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1996년도 나노 테크놀로지 Survey

Nano-technology Survey (1996)

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ABSTRACT

The purpose of the survey is to identify possible new areas of research relating to nanotechnology and in particular areas in which the established facilities of the Centre for Metrology can be employed to good effect.

This survey indicates that nanotechnology, a sub set of the more embracing Nano Science, is a rapidly developing discipline with good potential for Electronic and Mechanical Engineering. Nanotechnology includes three areas: Nanometrology, Nanometer positioning and Control, and Nanomanufacturing. In each of the areas, the current research situation and developing trends have been summarised. Possibilities for future work are indicated.

INTRODUCTION

The term nanotechnology was probably first introduced by Taniguchi(1) in 1983 but a more accurate and widely accepted definition was given by Mckeown(2) in 1986 who defined it as the technology where dimensions and tolerance in the range of 0.1 nm to 100 nm(from the size of an atom to the wavelength of light) are crucial. This definition is too all-embracing to be of practical value because it could include, for example, atomic physics and indeed the whole of chemistry. Yashida(8) divides nanotechnology into two categories, one is the nanostructure-structure technology of such molecular elements, and the other is nanoprecision technology. This later category is of more interest. Franks(3) has narrowed down the field covered by nanotechnology to manipulation and machining within the dimensional range, defined above by modern nanotechnological processes.

Taniguchi(1) presented a graph of Achievable Machining Accuracy for precision manufacturing covering most of the twentieth century. Machining capability at the nanometer level was predicted over a decade ago and these predictions have rapidly been proved correct.

Since the nanotechnology has developed very rapidly and has been recognised as being essential for the production of many new high technology products. It is of importance to the mechanical, electronic and optical industries with products including nanoelectronics, optical discs, disc reading heads, precision translation stages, fine

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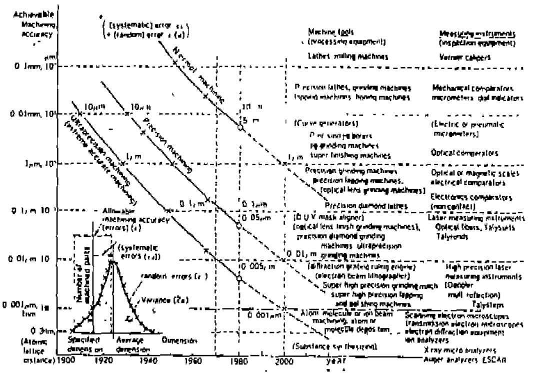

Fig. 1 The Developments of Achievalble "Machining" Accuracy (Taniguchi, 1983)

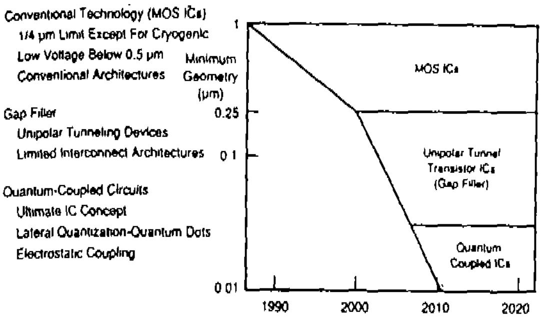

Fig. 2 Potential Scenario for Non-cryogenic Integrated Circuit Technology [Bate 1990]

powder technology, molecular computers, molecular bearings, atomic switches and the fabrication of new materials. A good example is the application of nanotechnology in "nanoelectronics". Bate$^{(4)}$ considers that the scaling of conventional IC technology below 0.1 μm minimum geometries will never be practical except in cryogenic modes of operation. Commercial and technical interest leads to the development of a revolutionary approach to IC technology, i.e. "nanoelectronics" which is based on the devices in the physicist defined "quantum regime" and will permit down-scaling of minimum geometries to continue well below 0.1μm (Fig.2). Such devices will have fabrication tolerance requirements as small as sub-nanometers. This is clearly achievable.

In order that manufacturing can be successfully accomplished in this domain, new instruments are required which will have near-atomic resolution$^{(5)}$. It is necessary to manipulate and control elements on a scale sufficiently small to involve operations with individual atoms and molecules$^{(6)}$, and serves as a significant engineering challenge for this decade$^{(1)}$.

In Japan, the importance of nanotechnology has been recognised and can be judged by the fact that the government has founded the Yoshida Nano-Mechanism Project, which is part of the ERATO programme and has allocated US $12 million$^{(8)}$ to the activity. This is a forward-looking project in which research and development is being undertaken by a powerful combination of industry, university, foreign guest research workers and even foreign institutions. The project is being carried out by three groups: The basic analysis group, the measurement and control group and the Processing group. They are concentrated on the techniques acquired in building the instruments and the understanding derived from use of these instruments in the nanometer region.

In the UK in order to initiate a national programme in support of nanotechnology, a consultative meeting was held towards the end of 1986, entitled "Nanotechnology-opportunities for the future"$^{(9)}$. A strategy committee has been formed to oversee the development of the initiatives and to advise on priorities.

Further support has been provided through the provision of funds under the government's LINK scheme, which aims to promote the exploitation by UK industry of advances in both science and technology. NPL, the National Physical Laboratory, with its wide experience of nanotechnology, co-ordinates this work on behalf of the Department of Trade and Industry$^{(9)}$. Nanotechnology has received £6 million government funds over a four year period, which is expected to rise to

£10million. As a result of study by the Strategy Committee it soon became evident that core areas of current and foreseeable industrial significance are as follows:

- The technology of positioning and control to nanometer accuracy
- Ultra-precision machining by refining conventional mechanical methods and the newer energy beam machining technique
- Nanometer metrology
- Nanometer fabrication

The need for, and the potential of nanotechnology has also been recognised by major corporations, research laboratories, and some universities and as a consequence, the field has expanded in scope.

Based on Franks' definition of nanotechnology, this report will be an attempt to highlight some efforts related to a nano science laboratory conditions and instruments in following three areas:

-Nanometrology

-Nanometer Positioning and Control

-Nanomanufacturing

Nanometer fabriaction is outside the scope of this survey

NANOMETROLOGY

Many of the developments in nanotechnology depend for successful application upon ability accurately to measure minute displacements. Hocken(7) explained that for many years the common gauge-maker's rule of ten applied, i.e. the measurement accuracy must be better than the desired manufacturing tolerance by a factor of ten. In recent years, this has been relaxed to a factor of four, primarily because of the inability of the metrologist to reach the requisite accuracy at this juncture. It is believed however, that when measurement accuracy aided by the provision of special measuring environments, the factor will be increased to six.

Length standard

Kunzmann(10) attempted to discuss what he considered to be the major tasks in dimensional metrology. They are:

-Realisation of the unit of length or angle.

-Measurement of translation of rotation.

-Transfer of measurands from the reference system to the test piece.

He also pointed out that the best definition of the unit of length is given by the vacuum wavelength of the Iodine Stabilised HeNe laser ($\lambda_0=0.633\mu$m)with a relative accuracy of $\mu/\lambda_0=10^{-10}$

Hocken(7) pointed out that the problem of using HeNe laser for length standards is related to the value of the periodicity which can be used for counting purposes, namely, the wavelength of visible red light which is around 633 nm. For achieving the high precision required for the devices of the future, i.e. say 0.1 nm, involved in conventional interferometric terms, splitting a fringe into many thousand parts. Such interpolation is "error prone" and often requires averaging, inferring considerable processing time. what is needed is a well-defined scale whose basic periodicity is many times smaller than that of visible light. Teague(11) considered two alternatives, i.e. X-ray interferometer and a frequency-tracking Febray-Perot interferometer.

X-ray interferometry was first proposed and developed by Bones and Hart(12). Such instruments use the Silicon lattice, a highly stable artefact, to provide grating spacings and have periodicities(13), the X-ray interferometer, due to its "picometric sensitivity" and its very direct and extremely well defined traceability to the length standard, has been successfully used for calibration of displacement interferometers at nanometer and smaller scales at the University of Warwick.(14)

The disadvantage of such a instrument are that the bandwidth is very small with practical X-ray sources and therefore does not compete directly with the other sensors.

A more attractive alternative is the frequency-tracking Febray-Perot interferometer. Such instruments have been in use for some years for measuring the stability of materials(16). The problem with these devices is again the dynamic range, in that, as the cavity length is altered the frequency of the laser must by changed to maintain cavity resonance in order to measure the cavity length change in the frequency domain. A typical HeNe laser may be swept for about 800 MHz which, depending on cavity length, corresponds to only 16 nm for a 1 cm Febray-Perot interferometer(11).

Laser displacement measurement interferometers

Laser displacement measuring interferometers are very useful for nanometer level machining or measurement since no other instrument has such a wide dynamic range and such a high displacement measurement resolution(17). In recent years, much research has been carried out in the analysis and in the improvement of measurement accuracy of laser interferometers. The frequency of the H_eN_e laser can be stabilised to significantly better than 1 part of 10^8 and errors in frequency stabilisation are not a significant factor in measurement accuracy with this type of laser interferometer(18). Smythe(19) summarises the error sources in phase measuring interferometers (PMI). They are: illumination system, imagining system, camera system, phase modulation system, floor vibrations, and air turbulence, etc. which implies the precision of high performance nano science laboratories. Other comments are:

- System accuracy is limited by system non-linearities, the major sources of nonlinearities being phase modulation ramp, cameras and electronics.

- All interferometers contain errors in the reference wavefornt. A "perfect" test part can be measured, results stored and subtracted from any subsequent measurement. This procedure reduces the influence of the instruments inherent wavefront aberrations.

-The noise limit is determined by electronic/computational noise and environmental noise. Averaging of data will decrease the noise contribution, but not all noise sources will average successfully. Environmental noise is the largest noise component and is expensive to minimise. This is caused by floor vibrations and air turbulence. While it is often possible to average down floor vibrations, it is not necessarily so simple for air turbulence.

- PMI is mostly sensitive to vibration frequency from 5 Hz to 90 Hz. At 5 Hz vibration isolation tables are not very effective and sub-micron amplitudes at these frequencies degrade measurement.

Elstler(20) indicated that it is the refractive index of air, which depends on pressure, temperature, relative humidity and CO_2 concentration, that plays the dominant role in limiting the accuracy of measurements made with a 2-frequency laser interferometer. The Table below is taking form his paper.

Parameter	Nominal value	Change for which $\Delta n = \pm 1$ part in 10^7
Pressure	760 mmHg	+0.28 mmHg
Temperature	20.0°C	-0.1°C
Humidity	40%	-10%
CO_2 conc.	344 ppm	+6% ppm

Wyntjes (21) emphasised that temperature and pressure are the major problems. Local air turbulence and even air temperature changes due to the presence of human operatives are readily observable and contribute to measurement imprecision.

Another factor to be considered is the thermal expansion of the structure which maintains the relative positions of the interferometer cube and the moving mirror. As a consequence of these findings the University of Birmingham are developing LECCs(Local Environmental Control Cabinets) and has set in place a finite element research programe to investigate thermal expansions in complex structures.

In addition to the environmental effects, the accuracy of interferometers is limited by small non-linearities in the relationship between the phase of the beat signal and the actual displacement of the measurement-arm mirror. The non-linearities arise in two ways: one is optical in nature and involves imperfect segregation of the two laser frequencies between the arms of the interferometer. Another non-linearity arises from coupling between the post-detection and phase-measuring electronic signals and the photodiode in the receiver. Hosoe (17) indicated that stray reflections from the optical surface also produce a non-linear interference signal and a consequent loss of precision.

Many interferometric systems employ polarisation technologies to derive the electrical signals required for reversible fringe-counting from their optical outputs. These signals should be in phase quadrature, equal in amplitude and have zero mean DC levels. In practice the signals are not ideal and when resolving to sub-nanometer precision. These imperfections imposing a limit on the accuracy achievable by the interferometer system(22).

The most rewarding efforts of improving the accuracy of interferometers are concentrated on reducing environment errors and improving the linearity by improving the structure of interferometers or by introducing computing compensation.

Wynjes(21) suggested that in many instances, particularly where there is a long dead path(i.e. air path in the interferometer within which no measurements are made), temperature is measured at many points along the air path in order to achieve high measurement precision. Temperature and pressure corrections may be made manually or automatically, using an electronic "weather station" which is coupled to the data processor. Where extreme precision is needed it is even necessary to take into account pressure variations with vertical height if the optical path is not horizontal.

The common method of calculating a value of the refractive index of air is based upon Elden's equation (1996) using suitable sensors to take precision measurements of atmospheric pressure, temperature and humidity. Recently, an interference refractometer has been developed in NPL for direct measurement of the air refractive index and a comparison between the calculated and measured values has been reported by NPL. The results of the comparison have shown that where an uncertainty of the order of ± 1 part in 10^7 is acceptable in the refractive index of air, a calculated value may be employed. This source of uncertainty is reduced to approaching ± 1 part in 10^8 when a refractometer is used(23). The infractometer developed in NPL adopts the technique of scanning the optical path in the interferometer through at least one fringe and examining the phases, amplitudes and DC level of the signal to correct systems electronically for non-ideal optical signals. In this way the instrument achieved a measurement linearity in optical path length of 0.1 nm(22). In the same paper it also reported that with a laser source strong reflections are coherently linked to the interferogramm and even one tenth of one per cent of the beam energy can cause an anomalous variation in the interferometer signals and a nonlinearity error of 1.6 nm in the optical path length measured.

It is standard practice to minimise the effects of stray reflections from the nonbeam splitting surface by either employing a standard anti reflection coating on the surface or by slightly wedging the beam splitter plate. The latter practice is the most efficient and tilts the wavefront of any stray reflections that reach the photodetectors. This also makes the alignment procedure extremely difficult. NPL have designed a beam splitter and compensator plate for a two-beam interferometer which would maintain the accuracy of the instrument when resolving with sub-nanometric sensitivity and in addition, facilitates the alignment of the optical and mechanical axes of the measurement system(22).

As one of the activities of the Yoshida Nano-Mechanism Project, in order to eliminate air-turbulence-induced errors, an interferometer with two different laser beams using second harmonic generation has been developed(24). The main feature of the interferometer is that one of the two beams is far more ultraviolet with the difference between the refractive indices of air of the two beams becomes large resulting in less sensitivity to any errors due to refractive indices of air.

A new laser interferometer system has been developed at KONICA Corporation, Japan(25). The new system has a simplified optical layout, fewer optical elements, and a shortened optical path. As a result, thermal drift and non-linearity of the displacement measurement have been decreased in both the bi-frequency heterodyne system and the fringe-counting system. The system achieved subnanometer resolution(0.6 nm/LSB); high stability (2.5 nm/day); high linearity(less than 1 LSB); and high following speed(More than 1000 mm s^{-1}).

Using a 45 degree inclined quartz plate along the optical axis, a complete differential optical layout of an interferometer without any dead path was developed with reduced and smaller optical elements and fewer air boundaries(26). As a result, sub-nanometer stability an displacement measurement precision were achieved despite fluctuation of the local temperature in the measurement region.

Optical coupling can be introduced when the laser output is injected into the interferometer. Much of this initial coupling is a consequence of imperfect orthogonality in the polarisation states of the two laser frequencies. Babroff(34) found in his experiment that a typical value for this intrinsic coupling is 0.02, causing a non-linearity of about $\lambda/600$ for a plane-mirror interferometer. To eliminate the nonlinearity, a system is used to uncouple the two frequencies. In this system, the laser output is separated into two arms by a non-polarising beam splitter. Each arm consists of a $\lambda/4$ plate, a Glan-Taylar polarisor, and a $\lambda/2$ plate. The linearised beams emerging from each arm are recombined in a polarising beam splitter. The combined beam is then sent to the interferometer. By an interactive procedure, the optics are adjusted to simultaneously eliminate "beating" in each individual arm of the interferometer and also to eliminate all amplitude modulation in the beat signal when both arms are open. As a result, the residual non-linearity was typically less than $\lambda/1200$ and could be made as small as $\lambda/2400$

Heydemann(27) pointed out that phase shift errors, zero offset and gain differences may be found in most quadrature detectors. They may seriously affect the performance of the interferometer with which they are associated by increasing demodulation errors. Based on both theoretical analysis and experiments, a method has been proposed to determine the quadrature detector errors from experimental data and this makes suitable mathematical correction easily.

Oldham(28) reported that their experimental measurements show electronic limitation imposed by the phase measurement corresponds to timing errors of about 350 ps (±0.25% at 2 MHz) which will limit the precision of a simple Michelson interferometer to about 1/3000th of a wavelength at a reference signal frequency of 2 MHz.

Surface topography

Surface topography embraces surface form, waviness and roughness. Franks(29) indicated that the requirement of X-ray optics provided an important early stimulant for the development of instruments having dimensional measuring capabilities down to the 0.1 nm level. For measuring machines developed with measuring sensitivities meeting these requirements, the question arises as to exactly what it is that these instruments measure. In all cases there are both geometrical and physical interactions between the measuring instruments and the object being measured. With an inhomogeneous specimen a mechanical probe (AFM) will respond to both the topography and changes in the mechanical properties of the surface; an optical probe to topography and reflectivities of a surface; and an STM to topography and electronic properties of a surface.

NPL(29) have proposed that amplitude-wavelength (A-W) mapping is used to describe and interpret the performance specifications of measuring machines. On the map a fuzzy boundary is quantified by contours which represent measuring uncertainties, indicating weak and strong specimen-probe interaction areas. Franks(29) discussed the instruments developed at NPL, including mechanical probes, stylus laser profilometers, laser autocollimation profilometers and surface roughness polarisation interferometers, together with their A-W maps. It was concluded that the development of instruments for amplitude measurements of 1 nm and surface wavelength of 1 m will provide a challenging task for the metrology of the 90s as well as the early 2000s.

There are a number of factors that affect the surface profile obtained from mechanical stylus methods, such as the edge radius of the stylus, measuring force, dynamic characteristics of the instruments, etc. The non-contact measurements, such as an optical method, do not guarantee a profile or surface roughness measurement close to the real one because of their intrinsic limitations. Pariculary, in considering ultraprecision machined surfaces, the resolution in machining and that in measuring are so close that outputs from measuring instruments can hardly be relied upon. Therefore, much research has been done on comparing stylus and optical methods for measurement(31-33).

Horio(30) made a comparison of the scatter in surface roughness measurements obtained from various instruments including both stylus and optical types. He found that the value obtained by optical methods are apt to be greater than those obtained by stylus methods, and R_a or R_{rms} are more suitable for representing the surface roughness of ultraprecision machined surfaces than R_{max}. More recently work by Stout(35) suggests that S_a, S_q or S_{max} are even vore appropriate.

Creath(36) from WYKO Corporation discussed the limits of what is measurable using an optical profiler and how they may be extended. He indicated that the smallest feature measurable is twice the detector sampling spacing and suggested the use of a white light source with which the interferometer can be set up such that fringes will only be present when the surface under test is in focus thus simplifying the alignment. The ultimate measurement limit depends upon whether light reflected or scattered, off the test surface returns through the microscope objective. The limit of roughness measurement can be improved by using a multiple-wavelength technique(37), which will also increase the vertical measurement range of an optical profiler(38).

At the University of Birmingham the effect of digital operating variables, such as sample spacing and sample size, upon the measurement variation of surface profile has been investigated experimentally and analytically(35).

Many non-contact surface measurement methods, especially optical methods with lasers have been applied for "on-machine measurement" of the surface profile(39 40). However, with present methods it is necessary to set the specimens on the instruments and measuring ranges are very small, because their laser beams from the source are directed to the interferometers and detectors by prisms and mirrors. To improve this, Sakaya(41) employed a technique for the on-machine measurement of surface profiles using optical fibres and attained a vertical sensitivity of 10 nm and very large measurable height compared with other non-contact optical methods.

Laser beam straightness reference

The most accurate diamond turning machines use physical straightness references. These references are commonly made of optical materials, such as Zerodur(temperature insensitive material), and are flat enough to permit straightness measurement with an accuracy of 100~150 nm p-v. The straight edges for the large optical diamond turning machine at LLNL are 1.1 meters in length and allow a straightness of 25~50 nm p-v after calibration.

Recent developments(42) suggest that the use of a laser beam for a reference may be feasible. There are numerous techniques of creating a straight line reference system by means of laser(43 44). Workers at Osaka University has reported a laser beam straightness reference that has a resolution of 3.5 nm, although tests were limited to a 200 nm lenght. LLNL(45) developed a laser beam straightness reference using the diffraction pattern formed behind an opaque sphere illuminated by a plane wave to operate over a 4 meter range(46). With this device, the active mirror, sphere, Poisson line, pickoff assembly and position sensor are located in a vacuum. The initial experiments operating over a 56 cm path in air provide resolutions as low as 2 nm with a laser and quadrant detector.

Scanning Tunnelling Microscope(STM)

Until the advent of the STM, nanometric measurements of surface topography presented a very unbalanced picture of the surface because of the great disparity in the amplitude and surface wavelength resolution(29). In the instruments referred to the amplitude resolutions may be more than two orders of magnitude greater than this. The A-W map of an STM has been calculated for tip radii of 0.5 nm and flank angles of 54° in NPL(29). From the map it is clear that STM has considerable potential, for application to metrology, thus, opening up important areas of mapping that had hitherto been outside the measurement range.

STMs are already well known for the ability to image surface structures of conductive or semiconductive samples down to the atomic scale.

In nanometrology, recent research based on STM, has concentrated on imaging the extent of structural features of the surface. It also should be emphasised that very shortly after the development of STM, researchers are more interested in using STM, not only for observation but for the surface modification of the observed atoms or molecules(7). Therefore, much of the recent published work related to combining the electronic measuring capability of STM with its ability to produce structural change of surface. This area will continue to yield significant advances over the next decade.

Although the STM was originally developed for use in very high vacuum(VHU), condition scanning in air has become more commonplace in recent years as it is the normal environment for many surfaces which are under investigation. To date most STM work in air has been carried out on gold(47-49) and graphite surfaces(50,51), the former because gold is very inert to surface contamination, such as oxidation, and the latter because of its extreme flatness allowing fast scanning and high resolution. STM is also used to image the surface of various other materials, such as semiconductors(52,53), polymer films(54 55), oxide films(56), etc.

Morelance(55) has used an STM to record and image magnetic regions on the surface of a hard disc. As a result, tunnelling images were combinations of the surface topography and variation in the magnetic force between the Fe film tip and the disc surface. The best magnetic image resolution achieved was 20 nm. Wiesendanger(57) demonstrated that STM can also be a highly useful tool in the study of the topography and surface structure of magnetic materials down to the atomic level.

For STM imaging, the sample preparation, the tip material and the structure and dimensions of the tip are very important and will have a strong effect upon the results. Akama(58) has reported that a new STM tip fabricated by electro beam deposition(EBD) was not only fabricated on an atomic scale, but also had a capability for correctly imaging deeply structured patterns. It is impossible to measure sidewall roughness, even using an EBD tip, because the tip may not achieve good interaction with the sidewall surface through the tunnelling current. Shinji(59) has successfully achieved sidewall roughness measurement using a branched EBD tip which has a flat surface part and a sidewall part, together with an improved two-dimensional servo system.

It is recognised that during the imaging process, an STM can apply a considerable distortion force to a surface, which in the extreme case may distort the sample. Robert(5) demonstrated the controlled low-resistance damage and the high-voltage damage on various surfaces. The high-voltage surface damage can be utilised for surface modification, whereas the low-resistance surface damage complicates the interpretation of STM images. Also there are a number of effects that arise in STM images of surface, such as giant corrugation(60) and anomalous work functions(61) for which several very different mechanisms have been proposed(62 63), suggesting that some features of the imaging of surfaces are still not fully understood. At the very least these effects, as well as the presence of multiple tips(64), can complicate the interpretation of STM images. Emchy(47) suggested that it would be valuable to be able to study molecules on the several different substrates.

NANOMETER POSITIONING AND CONTROL

One of the technical keys in the expansion of nanometer-scale measurement and processing technologies in industry is by designing and building mechanisms capable accurately positioning tools or components on this scale.

Positioning fabricated components

Positioning fabricated components on a nanometer scale demands the development of linear coordinate motion tables capable of operating over a large displacement with nanometer positioning accuracy and with a fast dynamic response. The development of such devices is an important topic and areas of interest are the mechanism structures, actuators and sensors as well as control strategies. Among these, the behaviour of mechanical parts in the nanometer range is most important(8).

Structural mechanism

One of the projects of the Yoshida Nano-Mechanism Project was the development of a single mechanism with a positioning accuracy of 1 nm. This uses an actuator with a newly design AC synchronous linear motor and a rolling ball guide that has a resolution of 1 nm and a maximum speed of 200 mm s^{-1}(8). The research has indicated that the balls of the guide have special properties comparable to spring characteristics for nanometer positioning.

Kanai(65) reported that a 150kg carriage hydrostatically supported in the vertical direction and supported by bearing guideways in the horizontal direction and with a feed resolution of 1 nm or less has been developed. Very low stick-slip effects at approximately 100 nm/step are recorded.

Non-linearities in the slideway motion has become a topic of much interest. Cuttino(66) has shown that while a preloaded ball-screw can be used for nanometer resolution actuation; the response is not linear. The on-linearity has been shown to be a consequence of elastic windup in the screw and deformation at the ball contacts. A mathematical model is provided which predicts the friction and displacement as a function of input angle. The model serves as the basis of development of a control strategy to operate over a range of displacement commands.

For an ultraprecision grinding machine, at Ashikage University(67), a 200 kg carriage on plain bearing guideways has been successfully positioned to nanometer accuracy with a force operated linear actuator. The plain bearing guideways are used as a means of improving dynamic stiffness in the high frequency range and the force operated hydraulic linear actuator is used as a means of overcoming the resulting stickslip phenomena due to frictional loading of plain bearing and the compliance of the driving unit to improve feed resolution. The test results showed a feed resolution of 1 nm/step and a stiffness of more than 10 N nm^{-1}.

Otsuka(68) clarified the characteristics of three kinds of precise lead screws in the very short stroke range (0.1 μm) for nanometer level positioning. He concluded that the sliding motion exhibits stick-slip between the screw and nut; and that the ball screw behaves elastically. Overall the roller ball screw provides a nanometer positioning performance in spite of its large variation in friction torque.

Nomura(69) reported that a compact, low-height prototype of a six-axis precise positioning stage for micro fabrication has been developed. The X and Y axes have nanometer positioning resolution. The stiffness and dead band of the mechanism were improved by using rolling contact guides and the positioning resolution was improved by using a friction drive mechanism.

The relationship between rolling friction is nonlinear(70,71) and the rolling friction forms an hysteresis loop in the region where the effect of rolling begins(70). The effect of rolling friction on fine stage positioning and the methods of improving accuracy have been studied widely(68~69,72~74).

Futami(73) has studied the micro-dynamics of the rolling guide for a one-axis stage mechanism. The results show the force-to-displacement relationship is non-linear spring element and normal rolling element respectively.

Although the contact elastic deformation and friction result in non-linearities, until now most mechanisms for nanometer level positioning have employed rolling or sliding contact guides. Contactless guides, such as an air bearing which is free from friction and elastic deformation, are not used since high frequency vibration with amplitudes greater than several nanometers can occur. This is due to air turbulence and a precision nanometer range velocity sensor is not available for stabilisation(73). Recently, Shomokohbe(74) proposed a thrust active air bearing with an ultraprecision, infinite static stiffness and high vibration damping capability. In this mechanism, a non-contact sensor detects the relative position of an objective mass with respect to a reference. A controller and an actuator position the mass so that it follows the reference using the sensor outputs as the feedback signal. Possibly the best opportunity for nanometer resolution air bearing slideways is to extend the design procedures developed by Stout(75), which have been successfully applied by diamond turning machine manufacturers, both in the US and UK. A new procedure is currently being developed.

Control strategy

All nanometer positioning mechanisms operate in a close-loop control mode. To achieve a large displacement and nanometer accuracy positioning, most employ a control strategy based upon a combination of a coarse and a fine control action, whether driven by a single actuator or two actuators.

Shintaku(76) reported a positioning control with better than 1 nm steady state fluctuation and an 80 mm stroke. In this study, a single hydraulic cylinder was used as an actuator, with a coarse and fine positioning control. The elastic properties of a rubber-seal ring were utilised in the final positioning.

Futami(73) reported that a one axis stage driven by a single AC linear motor with long stroke, high velocity and nanometer positioning accuracy has been developed providing coarse and fine positioning control. The 100 nm resolution, 200 mm s^{-1} maximum velocity and 250 mm stroke were achieved by the coarse positioning mode. A resolution better than 1 nm was achieved by the fine positioning mode.

A friction drive six-axis positioning stage has been developed(69). The position controller for X and Y stages is given three control modes; a positioning mode for the low-gain range when the deviation is within 100 nm; a positioning mode for the high-gain range when the deviation is greater than 100 nm; and a traversing mode for fast movement. In this way, 1.25 nm resolution is attained.

Standard feedback control schemes, such as proportional control, PID, PD control, etc. are employed to control some nanometer positioning mechanisms successfully. The six-axis stage with nanometer positioning(69) is controlled by a PID position controller. In Futami's stage with better than 1 nm resolution, the coarse control is a combination of the proportional position control and proportional-integral velocity control, with an integral position control for fine position control(73).

Although standard feedback control schemes can improve positioning accuracy, the dynamics of lead screws at the nanometer positioning level are non-linear and advanced control design techniques are necessary to obtain further improvement in accuracy.

Hubbel(72) proposed a model reference adaptive control for a ball-screw driven precision slide. This control scheme includes a reference model which generates an ideal response and adaptive laws for adjusting variable parameters to ensure that the plant output follow the reference model output regardless unknown plant parameters. Experiments have shown that the model reference adaptive control scheme to be more robust with respect to the non-linear dynamics than a PI scheme.

Otsuka(68) studied nanometer level positioning using three kinds of precise lead screws. His study indicated that by conventional proportional control, a large position deviation error is caused from the quantification of a proportional gain and D/A converter. However, with "bit" control the deviation error can be reduced to below 2.5 nm.

For position measurement, laser interferometers(68 77) and capacitive sensors(73,77) are widely used. However, the laser interferometer requires a relatively large space which is not compatible with a compact unit design. Nomura(69) reported that by employing a phase division technique, the displacement can be detected with a resolution of 1.25 nm using a 10 ㎛ pitch optical linear scale. Compared with laser interferometers, an optical linear scale has the advantage of robustness with respect to air turbulence and offers compactness due to the small number of parts.

Actuators

The piezoelectric transducer is the most widely used actuator in nanometer level positioning(74,78,79) due to its extremely fine position change i the nm range, no moving parts, large force fast expansion and high efficiency. A commercial(X, Y, Z) piezo transducer macro-stage has been applied to expand the image range of a STM(80). The STM is limited in image range to a few tens of microns. In this study, the image range of a STM is expanded up to 150-150 ㎛, with the possibility of atomic resolution. The basis of the design is the use of a series of pivoted lever arms to amplify to motion of piezo actuators.

Although a piezo transducer is a suitable actuator for nanometer level positioning, it has a short travel of only several tons of microns. For a wide positioning range, either the motion of the piezo transducer needs to be amplified by a displacement amplifier, i.e. a hybrid design(78,80), or a piezo transducer should be used in combination with a coarse actuator(69).

Although a combination of a coarse actuator and a piezo actuator is effective for a wide positioning range, a coarse actuator with sufficient stiffness is relatively large and such a combination may not meet the requirements for compact design.

Many hybrid design piezotranslators can have a travel of up to 1 mm with solid state joint(bending zones), which as elastic centres of turning joints, pass on small changes in the angle without any play (81). There are a number of problems limiting the applications of such hybrid design piezo translators in nanometer positioning. They are:

- The dynamic response is mainly dependent upon the stiffness of the mechanical system. An increase in the stiffness will cause a decrease in the displacement of the actuator.
- For large displacement amplification, multi-linkage mechanisms are needed which complicate the structure and increases the size of the actuator. Such a mechanism may not meet the requirements for a compact design.
- The positioning surface executes a tilting angle which will reduce the positioning accuracy or needs a more complicated control.

Therefore, there is a potential need for the development of other types of displacement amplifier, such as an hydro-static amplifier for use with piezo transducers.

There are many other types of actuators used in nanometer positioning, such as DC servo motors(68), force operated hydraulic linear actuators(65,67), AC motors(69), friction drive(69), etc. Recently, more interest has focused upon the use of contactless direct drive methods to simplify the structure and eliminate the friction force. AC moving-magnet-type linear motors(73) and magnetic suspension linear motors(77) have been used successfully.

Positioning microscope tools

In this area, the survey only consults STM.

Piezo transducers are commonly used as actuators for STM. They provide a simple way to convert electrical voltage signals into movements of a fraction of an Angstrom to microns. In a conventional STM, only a Z-piezo actuator is controlled by the feedback tunnelling curent to move the tip in Z direction and both the X and Y piezo actuators are driven in open-loop control mode for sample scanning. For scanning, a one to one relation between the applied voltage and the movement of the piezo actuator is desirable. Positional stability of the tip is also important. It is desirable that the positioning error is constant with defined limits of accuracy and without drift.

Hysteresis and time dependent creep are undesirable characteristics common to all piezo actuators. Hysteresis will cause a tip positioning error. This error can be eliminated by taking measurements only when the voltage is increasing or decreasing, but the measuring time is wasted. Creep shows up as drift in the STM tip position.

Newcomb(82) found that if the extension of a piezo actuator is plotted as a function of applied charge rather than applied voltage, hysteresis and creep virtually disappear and the characteristic becomes much more linear. Based upon this, control of the piezo movement by controlling the applied charge (charge control) instead of applied voltage has been proposed as a way to reduce hysteresis and creep(82). Unfortunately, the proposed charge control method is rather complicated. In Japan, as one of the projects of the Yoshida

Nano-Mechanism Project, a simple way to implement charge control of piezo actuators has been proposed which involves inserting a capacitor in series with the piezo actuator(83). The hysteresis and creep arise from the piezo's own capacitive change during its extension. By inserting a capacitor in series, the sensitivity of the charge on the piezo in relation to the piezo capacitance is reduced resulting in a reduction of both hysteresis and creep. The price paid for this method is that of operating at higher voltage levels. It should be noticed that this method is only used to test high voltage piezo actuators in a very small voltage range. A further study should be carried on for both high voltage and low voltage piezo actuators over a larger voltage range and the understanding of the fundamental relationship between the circuit's sensitivity and reducing its hysteresis.

An important experimental advantage, which may have wide implications for the future, is a significant change in the design of the tip scanning mechanism of STM. Instead of being attached to a piezo transducer acting only in one direction, the tip is attached to a piezo tube, the end of which can be scanned in any direction by applying suitable voltages to three sets of electrodes incorporated in the tube(84). This principle has been employed to develop a long range STM with a three dimensional piezo transducer macro-stage and scanning tube. The stage provides movement of the sample(X,Y,Z) and the tube provides motion of the tip(x,y,z).

NANOMANUFACTURING

Nanomanufacturing includes single-point turning, precise grinding, optical, e-beam, ion-beam and X-ray lithography, chemical and electrochemical deposition, sputtering, etc. (7). Central to the work in molecular manipulation are two instruments: the scanning tunnelling microscope (STM) and the atomic force microscope (AFM). In this report, only some applications of STM in nanomanufacturing are highlighted.

The STM shows great promise for fabricating small features and modifying surfaces down to the level of manipulating single molecules and atoms. Many methods have been proposed in the literature for such fabrication using the STM, such as contact, increasing the STM tip bias voltage and tunnelling current, applying tip bias voltage pulse, etc. In many cases, the mechanisms are still not well understood.

The simplest way of modifying a surface is probably to bring it in direct contact with the tip. This method has been explored widely and is still an active subject of research interest. In this method a STM is treated as a micromechanical tool and various size features are created by actually contacting the tip to the surface or using the tip to "push" atoms or molecules to the desired location. This method has been successfully applied by Van de Wall on Ag(001), Abraham on a gold foil, Jacklevic on Au(11) and Gimzewski on a silver foil(85). Cord(86) demonstrated nanometer scale control of the depth of penetration of the tip into a thin insulating film, and by laterally traversing the tip to machine away submicro-wide, 20 nm thick strips of the film without damage to the substrate or tip. However, the detailed mechanism of how the tunnelling current through the film can be used to control the machining depth is still unclear. Eigler(87) reported the use of STM at low temperature to position individual xenon atoms on a single-crystal nickel surface with atomic precision. He also suggested that the tip exerts a finite force on an adsorbate atom which exhibits of both Van der Waals and electrostatic effects.

An alternative way of performing surface modification with a STM consists of raising the tunnel junction energy by increasing either the bias voltage or the tunnelling current. The resulting high electric field and high current density can induce field evaporation an/or local melting, leading to local modification of the surface. Nanometer-sized defects (pits) on the surface of $Na_{0.9}Mo_6O_{17}$, a quasi-two-dimensional conducting oxide, has been created using rapid increases in bias voltage or current and then holding for several seconds(88). Holes with a diameter of hundreds of Angstroms on the surface of a $HoBa_2Cu_3O_{7-x}$ single crystal has been created by raising the sample bias voltage and tunnelling current(89). Becker(90) reported that an atomic-scale "bit" can be written on Ge(111) surface by raising the tip to surface bias voltage to -4.0 V at quiescent tunnelling current of 20 pA while the tip remained laterally stationary over the site chosen for modification. He has not observed such a transformation on the strongly and convolutely bound Si(111) surface even though tunnelling currents were increased to several nanoamps and bias voltage as high as 20 V. However, nanometer-scale grooves have been successfully created recently on Si(111) surface by Kobayashi(91) at relatively low bias voltage level. The importance of tip preparation in achieving reproducible results is emphasised. For W tips that were not electro-bombarded, groove formation was not reproducible and often did not occur even at tip biases up to 10 V. A possible explanation is the presence of an oxide layer of several nanometer thick on the tip. The field at the sample may be substantially reduced by the presence of this dielectric film near the end of the tip. The field at the sample may be substantially reduced by the presence of this dielectric film near the end of the tip. Kobayashi suggests that the discrepancy between his results and earlier attempts(90) to modify Si(111) is attributable to tip preparation. This is a controversial hypothesis that deserves further study. Marchon(85) has produced surface modifications on the 100 Angstroms scale on an Re(100) surface passivated by a saturation monolayer of sulphur and coated with a film of oil. In this study, similar features were obtained by both methods of contact and increase bias voltage.

Recently, more interest is shown in applying bias voltage pulses for surface modification, and in trying to establish the mechanisms by which the surface modification takes place. By applying bias voltage pulses, Lyo(92) reproducibly transferred Si atoms and Si clusters of tens of atoms from the surface to the tip and to deposit them at predetermined sites on the surface. The mechanism involves a field-evaporation process using a low-threshold field that is modified by chemical and mechanical tip-sample interactions. Schimmel(93) reported on the generation of atomically resolved nanometer-size surface modifications by applying bias voltage pulses on the surface of the layered semiconductor SWe_2. His experiments show that the observed structures are generated neither by chemical deposition nor by an etching process which is further supported by the fact that writing was also possible on a freshly-cleaved surfaces under high vacuum. In his experiments, no tip changes were observed and the modified surface was preserved, such that there is no indication of a transfer of material between tip and sample. He suggests that the mechanism involved was due to the transient electrical field. By applying bias voltage pulses, hillocks(94), holes(48), bumps(95), letters and complex symbols(49) were created on the surface of gold; the fibrils of poly(octadecylacrylate) on graphite were modified and cut(54), the thin oxide films on silicon were modified(56), and "hole-hill" combinations("bits") and L-shape structure was created on highly oriented pyrolytic graphite(96).

STM has also been applied to lithographic microprocessing of amorphous materials in air(97). In this process, phase transformations were induced in the thin-film of a-Si:H on silicon by low-energy electron irradiation. Electronic characterisation of the surface before and after the phase transformation indicated a change in the local conductivity directly below the tip. Subnanometer lines were formed on these thin films by application of multiple, 10 V, 35 ㎲ voltage pulses between the tip and the sample. Nanolithography on Ⅲ-V semiconductor surfaces has been integrated with molecular beam epitaxy for the fabrication of one-and zero-dimensional quantum structures by using STM.

STM has also been used for electrochemical deposition and direct deposition. A new method for electrochemical deposition of nanometer-scale silver pillars on graphite has been described(51). These features were produced following the application of tip bias voltage pulses in dilute, aqueous silver fluoride. The bias pulse first induces formation of a bi-layer deep pit which then nucleates electrochemical silver deposition. Ehriches(98) described a method for directly depositing 10 nm metal lines on Si(111) and metal substrates. In this process, organ metallic gases were decomposed under the tip pulses to deposit these lines in a single step.

STM has been employed in recent years in attempts to develop atomic-scale electronic devices, both by examining device-like characteristics in pre-existing structures, and by creating new structures by the precise manipulation of atoms or molecules with the STM tip. Eigler(99) reported the operation of a bi-stable atomic switch that derives its function from the motion of a single xenon atom reversibly between stable positions on each of two stationary conducting "leads", corresponding to the STM tip and a nickel surface. Mo(100) reported that the STM was used to control the configuration of antimony cluster on the Si(001) surface. In particular, the STM tip induced a reversible rotation between two orthogonal orientations of individual antimony dimers on the surface. This simple rotation can be explained by an atomic-scale torque exerted on the antimony dimers by the STM tip. The reversibility of this process could provide a basis for making atomic-scale memory cells.

Sub micron manufacturing opportunities

Over the last two hundred years, manufacturing technology has advanced primarily as industry has improved its ability to measure accurately. Hence manufacture, measurement and function are inextricably linked. During this period the precision of fabrication has improved by five orders of magnitude.

The driving force to this technology is found primarily in integrated electrons as well as its support equipment. This extends into bio-engineering, physics and chemical engineering. Sub micron manufacture is an important relation and a precursor to nano science and technology. The two areas are placed in context in Figure 3.

The subject embraces:

a) ultra-precision machining processes

b) production of high purity, homogeneous materials

c) ultra precision computer numerically controlled manufacturing machines

The most significant development in sub micron manufacture are

a) single point diamond and cubic boron nitride cutting

b) multipoint abrasive cutting and burnishing(e.g. grinding)

c) free abrasive process(e.g.lapping)

d) chemical machining(e.g.corrosion and etching)

e) energy bean processes

f) a new, but potentially the most powerful, the science of engineered surfaces

The controlling influence of this technology is the design and performance of ultra precision machines and the close control of the manufacturing environment. Both are required in parallel.

The design and manufacture of ultra precision machines implies that these machines will always provide carefully controlled manufacturing conditions as a result of highly stiff low friction machines, having appropriate internal damping and with non-influencing couplings operating in a precision environment. Machines also need high resolution displacement transducers(optical gratings and laser interferometry) as well as specific control of speed achieved through electronic gearboxes.

PRODUCT OPPORTUNITIES

Typical components which require this precision are mirrors for high output carbon dioxide laser resonators, spherical bearing surfaces, infra red lenses in germanium for thermal imaging, optical scanners for laser printers, as well as elliptical and X-ray mirrors.

When machining in the ultra precision region implies very fine chips or slivers of material are removed. At these levels moveable dislocations in metal crystals approach zero, and therefore the cutting forces have to overcome the very large atomic bonding forces within individual crystals.

As legislation forces companies to minimise energy consumption and environment emissions, the drive for smaller tolerances and better surfaces increases.

For example McKeown(101) has indicated that the next generation of civil aircrafts will have to meet demands for lower pollution, higher efficiency, lower maintenance and lower running costs. In the area of turbo fans themselves, fuel consumption may drop by approximately 40 percent.

The rapid development of computers and their components again provide a drive towards ultra precision and nano-technology, driven largely by the need for great chip density. Similar comments can be made in the areas of telecommunications.

Product and business opportunities in ultra precision manufacturing technologies

Product	Comment
Prosthetic devices	Lighter, cheaper, longer life, increased function.
Smart pills	Internal sensors, dose regulation.
Catheter based medical diagnostics	Improved imaging systems and analysis. Therapy systems and micro surgery non-trauma surgery.
Photonic products	Miniaturisation.
Micro filters	Many environment applications.
Micro optical systems	High speed bean positions. Scanning shutters.
Compliant and active probe micro-assays	Applicable to micro electronic manufacture, biological and neural investigation.
Micro switches	Faster operation, less power consumption.
Deformable structures	Valves, micropositioning analogues of muscle.
Semi-solid fuel injectors	Cost and control low weight.
Mass storage	Even denser packing. Higher speed devices.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Nano accuracy actuator with large positioning range

Positioning fabricated or measured components on a nanometer scale demands the development of fast response linear co-ordinate motion stages capable of operating over a large displacement range with nanometer level positioning accuracy.

The piezo transducer is the most widely used actuator in nanometer level positioning since it offers high positional resolution combined with no moving parts, large force, fast expansion and high efficiency. It can be directly used in an open-loop control mode with nanometer level accuracy, such as driving the top of STMs in X and Y direction for sample scanning over the range of 150 μm.

However, for a wide positioning range capability either the motion of the piezo transducer has to be amplified by a multi-leverage displacement amplifier or should be used in combination with some form of coarse actuator.

In both the cases, except when using a complex mechanical structure to achieve nanometer level positioning accuracy, a close-loop control mode has to be employed. This not only increases cost, but creates difficulty in meeting the requirements for a compact design.

Several possible approaches may be attempted to produce a piezo driven stage operated in an open-loop control mode and having a millimeter range of movement with nanometer level positioning accuracy.

One possibility is to use a hydro-static displacement amplifier together with a piezo transducer. Such a device is in the early stages of development. The simple structure, high amplification and high stiffness combined with minimum moving friction offers good potential. This development resulted from the recent SERC contract work relating to high performance jet actuators powered by piezo stages.

In addition to the short range movement limitation, the high hysteresis and creep characteristics of piezo transducers causes errors and limits their application as actuators.

The inserting of a capacitance in series with a piezo transducer has been proposed to reduce hysteresis an creep for high voltage piezo transducers and has been tested over a small voltage range. High voltage piezo transducers operate normally at 1,000 volts and to effectively reduce the hysteresis and creep, the operating voltage has to be increased several times. This can cause some difficulties in practical applications. It is however, possible to employ this method on low voltage piezo transducers operating at 100 volts.

Combining the hydrostatic displacement amplifier with a low voltage piezo transducer, it is possible to develop a piezo-driven stage operated in an open-loop control mode with over one millimetre movement range and nonometer level positioning accuracy. Nano precision air bearing translators also offer a useful solution to stage translation.

2. Surface technology with STM systems

Since its invention in the early 1980s, the STM has been widely used in surface modification down to the level of manipulating single molecules and atoms. This is a very new area and there are many potential fields waiting for exploration, such as the mechanisms of the surface manipulation, the effects of tip materials, tip shapes and tip preparation upon the modification, the importance of surface preparation and the methods of surface modification.

For research on surface technology with STMs, additional instrumentation and expertise may be needed, namely:

- Surface and tip preparation instruments, such as electro bombarding and argon-ion sputtering instruments.
- Expertise in modern physics.
- Expertise in substrate technology.
- Residual stress control for specific surface properties

3. Laser beam as straightness reference

Recent developments suggest that the use of a laser beam for straightness reference is feasible. Research in this field is still at a laboratory stage and nanometer accuracy levels have been limited to a range of several tens of centimetres.

There are numerous techniques of creating a straightness line reference system with lasers and there are many problems to solve. This research topic is appropriate for investigation using the present facilities of the school.

4. Comparison of the scatter in surface roughness measurements obtained from the WYKO and stylus type instruments

Current approaches to standardisation are likely to converge stylus and optical characterisation. The University of Birmingham is currently the leader in this field.

5. Reducing errors of laser interferometers caused by environmental turbulence is an interesting research direction

In recent years, much research has been carried out in error analysis and in improving the measuring accuracy of laser interferometers. Work remains to be done in reducing errors due to environmental conditions, such as vibration, temperature, pressure, humidity and CO_2 concentration. These have a dominant role in limiting the accuracy of measurements made with laser interferometers.

DEVELOPMENT BY THE YEAR 2020

Moore's Law, which states that every eighteen months computers will halve in size and double in power, by the year 2020 molecular level computers will become a reality. To achieve this technology, current manufacturing and fabrication techniques will have to be completely superseded. Although developments at the US FAB 6 facility indicate that silicon circuits having a dimension which is one twentieth of a human hair, will be a reality, this is probably the physical limit of current technological extrapolation.

The future therefore lies in the engineering of biological devices and biological machines. The most sophisticated one which already exists, is the human body.

The route to molecular engineering will first by addressed through the manipulation of bacterial protein. This compound changes shape (sometimes colour) when subjected to light. It therefore has the the capacity to be developed into molecular switches. If the protein is developed into a 'data cube" this can be programmed by the application of light to activate protein to make them operated as binary switches. The result is likely to be computers which are part biological units and part semiconductor chips which have massive storage and data manipulation capability. Note some projected applications of this technology currently being progressed by the US military, where brain impulses are being used to control flight simulators (research level only at present).

The logical way forward is to consider molecular assembly and self assembly to arrange materials atom by atom(STM was the first real breakthrough in this technology as mentioned earlier in this report). The real solution will be to build machines which can make other machines (the human body works in this way). Such machines will be known as Assemblers. The key technological change will be the development of assembly, as is currently seen in biological systems. This is in direct contrast to current manufacture where products are fabricated from the outside.

So far the development in nano scale machines has been limited to relatively simple devices, for example the construction of nano scale bearings, tubes and gear trains. Typically simulations of nano gear performance has indicated that several millions of revs per minute are possible without failure. Super materials, such as lightweight diamond-like materials in construction, because of their mechanical properties, diamond-like materials will feature significantly in aircraft, aerospace and road vehicles. Rank Xerox at Palo Alto in California is already working in this area.

Extrapolating the future suggests that many conventional industries will disappear, so will much industrial pollution as this will be a negligible side effect in nano fabrication. Opportunities will exist to clean up the environment through the application of biological machines where constructed molecules extract pollutants. New developments in medical technology are foreseen which will apply specially developed machines to replace intrusive repair with molecular repair. The emphasis will be on keeping people healthy rather than corrective medicine and surgery.

It is difficult to go beyond these predictions at the present time, but it is believed that these are only typical of the progress which will be made. Free thinking bio chemist such as Dresden have envisaged the impact of nano science on technology, science and society in general, and his book has become the guiding work in this rapidly developing subject.

REFERENCES

1. N.Taniguchi, "Current status in, and Future Trends of Ultraprecision Machining and Ultra Fine Materials Processing", Annals of the CIRP 32(2), 1983.
2. P.A. McKeown, "High Precision Manufacturing and the British Economy", James Clayton Lecture, Proc. of the Inst. of Mech. Engng., 200 76, 1986.
3. A. Franks, "Nanotechnology",J, Phys. E:Instrum. 20 1987.
4 R.T. Bate, "Nanoelectronics", Nanotechnology, Vol. 1, No. 1, July 1990.
5. D.J. Whitehouse, D.K.Bowen, D.G. Chetwynd and S.T.Davies, 'Nano-calibration for Stylus-based Surface Measurement", J. Phys.E:Sci. Instrum. 21, 1987.
6. R. Feynman, "There is Plenty of Room at the Bottom", Miniaturisation, H.Gilbert Ed., Reihold, 1961.
7. R.J.Hocken and J.A. Miller, "Nanotechnology and its Impact on Manufacturing", Proc. Japan/USA Symposium on Fexible Automation, Vol. 1, ASME, 1992.
8. S.Yoshida and K.Lizuka, "Approaches to Nanometer Technology-a Review of the Yoshida Nano-Mechanism Project", Nanotechnology, Vol. 1, No. 1,July 1990.
9. Franks, "Nanotechnology at the National Physical Laboratory and the UK National Initiative on Nanotechnology", Proc. ASPE, 3rd Ann. Prec. Engng. Conf., Atlanta, GA, October 1988.
10. H.Kunzmann, "State-of-the-art and Ultimate Physical Limitations of Dimensional Metrology", Proc. ASPE 1991 Ann. Conf., Santa Fe, N. Mexico, October 1991.
11. E.C. Teague, "Nanometrology", AIP Conf. Proc. 241 Scanned Probe Microscopy, Santa Barbara, CA, 1991.
12. U.Bones and M. Hart, "An X-ray Interferometer", Appl. Phys. Lett. 6, 1965.
13. R.D. Deslattes and J.E.G. Kesskr, Proc. of CPEM-90, in IEEE Tran. Instrum. Means. IM-40, April 1990.
14. D.G. Chetwynd, S.C. Cockerton, S.T.Smith and W.W.Fung, "The Design and Operation of Monolithic X-ray Interferometers for Superprecision Metrology", Nanotechnology, Vol. 1, NO.2., 1991.
15. D.G. Chetwynd, D.R. Shwarzenberger and D. K. Bowen, "Two-dimensional X-ray Interferometry", Nanotechnology, Vol.1,No. 1, 1990.
16. S.R. Patterson, Lawrence Livermore National Laboratory (LLNL) Report #UCRL-53787, February 1988.
17. S. Hosoe, "High Precise and Stable Laser Displacement-Measurement Interferometer with differential Optical Passes in Practical Use", Nanotechnology, Vol. 4, No. 4, 1993.
18. M. A. Zumberge, "Frequency Stability of a Zeeman-stabilised laser", Appl. Opt.24, 1985.
19. R. A. Smythe, "Practical Metrology Design Considerations for Laser Based Phase Measuring Interferometry", Proc. ASPE 3rd Ann. Prec. Engng. Conf., Atlanta, GA, October 1988.
20. W.T. Estler, "High-accuracy Displacement Interferometry in Air", Appl. Opt. 24, 1985.
21. G.G. Wyntjes, D. Michell and M. Hercher, "Scales vs. Interferometers: A Comparison of Metrology Systems", Proc. ASPE 1991 Ann. Conf. Santa Fe, N. Mexico, October 1991.

22. M.J. Downs, "A proposed Design for an Optical Interferometer with Subnanometric Resolution", Nanotechnology, Vol. 1, No. 1, 1990.
23. K.P. Birch and M.J. Dows, "The Results of a Comparison between Calculated and Measured Values of the Refractive Index of Air", J. Phys. E: Sci. Instrum. 21, 1988.
24. A. Ishide, "Two-wavelength Displacement-measuring interferometer using Second-harmonic Light to Eliminate Air-turbulence-induced Errors", Japan, J. Appl. Phys. 28, March 1988.
25. H. Shigeru, "Laser Interferometric System for displacement Measurement with High Precision", Nanotechnology, Vol. 2, No. 2, 1991.
26. H. Shigeru, "Highly Precise and Stable Laser Displacement Measurement Interferometer with Differential Optical Passes in Practical Use", Nanotechnology, Vol. 4, No. 4, 1993.
27. P.L.M. Heydemann, "Determination and Correction of Quadrature Fringe Measurement Errors in Interferometers", Appl. Opt., Vol. 20, No. 19, Oct. 1981.
28. N. Oldham, R. Hetric, J. Kramar, W. Penzos, T. Wheatly and C. Teague, "Electronic Limitations in Phase Meters for Heterodyne Interferometry", Proc. ASPE 1991 Ann. Conf., Santa Fe, N. Mexico, Oct. 1991.
29. A. Frank, "Nanometric Surface Metrology at the National Physical Laboratory", Nanotechnology, Vol. 2, No. 2, 1991.
30. K. Horio and T.Kasai, "Comparison of Some Instruments for Measuring Mirrolike Surface", Nanotechnology, Vol. 2, No. 2, 1991.
31. D. J. Whitehouse, "Comparison Between Stylus and Optical Methods for Measuring Surfaces", Ann. CIRP37, 649253, 1988.
32. J.M. Bennett and L. Mattson, "Introduction to Surface Roughness and Scattering (New York: Optical Society of America) pp. 13-17.
33. K.Miyamoto, "Measurement of Surface with Contact and Non-Contact Method", J.Japan Soc. Prec. Engng. 51(4), 674-80, 1985.
34. N. Bobroff, A.E. Rosenbluth and D. Golding, "Measuring and Correcting the Non-Linearity in Hetrodyne Interferometers", Proc. ASPE 1991, Ann. Conf., Santa Fe, N. Mexico, Oct. 1991.
35. T. Y. Lin, P. J. Sullivan and K. J. Stout, "The Measurement Variation of Surface Profile Parameters: A Viewpoint from Standardisation", Proc. SPE, Ann. Conf., Santa Fe, N. Mexico, Oct. 1991.
36. K. Creath, "From Angstroms to Microns: Examining the Limit of Optical Profilers", ASPE 3rd Ann. Prec. Engng. Conf., Atlanta, GA, Oct. 1988.
37. K. Creath and J. C. Wyant, "Interferometric Roughness of Machined Parts", Proc, SPIE 954, 1988.
38. K. Creath, "Stop-height Measurement Using Two-Wavelength Phase Shifting Interferometry", Appl. Opt, 26, 2810-2816,(2987)
39. G.E. Sommargren, "Optical Heterodyne Profilometry", Appl. Opt. 20, 40, 1981.
40. Y. Tanimura and K. Toyoda, "Non-Contact Measuring Instrument of Micro-Shapes with Laser Interferometer", J. Jpn. Soc. Proc. Engng. 50, 1617, 1984.
41. K. Sakaya and T. Ohura, "On-Machine Measurement of Surface Profile by Fibre Optic Heterodyne Interferometry", Proc. ASPE Ann. Conf., Santa Fe, N. Mexico, Oct. 1991.
42. N. Ikawa, S. Shimada and H. Morooka, "Laser Beam as Straight Datum and its Application to Straightness Measurement at nanometer Level", CIRP Ann. 1988, Manufacturing Technology, Vol. 37, Jan. 1988.
43. V. E. Hart and E.W. Colson, "Installation

and Alignment of LAMPE 201 MHz and 805 MHz Linac Tanks", LASL, Los Alamos, N.Mexico, 87544, LA-DC-72-1298.

44. H. D. Betz, "An Asymmetry Method for High Precision Alignment with Laser Light", App. Opt., Vol. 8, No. 5, May 1969.
45. R.F. Schenz and L. V. Griffith, "Development of an Extended Straightness Measurement Reference", Proc. ASPE 3rd Ann. Prec. Engng. Conf., Atlanta, GA, Oct. 1988.
46. E. Hecht and A. Zajac, Optics, second printing, May 1985, Addison-Wesley Publishing Co., Menlo Park, California, London, P. 374.
47. R. Emch, J. Nogami, M.M. Dovek, C.A. Lang and C. F. Quate, "Characterisation of Gold Surface for Use as Substrates in Scanning Tunnelling Microscopy Study", J. Appl. Phys. 65 (1), Jan. 1989.
48. B. H. Millack, C. J. Robert and W. S. Steer, "Surface Modification and Atomic Resolution on a Vacuum-Annealed Gold Foil in Air by Scanning Tunnelling Microscopy", J. Appl. Phys. 67 (4), Feb. 1990.
49. Y.Z. Li, L. Vazquez, R. Piner, R. P. Anders and R. Reifeberger, "Writing Nanometer-Scale Symbols in Gold using the Scanning Tunnelling Microscope", Appl. Phys. Lett. 54 (15), April 1987.
50. C.J. Rorbert, M.J. Wilkindt, G. Beamson, M.C. Davies, D.E. Jackson, P.D. Scholes, S.J.B. Tendler and P.M. Williams, "The Demonstration of Controlled Surface Modification Achievable with a Scanning Tunnelling Microscope on Graphite, Mettanic Films, Organic Molecules and Polymeric Bimolecules", Nanotechnology, Vol. 3, No. 3, 1992.
51. W. Li, J.A. Virtanen and R.M. Penner, "Nanometer-Scale Electrochemical Deposition of Silver on Graphite using a Scanning Tunnelling Microscope", Appl. Phys. Lett. 60(10), March 1992.
52. J.A. Dagata, W. Tseng, J. Benett, J. Schneir and H.H. Harary, "Nanolithography on III-V Semiconductor Surface using a Scanning Tunnelling Microscope Operating in Air", J. Appl. Phys. 70(7), Oct. 1991.
53. M.A. Harmer, C.R. Fincher and B.A. Parkison, "Scanning Tunelling Microscopy of the Surface Topography and Surface Etching of Nanoscale Structure on the High-Temperature Superconductors", J. Appl. Phys. 70(5), Sept. 1991.
54. T. R. Albrecht, M.M. Dovek, C.A.Lang, P. Grutters and C.F. Quate, "Imaging and Modification of Polymer by Scanning Tunnelling Microscopy", J. Appl. Phys. 64(3), Aug. 1998.
55. J. Moreland an P. Riu, "High-Resolution, Tunnelling-Stabilised Magnetic Imaging and Recording", Appl. Phys., Lett. 57(3), July 1990.
56. J.Jahanmir and P.E. West, "Local Modification of Thin Sio$_2$ films in a Scaning Tunnelling Microscope", J. Appl. Phys. 667(11), June 1990.
57. R. Winsendanger, I.V. Shrets, D. Coey and S. Graser, "Topographic and Magnetic-Sensitive Scanning Tunnelling Microscope Study of Magnetite", Science, Vol. 255, Jan. 1992.
58. Y. Akama, E. Nishimura, A. Sakai and H.M. Urakami, J. Vac, Sci. Technol. A8, 429, 1990.
59. M. Shinji, B. Masakazu and S. Akinobu, "Atomic Layer Etching and Sidewall Roughness Measurement using the Scanning Tunnelling Microscope", Nanotechnology, Vol. 3, No. 3, 1992.
60. J.M. Soler, A.M. Baro, N. Garcia and H. Rohrer, Rew. Lett. 57, 444, 1986.
61. J. Tersoff, Phys. Rew. Lett. 57, 440, 1986.
62. H. Mamin, E. Ganz, D. W. Abraham, R. E.

Tomson and J. D. Clarke, Phys. Rew. B34, 9015, 1986.

63. J.B. Pethica, Phys. Rew. Lett. 57, 3235.
64. H. A. Mizes, S.I. Park and W.A. Harrison, Phys. Rew. B36, 4491, 1987.
65. A. Kanai, J. Yoshioka and M. Miyashita, "Feed and Frictional Load Characteristics of Carriage on Plain Bearing Guideways in the Range of Nanometer Positioning", Proc, ASPE 1991 Ann, Conf., Santa Fe, N. Mexico, Oct. 1991.
66. J. F. Cuttino and T. A. Dow, "The Preload Ball Screw as a Nanometer Actuator", Proc. ASPE 1991 Ann. Conf., Santa Fe, N. Mexico, Oct. 1991.
67. A. Kanai, H. Sano, J. Yoshika and M. Miyashita, "Positioning of a 200 kg Carriage on Plain Bearing Guideways to Nanometer Accuracy with a Force-Operated Linear Actuator", Nanotechnology, Vol. 2, No. 2, 1991.
68. J. Otsuka, "Nanometer Level Positioning using Three Kinds of Lead Screw", Nanotechnology, Vol. 3, No. 3, 1992.
69. T. Nomura and R. Suziki, "Six-Axis Controlled Nanometer-Order Positioning Stage for Microfabrication", Nanotechnology, Vol. 3, No. 3, 1992.
70. T. Koizumi, H. Shibazaki, T. Nishino and N. Nishiwaki, "Study of Rolling Friction-Behaviour of Small displacement of Starting Rolling Friction", J. Jpn. Soc. Lubrication Eng. 27, 1982.
71. T. Nomura, T. Kubo, R. Suzuki, S. Sekiya and M. Kamiya, "High Precision Alignment Stage for Microlithography", Opt./Laser Microlithography, SPIE 922, 66-72, 1988.
72. P. I. Hubbel and P. I. Ro, "Model Reference Adaptice Control of Non-Linear Microdynamics of a Ball Screw Driven Precision Slide", Proc. ASPE 1991 Ann. Conf., Santa Fe, N. Mexico, Oct. 1991
73. S. Futami, A. Furntani and S. Yoshida, "Nanometer Positioning and its Micro-Dynamics", Nanotechnology, Vol. 1, No. 1, 1990.
74. A. Shimokohbe and H. Aoyama, "An Active Air Bearing: A Controlled-Type Bearing with Ultra-Precision, Infinite Static Stiffness, High Damping Capability and New Functions", Nanotechnology, Vol. 2, 1991.
75. K.J. Stout, "Personal Notes"
76. K. Shintaku, "A Precise large Displacement Control on a Linear Actuator", System Control, 29, 609-617-1985.
77. D.L. Trumper and A.H. Slocum, "Nanometer Motion Control via Magnetic Suspension", Proc. ASPE 1991 Ann. Conf., Santa Fe, N. Mexico, Oct. 1991.
78. F. E. Scire and E.C. Teague, "Piezo Driven 50 Micrometer Range Stage with Subnanometer Resolution", R.S.I., 49, 1735, 1973.
79. R.D. Young, "Micromeasurement with the Piezo-Flex Stage", WYE CREEK Instruments, Frederiok, MD 21701.
80. C. Larigne, J.A. Miller and R.J. Hocken, "A Long Range STM/AFM", Proc. 1991 Ann. Conf., Santa Fe, N. Mexico, Oct. 1991.
81. "Piezo Guide, Piezopositioning Technology Part 1". Catalogue PZ36E, Physic Instrument GmbH and Co., Siemesstr, 13-15, D-7517 Waldbroom, W-Germany.
82. C.V. Newcomb and I. Flinn, "Improving the Linearity of Piezoelectric Ceramic Actuator", Electronic. Lett. Vol. 18, No. 11, May 1982.
83. H. Kaizuka and B. Siv, "A Simple Way to Reduce Hysteresis and Creep using Piezoelectric Actuator", Jpn. J. of Appl. Phys., Vol. 27, No. 5, May 1988.
84. G. Binning and D.P.E. Smith, "Single-Tube Three-Dimensional Sconner for Scanning Tunnelling Microscope", Rew. Sci. Instrum. 57, 1986.

85. B. Marchon and M. Salmeron, "Surface Modification of a Passiveted Re(0001) Surface by Scanning Tunnelling Microscope", Surf. and Coating Tech., 36, 1988.
86. M. A. McCord and R.F.W. Pease, "Scanning Tunnelling Microscope as a Micromechanical Tool", Appl. Phys. Lett. 50(10), March 1987.
87. D.M. Eigler and E.K. Schweizer, "Positioning Single Atoms With a Scanning Tunnelling Microscope", Nature, Vol. 344, 5 April 1990.
88. D. Saulys, G. Rudd and E. Garfunkel, "Scanning Tunnelling Microscopy Assisted Oxide Surface Etching", J. Appl. Phys. 69(3), Feb. 1991.
89. R.S. Becker, J.A. Golvchenko and B.S. Swartzentruber, "Atomic-Scale Surface Modifications using a Tunnelling Microscope", Nature, Vol. 325, Jan. 1987.
90. A. Kobayashi, F. Gray, R.S. Williams and M. Aoro, "Formation of Nanometer-Scale Groove in Silican with a Scanning Tunnelling Microscope", Science, Vol. 259, March 1993.
91. I.W. Lyo and P. Avouris, "Field-Induced Nanometer-to Atomic-Scale Manipulation of Silicon Surface with the Scanning Tunnelling Microscope", Science, Vol. 253, July 1991.
92. T. Schimmel, H. Fuchs, S. Akari and K. Dransfield, "Nanometer-Size Surface Modifications with Preserved Atomic Order Generated by Voltage Pulsing", Appl. Phys. Lett. 58(10), March 1991.
93. T. Schaub, R. Wiesendanger and H.J. Guntherodt, "Comparative Study of Different Tip Materials for Surface Modification by the Scanning Tunnelling Microscope", Appl. Phys. Lett. 54(15), April 1989.
94. R. Emch, J. Nogami, M.M. Dovek, C.A. Lang and C.F. Quate, "Characterisation of Gold Surface for use as Substrates in Scanning Tunnelling Microscope", J. Appl. Phys. 67 (1), June 1990.
95. J. A. Miller and R. J. Hocken, "Scanning Tunnelling Microscopy Bit Making on Highly Orientated Pyrolytic Graphite: Initial Results", J. Appl. Phys. 68(2), July 1990.
96. J. Jahanmir, P.E. West and S. Hsieh, "Surface Modification of a-Si:H with a Scanning Tunnelling Microscope Operated in Air", J. Phys. 65(5), March 1989.
97. E.E. Ehrichs, S. Yon and A.L. deLozanne, "Direct Writing 10nm Feature with the Scanning Tunnelling Microscope", Appl. Phys. Lett. 53(23), Dec. 1988.
98. D.M. Eigler, C.P. Lutz and W.E. Rudge, "An Atomic Switch Realised with the Scanning Tunnelling Microscope", Nature, Vol. 352, Aug. 1991.
99. Y.W. Mo, "Reversible Rotation of Antimony Dimers on the Silicon (001) Surface with a Scanning Tunnelling Microscope", Science, Vol. 261, Aug. 1993.