on both facets. The waveguide in the gain medium is curved such that it makes an angle of $10^\circ$ to the cavity side chip facet, thus reducing parasitic reflections, as shown in figure 6. The tuning element is a TFF that is placed in the path of the collimated output from the RSOA. It is rotated by a piezo-electric motor and encoder unit to allow a selected wavelength to pass through. A micro-optic ball lens is used to collimate the light beam and a reflector is used to form the end of the laser cavity [30]. The full range of wavelength tuning can be carried out in under a second.
Two possible modes of operation are possible with the chip interferometry system. Firstly, a wavelength multiplexed scanning head, using a grating and collimating objective lens can be used to acquire a surface profile, as described in §2c: tech III. Secondly, a Fizeau-type head may be used, which, when combined with the wavelength scanning supplied by the tunable laser, can provide absolute distance measurements of a single point in a manner similar to that shown in §2d: tech IV.

A large wavelength-tuning range, a reasonably high output power and stable single longitudinal mode operation are all important for surface measurements using interferometry. The test results of the output power as a function of the wavelength of the chip tunable laser at a drive current of 250 mA are shown in figure 7. It can be seen that the output power is close to 0 dBm (1 mW) at wavelengths over the whole tuning range of 92 nm (1500–1590 nm), as shown in figure 7. The maximum output available from the laser is approximately 5 mW.

Figure 8 shows the tunable laser packaged into a daughterboard. Figure 9 shows a single tuned longitudinal mode from the laser, the side-mode suppression ratio at 1550 nm is more than 45 dB.

In order to ascertain the accuracy of the system setup, a piezoelectric translator (PZT) was used to displace the reference mirror in 50 nm steps over a 200 nm range. The profile of the mirror surface at the same position was measured after each step. The difference between each consecutive step was then taken and is plotted in figure 10. It can be seen that the displacement between each consecutive step is approximately 50 nm. The displacement data at each consecutive step were then averaged and a linear fit made to the data. The standard deviation of the average displacement data from the linear fit is 3.21 nm.

This measurement technology has the advantage for online measurement where miniature size is essential for embedding the metrology tool onto the manufacturing platform. Specifically where access makes it impossible for cables
Figure 8. Prototype chip interferometer module. PCB, printed circuit board. (Online version in colour.)

Figure 9. Side-mode suppression ratio at the wavelength of 1550 nm. It shows a single longitudinal mode. (Online version in colour.)

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to be routed, there is potential for this device to be battery operated, with wireless telegraphy used for transferring control and data. The telecommunications technologies associated with the chip interferometer are intrinsically high speed, and the next-developed devices are anticipated to provide measurement datasets at rates of tens of kilohertz, through the use of faster laser tuning and on-chip phase modulators.

(c) Spectral scanning interferometry (tech I and II and IV)

This measurement technique combines tech I and II and tech IV. It intends to provide full-field surface measurement for the large manufacturing systems. The basic configuration of the surface measurement system is illustrated in figure 11. The measurement system is composed of two Linnik interferometers that share a common optical path. The measurement interferometer, illuminated by a white-light source, is used to acquire a three-dimensional surface of the sample. The reference interferometer, illuminated by a near infrared super-luminescent light-emitting diode (SLED), is used to monitor and compensate for the environmental noise, e.g. temperature drift, mechanical vibration and air turbulence. As the two interferometers suffer similar environmental noise, the measurement interferometer will be capable of measuring surface information once the reference interferometer is ‘locked’ into the compensation mode.

An acousto-optic tunable filter (AOTF) is an electro-optical device that can be described as an electronically tunable optical filter. This is implemented using a birefringent crystal (such as tellurium dioxide) whose optical properties vary upon interaction with an acoustic wave. The acoustic wave is produced by a piezoelectric transducer attached to the AOTF crystal. In response to the acoustic wave.
The wavelength scanning interferometry system. DAQ, data acquisition; PD, photodiode; PI, proportional-integrand. (Online version in colour.)

wave that propagates through the AOTF crystal, the crystal lattice structure is alternately compressed and rarefied. This refractive index fluctuation produces the elasto-optic effect that diffracts incident light.

The beams from the AOTF-filtered white-light source and the SLED are coupled by a dichroic beamsplitter that is highly reflective at the SLED wavelength and transmissive in the visible-light wavelength range. After passing through the dichroic beamsplitter, the light beam is coupled to an optical fibre path cable by a fibre-coupling lens. The light beam is transmitted to the interferometer system and collimated by a lens. The system adopts a Linnik configuration that has the ability to compensate for chromatic dispersion and other optical aberrations. Light reflected by the sample and the reference mirror are combined by a beamsplitter to generate an interferogram.

A key feature of this system is the AOTF. It is placed after the white-light source to select a specific wavelength, thus producing an interferogram at the charge-coupled device (CCD) sourced by only that wavelength. The selected light wavelength is determined by

$$\lambda = \Delta n \alpha \frac{v_a}{f_a},$$

where $\Delta n$ is the birefringence of the crystal used as the diffraction material and $\alpha$ is a complex parameter depending on the design of the AOTF. $v_a$ and $f_a$ are the propagation velocity and frequency of the acoustic wave, respectively. The wavelength of the light that is selected by this diffraction can therefore be varied simply by changing the driving frequency, $f_a$. Different wavelengths of light pass

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through the AOTF in sequence so that a series of interferograms are detected by the CCD. The absolute optical path difference can be calculated by analysing these interferograms.

A self-calibration method has been used to compensate for the axial (vertical) vibration resulting from environmental noise [31]. In this system, the reference interferometer is illuminated by a SLED and is employed together with an electronic servo feedback unit. Light output from the laser is combined with the measurement light and travels almost the same optical path as the measurement interferometer. As a result of the shared optical path, noise occurring in the measurement light and travels almost the same optical path as the measurement interferometer. The interferometer output from this system can be rewritten from equation (2.9),

\[ I_{x,y}(k_m) = I_{DC_{x,y}}(k_m) + I_{AC_{x,y}}(k_m) \cos[\theta_{x,y}(k_m)]. \] (3.5)

Through the AOTF in sequence so that a series of interferograms are detected by the CCD. The absolute optical path difference can be calculated by analysing these interferograms.

\[ M \] frames of intensity data captured from the whole CCD array having \( p \times q \) pixels can be represented by a matrix

\[ I_{x,y} = \begin{bmatrix}
[I(1), I(k_2) \cdots I(k_M)]_{1,1} & [I(1), I(k_2) \cdots I(k_M)]_{1,2} & \cdots & [I(1), I(k_2) \cdots I(k_M)]_{1,p-1} \\
[I(1), I(k_2) \cdots I(k_M)]_{2,1} & [I(1), I(k_2) \cdots I(k_M)]_{2,2} & \cdots & [I(1), I(k_2) \cdots I(k_M)]_{2,p-1} \\
\vdots & \vdots & \ddots & \vdots \\
[I(1), I(k_2) \cdots I(k_M)]_{q,1} & [I(1), I(k_2) \cdots I(k_M)]_{q,2} & \cdots & [I(1), I(k_2) \cdots I(k_M)]_{q,p-1}
\end{bmatrix}. \] (3.6)

The phase-shifting evaluation procedure is applied individually for each pixel and matrix (3.7) is computed,

\[ \theta_{x,y} = \begin{bmatrix}
[\theta_1, \theta_2 \cdots \theta_M]_{1,1} & [\theta_1, \theta_2 \cdots \theta_M]_{1,2} & \cdots & [\theta_1, \theta_2 \cdots \theta_M]_{1,p-1} \\
[\theta_1, \theta_2 \cdots \theta_M]_{2,1} & [\theta_1, \theta_2 \cdots \theta_M]_{2,2} & \cdots & [\theta_1, \theta_2 \cdots \theta_M]_{2,p-1} \\
\vdots & \vdots & \ddots & \vdots \\
[\theta_1, \theta_2 \cdots \theta_M]_{q,1} & [\theta_1, \theta_2 \cdots \theta_M]_{q,2} & \cdots & [\theta_1, \theta_2 \cdots \theta_M]_{q,p-1}
\end{bmatrix}. \] (3.7)

Then, by applying equation (2.10) to each phase matrix, an areal topography is obtained, as shown in matrix (3.8),

\[ h_{x,y} = \begin{bmatrix}
\frac{\Delta \theta_{1,1}}{2(k_M - k_0)} & \frac{\Delta \theta_{1,2}}{2(k_M - k_0)} & \cdots & \frac{\Delta \theta_{1,p-1}}{2(k_M - k_0)} \\
\frac{\Delta \theta_{1,2}}{2(k_M - k_0)} & \frac{\Delta \theta_{2,2}}{2(k_M - k_0)} & \cdots & \frac{\Delta \theta_{2,p-1}}{2(k_M - k_0)} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\Delta \theta_{1,q}}{2(k_M - k_0)} & \frac{\Delta \theta_{2,q}}{2(k_M - k_0)} & \cdots & \frac{\Delta \theta_{p,q}}{2(k_M - k_0)}
\end{bmatrix}. \] (3.8)
Owing to the parallel nature of the captured signal, it is possible to achieve the fast data processing by using a dedicated graphics processing unit (GPU). It has been verified that 250 frames of $672 \times 502$ pixels obtained by this measurement system may be processed in less than 1 s with a commercial 240 core GPU.

A prototype system has been developed, as shown in figure 12. A white-light source as the measurement interferometer source and an infrared SLED is used to monitor and compensate the environmental noise. The radio frequency applied to the AOTF$^1$ was scanned from 80 to 110 MHz in steps of 10 kHz, corresponding to a wavelength interval of 0.48 nm. This range of radio frequencies provides a range of scanning wavelengths from 680.8 to 529.4 nm. Interferograms (300) were recorded by a high-speed CCD camera$^2$ at a frame rate of 100 frames per second [31]. Figure 13a shows the intensity distribution recorded by one of the CCD pixels and figure 13b shows the corresponding retrieved phase of this intensity distribution, as determined by the data-processing procedure described earlier.

The vertical measurement range of such a system is dependent on the coherence length of the filtered light source. AOTFs are available to produce coherence lengths of up to 300 $\mu$m, and the unambiguous height range is half of this. In addition, the depth of focus of the objective lens is also a limiting factor. The lateral range and resolution is dependent upon the field of view and numerical aperture of the microscope objective used.

$^1$Model LSGDN-1, SIPAT Co.

$^2$Model OK-AM1131, JoinHope Image Tech. Ltd.
This measurement method is potentially used in large diamond turning machines, roll-to-roll manufacturing processes, hot embossing and the UV-cured film manufacture of structured surfaces. The measurement method can also have numerous other applications in precision machining, micromachining and the general manufacture of surface reliant products such as embossed sheet steel.

This method represents a breakthrough in the speed at which areal datasets of surface topography can be acquired because of the removal of mechanical scanning from the measurement method. The technique also has good potential for the measurement of multi-layer films, as each layer represents a different surface, with a different frequency response. The measurement speed, combined with active vibration compensation, is advantageous for shop-floor measurement. The prototype instrument shown in figure 12 is planned to be applied to large diamond-turned drum masters for roll-to-roll-structured film manufacture. The speed of acquisition is essential for inspecting the large surface area involved.

(d) Dispersive interferometry with a fibre multi-probe (tech II and III and IV)

Remote fibre probes may be usefully employed with a separate set of interrogation optics and light sources. While the benefits are obvious in terms of online mounting on machine tools, another potential advantage is the potential for multi-probing. Here, several relatively cheap fibre-linked probe heads may be combined with a single interrogation unit. Some form of optical switching or other form of multiplexing must be provided and the bandwidth requirements for the interrogation system increase as more probe heads are added.
One example is a dispersive white-light interferometer that can provide multi-probe potential through two specific advantages.

— Short coherence light from a super-luminescent diode (SLD) allows the use of a common-mode fibre connection. Here, both the reference and measurement are contained within the fibre. The reference arm is created by the Fresnel reflection from the uncoated GRIN lens. The measurement arm is created by the light reflected back from the measurand surface. The two lights combine non-coherently until they reach the unbalanced interrogation interferometer, sometimes termed a coherence discriminator. There the paths are then balanced, and an interference signal retrieved (figure 14).

— The dispersive white-light technique can acquire the surface height with minimal processing and no mechanical devices, making the bandwidth of the CCD line array the limiting factor. As such, switching between remote probes is feasible using, for instance, an optical fibre switch. It is possible to multiplex a separate laser interferometer into the same path to retrieve ambiguous phase with high resolution while the dispersive white-light technique is used to discern fringe order.

A dispersive white-light profilometer has been demonstrated in bulk optic form [33]. In addition, a fibre-probe-based method using a high-dispersion optical fibre has also been demonstrated, but the lack of a common-mode fibre path appears to limit measurement repeatability to more than 100 nm [34].

The key to the dispersive white-light interferometer is that a dispersive element is placed in one arm of the interferometer. One example of a dispersive element is a pair of matched transmission gratings. If the dispersion is constant over the small wavelength range, the refractive index, \( n \), (and thus path length) varies linearly with wavenumber, \( k \), such that

\[
n(k) = n(k_0) + \alpha(k - k_0), \tag{3.9}
\]
where $k_0$ is the central wavenumber of the light source and $\alpha$ is the dispersion parameter. The result is that each component wavelength of the white-light source used to illuminate the device has a different path length and thus the interferometer is balanced only at one point.

When the intensity from the interferometer is analysed spectrally, and neglecting any attenuation and polarization effects in each arm, the resultant response, $I(k)$, is found to be

$$I(k) = A(k) + B(k) \cos \theta(k).$$  \hfill (3.10)

The phase $\theta(k)$ is dependent on the optical path length and may be written with respect to equation (3.9) as

$$\theta(k) = 2k[z - d\{n(k_0) + \alpha(k - k_0) - 1\}].$$ \hfill (3.11)

The result of this is that a symmetric intensity pattern is formed with a definite central peak located at $k_c$. The response of the phase difference with changing wavenumber is shown in figure 15a.

It can be seen from equation (3.11) that the peak of $k_c$ occurs only at an absolute distance, $z_0$, that is determined by the length, $d$, and dispersion coefficient, $\alpha$, of the dispersive element. If the path length changes, then the position with respect to wavenumber of the intensity peak also changes linearly. By determining the wavenumber at which the peak occurs, the new path difference $z$ may thus be determined absolutely.

An advantage of this technique is that the measurement range is scaled by the amount of dispersion in the reference arm. Thus, the system may be operated with a range of a few nanometres to several hundred micrometres. The resolution is

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limited by the number of spectrometer pixels available and currently it can reach 8192 pixels. Multi-probing potential with this technique also points towards a way of reducing the cost of metrology by providing low-cost multiple probe heads with a single interrogation unit.

4. Conclusion

This study has addressed the problems and challenges in the subject area of surface measurement for next-generation precision and ultra-precision manufacture, for example: (i) large-scale (up to metres) ultra-precision (nanometre tolerance) components with complex surfaces such as, telescope mirror segments; photovoltaic panels and large substrates, in which the measurements do not allow removal from a machine tool/production line and (ii) precision surfaces with very small size that work in extreme environmental conditions, such as fuel shells for inertial-confinement fusion. The next generation of measurement devices/instruments will require accessibility into manufacturing environments, online, non-contact and high-speed operation combined with ease of use, a small footprint and robustness. At the same time, they must match the same level of measurement uncertainty as current state-of-the-art laboratory-based measurement systems, while also matching affordability in terms of reducing manufacturing costs.

This study has discussed how rethinking some fundamental techniques, invented across several discipline areas, can create new measurement techniques to provide a quick advance. In this study, five basic principles, multi-wavelength scanning interferometry, self-calibrating interferometry, wavelength division multiplexing, wavelength absolute measurement and ‘Lab-on-a-chip’ microsystems, have been briefly introduced. This has led to four types of measurement systems that structurally combine these techniques in some fashion. This study has presented these techniques as having the potential to overcome current measurement problems and challenges, and has shown their feasibility for manufacturing environment applications.

The research work and experimental studies in this study show the following. (i) An optical-fibre-based surface interferometer with a remote mountable single-point wavelength scanning probe could provide a 9mm scanning range over a profile in less than 1s. It can reach sub-nanometre vertical resolution with 340–750nm vertical ranges depending on the source wavelength. (ii) An integrated-optic chip interferometer that presents a miniaturized measurement system. Current experiments have shown that this optical chip has a laser tuning range of approximately 92 nm while maintaining greater than 5mW output power, 40pm tuning resolution and less than 1s tuning period, all fully integrated into a single small package. The system has two possible modes of operation. The first is using a wavelength division multiplexed scanning probe head for profile measurement and the second is in a Fizeau-type configuration that can provide absolute distance measurement of a single point. (iii) A spectral scanning interferometer provides full-field surface measurement for large manufacturing systems, with a 1s measurement period and sub-nanometre resolution over a 300μm vertical range. Furthermore, it has the capability for multi-layer thick- and thin-film
measurements. (iv) A dispersive white-light interferometer providing single-point measurements with a compact fibre-linked probe. It can reach a 10 kHz measurement rate with nanometre resolution over a measurement range of several hundred micrometres.

These measurement methods have the potential and feasibility for manufacturing environment applications. Some can be used online in large diamond turning machines, large substrate manufacturing processes, hot embossing and UV-cured film manufacture of structured surfaces. Others can be used for numerous applications in precision machining, micro-machining and the general manufacture of surface reliant products such as embossed sheet steel.

Beside the challenges in the instrumentation aspects being discussed through this study, looking forward, the integration of these measurement techniques into the manufacturing environment will lead to further challenges, which include the establishment of measurement coordinate systems in machine-tool environments, calibration methods and traceability for fast online measurement, and surface characterization in conjunction with machine-tool error diagnostics and compensation. The integration will also concern the creation of mechanical and control solutions for device/instrument delivery, plus swarf and vaporized coolant removal. In summary, if ultra-precision/precision/nanosurfaces are to become economically viable in both science programmes and high add valued technology, all the earlier-cited challenges in measurement must be systemically solved in parallel with the evolution of the manufacturing process, to produce the enabling future envisioned.

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