Introduction

There is a vast array of sensors available to us at present. Sensors are selected according to the particular measurand and in many cases, the particular application, e.g. interfacing to a control system. Sensors are generally required to work in parallel with signal conditioning electronics, and may then be either used as a stand-alone measurement system or incorporated into a control system for real-time sensory feedback.

Depending on the measurand there is a vast array of sensors that can be used for surface and textural characterisation. One of the standard methods for investigating the surface profile is to use a profilometer[1]. A profilometer utilises a stylus much in the same way as a record player follows the variations along the track of a record, the main difference being that the profilometer uses optical sensing to determine the attitude of the stylus. In a record player the stylus generates a signal by electromagnetic induction (moving coil or moving magnet). The potential disadvantage of the stylus-based systems is modification of the surface, due to contact being made by the stylus. However, the use of optical based profilometry is able to circumvent this, and a number of systems have been developed so far. Abou-Zeid and Wiese developed a compact interference profilometer that uses a wavelength-tunable diode laser as an optical stylus, with a measurement uncertainty of around 10nm[2]. A number of profilometry systems based on interferometry have also been reported[3,4]. Cuthbert and Huynh[5] have designed an optical system for fast non-contact measurement of surface texture, based on the optical Fourier transform pattern of the surface, which is correlated with the surface roughness obtained using a stylus based instrument.

Moving into the new millennium we are faced with the increasing demands of hard disk drive technology. Data storage density continues to increase, necessitating that the head flies even closer to the disk surface: state-of-the-art flying heights currently being around 15nm. This is coupled with the increasing demand for faster track access, which means that the disk drive is required to operate at increasingly higher speed. This represents a challenge for PCs operating in the office environment, but presents more
serious difficulties for computers working in conditions where they are subjected to shock and vibration. This is of particular interest to military and aerospace applications; and to a lesser extent will also affect users of laptop computers.

This paper looks at a variety of sensor systems used in the CRIST research laboratory for the characterisation of magnetic media and data storage systems, namely: scanning laser microscopy, magnetic force microscopy, dual beam polarisation interferometry, CD-ROM optics and thick film piezoelectric sensors. Finally, there is a brief look at a complete sensor-control-actuator system, which includes optical beam deflection for displacement (or topography) sensing, which is currently being investigated for the improved operation of hard disk drives.

A. Dynamic scanning laser microscopy

Scanning laser microscopes are extremely useful tools for high-resolution point-by-point imaging of sample surfaces. The most common configuration employs a stationary laser beam, which can have either continuous or modulated (intensity or polarisation) output. The laser is brought to a focus using a microscope objective to yield a diffraction-limited spot, which is typically around 1μm on the sample surface. The sample can then be micro-positioned, with a motorised x-y stage, with respect to the sample and the reflected light collected by one or more detectors. An alternative configuration employs a pair of scan mirrors to move the spot on the sample surface. This set-up is significantly more complex as it requires autofocus to maintain the same size spot at all points of the scan, and there is a trade-off between scan area and resolution. For example a 5mm × 5mm area can be scanned with a resolution of around 30μm[6]. However, the two systems are often combined: scan mirrors (high speed scanning) and x-y stage (large area scan). The use of different detectors and polarisation sensitive/insensitive optics enables different information to be acquired.

In our laboratory a scanning laser microscope has been designed and built to observe the dynamic behaviour of domain switching during the thermo-magnetic write process and the subsequent magnetisation state (domain orientation) in thin-films and devices[7-9]. It can also be used to write to magneto-optic disk material thermomagnetically prior to imaging. Images are derived from the longitudinal and polar magneto-optic Kerr effects, which are wavelength dependent.

The microscope system has been made modular, which enables the imaging system to be flexible and allows further functionality to be added as required. An overview of the system is shown in Figure 1. The scanning laser microscope is constructed around the basic frame of a Leitz Metalloplan optical microscope, mounted on optical breadboard along with other optical and mechanical components, as shown in Plate 1.

The various modes of operation of the SLM are as follows:

- XY table scanning mode. In the XY scan mode a sample is raster scanned beneath the laser spot via a Burleigh XY Worm Table, with a resolution of 4nm. The
magnetic or intensity (pseudo-topographic) information is then extracted by sampling all the photo-detector outputs using the computer I/O board, then applying the required algorithm to the data. Plate 2 shows bubble memory magnetic domain patterns using the polar Kerr effect (scan area $32\mu m \times 40\mu m$). The reflected light intensity is a function of the sample magnetisation (domain orientation), and LabView enables the reflected intensity to be represented by a grey scale image. The change in intensity represented here is typically less than 1 per cent.

- **Galvanometer scanning mode.** In the galvanometer scan mode the sample is held stationary whilst the laser spot is raster scanned over it via the scanning mirrors. The galvanometer position is controlled using the computer I/O board voltage outputs. Again the computer processes magnetic or topographic information after it is sampled to create an image. Plate 3 shows a pseudo-topographic (reflected intensity) image of an integrated circuit layout (galvanometer scan area $100\mu m^2$).

- **Dye pulse laser.** A further imaging mode of the SLM utilises a dye pulse laser. This requires the software to trigger a waveform generator, and at a set time period later trigger the laser. Finally, at some point in time after this, data are acquired from the photo-detectors. Each of these time periods must be accurately related to the others. The magnetic image is retrieved from the quadrant photo-detectors as for other modes of operation.

- **CCD camera image acquisition.** Another mode of image acquisition uses a super-cooled CCD camera, triggered after a pulse of light has illuminated a sample. The camera is supplied with a set of functions in the form of a Windows dynamic link library (DLL), also known as an application program interface (API). These functions cover all that is required to operate the camera.

**B. Magnetic force microscopy**

The magnetic force microscope (MFM) is based on the atomic force microscope (AFM)[10]. In the AFM a small probe, a silicon cantilever with an atomically sharp tip, is brought into contact with a sample surface, and raster scanned across it. The resultant deflection of the tip is recorded and used to create an image of the surface topography. In magnetic force imaging the tip is coated in a ferromagnetic material, and moved away from the surface several tens of nanometres. It is then raster scanned, and the interaction between the magnetic field of the sample and the tip recorded to create an image of the magnetic forces.

The development of our MFM, shown in Plate 4, is based on a versatile, modular form,
enabling easy access to the specimen and easy change of tips/cantilevers[11]. It uses optical beam deflection to sense cantilever movement and is designed to operate in either topographic or magnetic force imaging modes. This system is also designed to work in low vacuum (or in a helium atmosphere). The benefits of vacuum (and helium) operation are significant, since the removal of much of the normal viscous air damping enables a significant increase in the cantilever’s effective Q-value, as operation moves into the molecular damping region (independent collisions of non-interacting air molecules). This in turn results in better resolution of images produced by resonant techniques. Plate 5 shows an image of the topography of a hard disk surface (scan area $1\mu m \times 1\mu m$), showing granular structure of surface and diagonal grooves from texturing process.

A variety of scanning modes exist for the MFM. The “static” scan, as described above, is the simplest; however, this requires samples with relatively powerful magnetic fields. Resonant scanning is a standard mode of operation, where the cantilever is resonated, and the effects of the sample’s fields on that resonance are monitored in different ways to create an image. In recent years LiftMode™ has being recognised as a very useful mode of operation[12]. In this case the topography of the sample is mapped out with an initial scan, from which the data are used to control the height of the MFM probe, in resonant mode, to do a second magnetic scan. This results in removal of topographic effects from the resulting magnetic image.

The design and function of the probe used to interact with the stray fields from a magnetic sample are a major MFM research subject. The standard ferromagnetic design has several inherent problems. The tip magnetisation can suffer from hysteresis over time, together with wear and damage during its useful life. The magnetic properties of different samples, i.e. if the sample is magnetically “hard” or “soft”, mean that a range of different designs and coatings need to be employed. Therefore, an instrument must be reconfigured each time a new type of sample is imaged. Furthermore, these imperfections may have serious consequences in the acquisition of useful, quantifiable data.

We are currently investigating a new type of MFM probe that uses an electromagnetically induced field as a replacement for the standard probe’s stray field. Although electromagnetic MFM probes have been described before, this design is unique[13]. The field is induced around a micro-fabricated aperture using a controlled current. The aperture would be situated near the end of a standard cantilever that has been coated in a conductive material, e.g. gold. This design has the advantage that the specimen interaction is variable, giving controllable field intensity, and as such the results would be repeatable. The new probe has been theoretically simulated to create images of magnetic domain patterns, and it is anticipated that work on the fabrication of these new and innovative probes will begin soon. The practical issues of using the probe in our MFM instrument are also undergoing analysis.
C. Dual beam polarisation interferometry

Optical interferometry is a well established technique for precise and non-contact measurement. Various types of interferometry, such as heterodyne interferometry[14], sinusoidal phase modulating interferometry[15], and phase-shifting interferometry[16], have been developed to make high resolution measurement of small displacements. However, apart from the complexity of the system construction, these existing methods are generally feasible only for low-speed measurement applications. When a high-speed measurement is needed, it is difficult to find a suitable technique if the measurement accuracy requirement is high. The speed limitation in these displacement measurement interferometers is mainly due to the use of slow modulation or scanning techniques. In the CRIST laboratory, a dual beam polarisation interferometer has been constructed, which can be used for high-speed measurement of dynamic morphology/topography, and in our case for the complex measurement of dynamic disk head flying height[17,18].

The polarisation interferometer configuration utilises two orthogonally-polarized light beams to remove the directional ambiguity of the displacement, and is shown schematically in Figure 2. The main part of the interferometer utilises a polarising beam splitter PBS1, two quarter-wave plates QW1 and QW2, two mirrors M1 and M2, and a non-polarising beam splitter NPBS1 as both a beam splitter and phase shifter.

Employing a polarising beam splitter PBS1 makes the best use of the laser beam and prevents the returning beam from feeding back into the laser diode. The mirror M2 is driven by a piezoelectric translator (PZT1), which can be used to perform system calibration. Mirror M3 is used as a reference plane when single point displacement is measured. When the system is used to measure the relative displacement of two adjacent points, such as the vertical movement of the hard-disk read/write head relative to the disk surface, M3 is removed and the reference beam is extracted by NPBS1 to the second measurement point. Mirror M2 can also be micro-positioned manually to adjust the spacing of the two measurement points. A 670nm wavelength laser diode is used as the light source. The laser beam passes through the polariser and enters the polarising beam splitter PBS1. Then the s-polarised component is coupled out and reflected by mirror M1 and focused on the measurement point on the sample. The p-polarised component passes through and is focused on the reference mirror or another measurement point.

The returning beam enters the interferometric receiver, which is used to measure the intensity and phase difference between the two polarised beams. The interferometric receiver consists of a non-polarising beam splitter NPBS2, two polarising beam splitters PBS2 and PBS3, a quarter-wave plate QW3 and four photo-detectors. The detected voltage signals are amplified and equalised, then sampled in by the computer through a 12-bit A/D converter board. The sampling rate of the A/D converter will determine the measurement speed of the system. The A/D converter board with a sampling rate of 20MS/s is commercially available at present. The computer, through a 12-bit D/A converter board and a high voltage (150V) amplifier also controls the piezoelectric translators.

We take the electric field of the two orthogonally polarised beams to be of the standard form:

\[ E_p = A_p \exp(i\omega t) \]  \hspace{1cm} (1)

\[ E_s = A_s \exp(i(\omega t + \phi)) \] \hspace{1cm} (2)

where \( \omega \) is the angular frequency of the radiation, \( A_p \) and \( A_s \) are the amplitudes of \( E_p \) and \( E_s \), respectively, and

\[ \phi = 4\pi(d + \Delta d)/\lambda. \] \hspace{1cm} (3)
In equation (3), $\lambda$ is the wavelength of the laser beam, $d$ is the static optical path difference between the two polarised beams and $\Delta d$ is the displacement to be measured. The wave intensity being received by each of the four photo-detectors ($P_{PD1}$ to $P_{PD4}$) is proportional to the square of the electric field, and by simple signal conditioning and processing quadrature signals $P_{PD2} - P_{PD1} = b_2 - b_1$ and $P_{PD3} - P_{PD4} = b_3 - b_4$ are obtained. The computer samples these signals with two channels of the A/D converter board. The displacement $\Delta d$ is then determined by phase evaluation and unwrapping[19].

To test the ability and effectiveness of this interferometer, several experiments have been conducted. A 12-bit D/A converter, with a 0-10V voltage output, drives another piezoelectric translator, PZT2, to move the sample. One of the measurement results is shown in Figure 3, in which PZT2 moves the sample in a saw-wave form with amplitude of about 8.5nm.

The dual beam polarisation laser interferometer can be used for accurate high-speed measurement of small displacements, vibration, and disk flying height. Theoretically, a 12-bit A/D converter can provide a measurement resolution higher than $\lambda/4,096$. However, because of the system noise, especially the electrical noise, the system in its present configuration has a general measurement resolution of about 0.5nm. The dual beam polarisation interferometer in its first version has been demonstrated to work effectively in our application. However, there are a number of issues to be addressed in order to realise its true potential. The interferometer will be developed from its present state to include a frequency stable He-Ne laser and the interferometer itself will be made to be compact and from thermally stable materials (invar as opposed to aluminium). These improvements will significantly improve the signal-to-noise ratio available, enabling more precise measurements of small displacements to be made. Choosing a higher sampling rate A/D board can also increase the system's measurement bandwidth.

D. CD-ROM optics

The interaction between the read-write head and the disc surface causes the flying height of the head above the surface to change, and so the dynamic morphology of the rotating disk(s) is extremely important. As the head moves outside its operating margin data-transfer becomes a problem, eventually leading to data-transfer error, as shown in Figure 4. As the disk (aluminium-magnesium, coated with a thin magnetic layer and thin lubrication layer) rotates at speeds of up to 10,000rpm the disk flexes radially and circumferentially and the CD-ROM optics will be utilised to measure these rotation-induced effects.

A CD-ROM drive utilises a laser with photodiodes to read data from the disk. The photo detector comprises four sensors and when the disk is perfectly focused the laser spot reflected off the disk will be centrally placed on the four sensors. The spot will then move either left or right to cover one pair of spots depending on the distance of the disk.

Figure 3 Measurement result for displacement amplitude of about 8.5nm

![Figure 3](image)

Figure 4 Effect of vibration on disk drive operations: 3.5” hard disk

![Figure 4](image)
The CD head is mounted to a micrometer controlled sliding table and aligned so as to reflect off of a typical hard disk drive disk. In normal operation two of the segments are summed and the difference from the other two segments is compared, to yield a signal four times greater than that observed from just the one segment.

Using an oscilloscope to monitor the signal on one of the photodiodes it was recorded that a peak voltage of 30mV was measured when the lens was 2.80mm away from the disks’ surface. The response from the detectors is linear with distance, with a change of ± 0.2mm yielding a change in output of ± 20mV, a response therefore of 0.1mV/μm. After signal conditioning, the response becomes 0.4mV/μm. Work in this area is part of ongoing research.

**E. Piezoelectric sensors**

An alternative means of characterising hard disk flutter is to use a thick film piezoelectric sensor, in this case polyvinylidene di-fluoride (PVdF). The sensor, in the form of a 110μm sheet, was used as a cantilever. When a piezoelectric material is deformed the potential difference across its electrodes is proportional to the average induced strain. The fixed end of the sensor was bonded to the drive’s chassis such that the cantilever is pre-tensioned against the disk. Any movement of the disk would therefore bend the cantilever from its static position. Because the cantilever is pre-tensioned, when the disk is static there is always a DC voltage. If the disc causes the cantilever to move from its static position there will be a change in the cantilever’s induced stress; the output voltage will increase as the strain increases and vice-versa. The end of the cantilever rests on the edge of the disk to sense maximum displacement. Figure 5 shows the results obtained using this sensor arrangement, for a 3.5" hard disk drive rotating at 4,500rpm. The first peak (at 75Hz) corresponds to disk rotation (disk clamping and spindle bearing), the second peak at around 500Hz corresponds to disk flutter, as predicted by finite element analysis, and the peaks at higher frequencies are attributed to disk-suspension arm interaction.

**F. Hard disk drive control system**

It is appropriate now to look at the control system that is being developed for active control of the read-write head for both track following and flying height[20]. Current hard disk drives utilise a voice coil motor for positioning the head with respect to the data tracks, and design the head suspension system such that air flow, due to the rapidly rotating disk, “lifts” the head to the desired height above the disk surface. The system developed in the CRIST laboratory will still use the voice coil motor for coarse track following, but fine positioning and flying height control will be affected using piezoelectric stack actuators, as shown in Plate 6. Stack actuators offer advantages of useful actuation at low voltage (< 3V) and wide bandwidth operation.

The attitude of the head is monitored using optical beam deflection (OBD), whereby a laser beam is deflected by a small mirror above “the head” on to a position sensing quadrant photodetector, capable of simultaneously measuring displacements in the horizontal and vertical planes. The output of the detector, which is linear for small displacements, and has spatial resolution comparable with interferometers (i.e. sub nm), is applied to the DSP implemented proportional integral and derivative (PID) controller for real time active control of the head suspension system. The suspension arm is set into resonance by applying bursts of band-limited white noise to the piezoelectric stacks and the resonant modes are sensed.
optically, for both data tracking and flying height control. However, actuation in one plane can induce resonance effects in the orthogonal plane, and vice versa.

Modified PID controllers have been implemented to control and position the suspension arm with adequate bandwidth and stability. Bode plots show that the PID servo system’s control loop for the tracking stage can be closed with a 25.6kHz gain cross-over frequency and phase and gain margins of 54° and infinity respectively. The flying height control stage is closed with a gain cross-over frequency of 2.33kHz and phase and gain margins of 51° and infinity respectively. Figure 6 shows the experimental open loop response and the theoretical closed loop response for track following, with the response for the flying height control similar to that for track following.

In an actual hard disk drive, position sensing would be achieved via the read/write head for flying height and from the tracking servo for track positioning. If data are read back from the disk, then according to the Wallace spacing loss equation[21], the amplitude of the read-back signal will be modulated by the spacing variations between the head and the disk due to the surface irregularities of the disk. The read-back signal from the magnetic head reflects the surface topography of the disk, and will provide a feedback signal for the control system.

Conclusion

In the CRIST laboratory a number of sensor systems have been developed for the characterisation of magnetic media and data storage systems. An SLM, with dynamic read-write capability, and an MFM have principally been developed for the characterisation of magnetic and magneto-optical thin films. By utilising the intensity imaging mode, the SLM is able to characterise the surface reflectivity with a spatial resolution of around 1μm. The MFM operates with the probe at constant height and so a prerequisite is that the surface topography is known. This is determined from a pre-imaging scan in AFM mode, whereby the probe tip is brought into contact with a sample surface, and raster scanned across it. The resultant deflection of the tip is recorded and used to create an image of the surface topography. The dual beam interferometer, for measuring head flying height, is so far able to measure dynamic surface topography of a rotating hard disk, with sub-nanometre resolution. Current instrument development is focused towards the simultaneous measurement of the head position, to realise the determination of its actual height above the disk surface in real time.

In parallel with this is work on the dynamic characterisation of disk drives for ruggedised operations, such as in seismic data logging. Two experimental systems have been

Plate 6 Suspension arm incorporating stack actuators for simultaneous head positioning and flying height control

Figure 6 Open and closed loop response for track positioning

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<tr>
<th>Simulated closed-loop response to unit step input (tracking)</th>
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<tr>
<td>Response (arb)</td>
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<td>0  0.2  0.4  0.6  0.8  1.0  1.2  1.4</td>
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<td>time (ms)</td>
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<td>0  5  10  15</td>
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<td>Experimental open-loop response (tracking)</td>
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developed for this based on CD-ROM optics and thick film piezoelectric sensors to measure the topography of the rotating disk drive under hostile operating conditions. Measurements of data-transfer to and from the disk will be used to further the understanding of data-transfer failure mechanisms under hostile operating conditions.

Operation of hard disk drives relies on the head-to-disk flying height being maintained at a constant height. A sensor-controller-actuator system has been developed to enable both the flying height and the track position to be maintained. Optical sensing is used at present to determine the attitude of the head and the response used to drive two independent actuators via a DSP implemented PID controller. Future developments of this system will include the replacement of the optical sensor by a direct measurement of the head’s position from the actual head readout signal itself. This will form the basis of a realisable system that will be developed commercially in partnership with our collaborators, the Data Storage Institute, Singapore.

References