Ultra-precision: enabling our future

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This paper provides a perspective on the development of ultra-precision technologies: What drove their evolution and what do they now promise for the future as we face the consequences of consumption of the Earth’s finite resources? Improved application of measurement is introduced as a major enabler of mass production, and its resultant impact on wealth generation is considered. This paper identifies the ambitions of the defence, automotive and microelectronics sectors as important drivers of improved manufacturing accuracy capability and ever smaller feature creation. It then describes how science fields such as astronomy have presented significant precision engineering challenges, illustrating how these fields of science have achieved unprecedented levels of accuracy, sensitivity and sheer scale. Notwithstanding their importance to science understanding, many science-driven ultra-precision technologies became key enablers for wealth generation and other well-being issues. Specific ultra-precision machine tools important to major astronomy programmes are discussed, as well as the way in which subsequently evolved machine tools made at the beginning of the twenty-first century, now provide much wider benefits.

Keywords: ultra-precision; telescopes; machine tools; measurement

1. Introduction

‘Measure what is measurable, make measurable what is not’

—ascribed to Galileo

Many twentieth-century drivers can be identified behind the improvement of manufacturing accuracy and fine feature fabrication. These include demands set by defence and weapons programmes, automotive and aerospace mass production, microelectronics, telecoms, medical imaging and, perhaps most significantly, large science programmes. This paper details some specific

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1Noted mathematician Hermann Weyl attributed the maxim as a quotation taken from the 1890–1909 edition of Galileo’s collected works: ‘Galileo enunciates the principle, “to measure what is measurable and try to make measurable what is not so as yet”’ [1, p. 4].

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ultra-precision developments, initially devised to meet demands of large science projects, which have now become key enabling technologies for renewable energy generation and environmental monitoring in the twenty-first century (figure 1).

Prior to looking at specific manufacturing advancements, it is perhaps appropriate to consider a number of important advances in the field of measurement science. At the end of the nineteenth century, Carl Edvard Johansson, a Swedish armourer inspector, invented the so-called combination gauge block set [2]. In the UK, these are referred to as slip gauges (‘slip’ meaning ‘ground’ in Swedish), while in the USA they are referred to as ‘Jo blocks’ after the inventor himself. Johansson had been concerned with the cost and the effectiveness of measurement tooling supporting the fabrication of rifles and ammunition. His concept was very simple: a set of accurate blocks of specific differing thicknesses that could be combined to make up any required measurement distance. The flatness and roughness of the gauge blocks were of a very high standard, typically 100 nm r.m.s. and 25 nm r.m.s., respectively. The high quality of the surfaces enabled the blocks to be wrung together, meaning the blocks would effectively stick to each other through a combination of surface tension, molecular attraction and air pressure as a consequence of their high-quality surfaces. The application of slip gauges to the calibration of micrometre callipers significantly advanced inspection for weapons manufacture (figure 2).

The benefits were soon recognized by Henry Ford, who engaged Johansson to support development of automobile production. Ford’s assembly concept was itself based on the so-called American System of Manufacture pioneered in armouries and exhibited with great impact at the Crystal Palace Great Exhibition in 1851 [3]. The concept demanded interchangeability of components for effective and efficient production. The impact of Johansson’s invention has since been globally significant and even today slip gauges remain a measurement artefact providing traceability for many manufacturers. Johansson was posthumously awarded a gold medal by the Royal Swedish Academy of Engineering Sciences in 1943 for his ‘simple’ invention of the combination gauge block set.
Subsequent measurement technologies have enabled higher manufacturing accuracy to be achieved with greater speed and ever more complex shape components. Critical measuring inventions included: the laser interferometer, the coordinate measuring machine (CMM) and the touch-trigger probe (figure 2).

When the first working laser was reported [7], Charles Townes, whose fundamental patent had anticipated its development, was famously told *without irony* it was ‘a solution looking for a problem’ [8]. The following half century, however, has revealed the laser to be a ubiquitous and necessary component in numerous diverse applications, and not least in the field of precision measurement. Its highly monochromatic and coherent output permits (through optical interference) very high-resolution measurement over extremes of distance scales; its low divergence and high intensity enable long reach, wide optical fields and fast measurement; its achievable stability of beam geometry and frequency allows extremely low-uncertainty measurements in a wide range of metrological applications. It has become the cornerstone of displacement, angle and form metrology, based on a number of principles—interferometry underlying the most sensitive, with sub-nanometre precision possible [9].

Whereas the CMM may arguably find origins in a nineteenth-century boatyard [10] or conceivably antecedents in eighteenth-century or earlier sculptors’ pointing machines used to ‘reverse engineer’ three-dimensional...
forms [11], realistically its birth was in the mid-twentieth-century combination of electronic measurement scales and kinematic machine design. What is now called the CMM was invented in the Ferranti company in 1956 and commercially introduced as a manually operated machine in 1959 and around the same time at the Digital Electronic Automation (DEA) company [4]. The later addition of sensitive electronic probes and automatic machine control had created fast automatic machines by the mid-1970s. Ultimately, the introduction of specific metrological software completed a recognizably modern CMM, which is now capable of sophisticated general dimensional metrology, in some cases achieving demonstrable dynamic ranges (maximum dimension : resolution) exceeding $10^9$ with measurement uncertainty ratios above $10^6$.

A specific invention that ushered in the age of automatic precision measurement was the touch-trigger probe [12]. It was initially conceived in Rolls-Royce specifically for low-force probing of delicate components of the Olympus jet engine. Its simple application to automatic control and its consistency of probe trigger force ultimately permitted high-speed precise probing of a range of components—even while the CMM itself was still in motion. This dynamic capability markedly improved the efficiency of CMMs, permitting measurement repeat rates at one per second or more.

(a) Relationship of ultra-precision technologies and nanotechnology

The ability to produce manufactured components to ever more demanding levels of accuracy has been identified by numerous researchers. In 1974, the Japanese precision engineering researcher, Taniguchi, defined nanotechnology as the production technology to achieve high accuracy and ultra-fine dimensions of the order of a nanometre [13]. His charts recorded and proposed improvements in machining accuracy capability (figure 3). These charts can be compared with Moore’s law, the mid-1960s prediction [14] based on contemporary trends that the integrated circuit (IC) transistor count-per-chip would double every 2 years; it is expected to hold more or less true until at least 2020 [15]. Taniguchi stated that the production technology required for nanotechnology must include machine systems for processing, together with appropriate measurement and control techniques. He highlighted that enabling of effective measurement was pivotal to the development of new manufacturing processes and practices. It is clear, though, that the recognition of the fundamental need for measurement can be traced through, for instance, Lord Kelvin: his fuller statement [16] often paraphrased as ‘to measure is to know’ harks back to the maxim attributed earlier to Galileo.

The field of nanotechnology was in practice established before Taniguchi coined the phrase itself. The Nobel Prize winner Richard Feynman advocated atom-by-atom construction and predicted the development of both the transistor and atom-scale microscopy in the late 1950s. Feynman’s widely cited lecture ‘There’s plenty of room at the bottom’ [17] has provided inspiration to physicists and engineers alike.

Feynman effectively predicted the direction of the microelectronics sector prior to its actual creation. He also highlighted the need for lubrication media of very low viscosity in order to enable nanometre-scale motions. As we shall see later with regard to ultra-precision machine developments that this point has been
very important. Just like Johansson, Feynman spent his early career within the defence sector, as a theoretical physicist at the Los Alamos Laboratory working with the Manhattan Project [18].

There is perhaps no comprehensive means, nor is it necessarily important, to differentiate the fields of ultra-precision engineering and nanotechnology. Optics fabricators can claim to have been applying ultra-precision technologies to produce surfaces having form accuracy of tens of nanometres for decades, if not centuries. Today the importance of the precise manipulation of light remains a major concern across many fields of science, including astronomy, gravity and fusion research. For established commercial sectors, such as microelectronics, telecommunication and displays, the ability to handle light to a similar level of precision remains a critical technical area affording products a competitive advantage. As we shall see later, that same ability has now become a priority topic in renewable energy generation and environmental monitoring.

Ultra-precision technologies include machine, process and metrology technologies that enable the manufacture or function of parts having nanometre tolerance surfaces or features applied to artefacts of differing scale. In this manner, we encompass small-scale components having nanometre-toleranced features. Such features would not necessarily comply with generally accepted definitions for precision engineering [19,20], which tend to be based on the relative ratio between the scale (size) and the accuracy of components. This precision engineering ratio is clearly some measure of difficulty of fabrication but perhaps does not reflect all advances in the manufacturing fields demanding ultra-precision attributes.

Of the many activities that have advanced ultra-precision manufacturing, this paper highlights some that have been facilitated by large science and defence sector programmes during the twentieth century and which are now in the

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twenty-first century being applied to address concerns that are critical in the context of growing population, consumption of resources and expectations of quality of life.

2. The development of ultra-precision machine processes before the twenty-first century

Ultra-precision processes include those which were based on conventional processes (such as turning, milling and grinding) and developed to become higher accuracy capability technologies. Other processes often referred to as non-conventional processes are based on energy beams and chemical mechanisms. In this section, we highlight the development of three important ultra-precision processing technologies: two of a conventional type and one considered non-conventional.

(a) Single-point diamond machining

Machining of components using lathes can be traced back to antiquity—a depiction of lathe turning exists in the tomb of Petosiris from around 300 BC [21]—although the technique is undoubtedly much older. The powered machine lathe was a key advance in the nineteenth-century’s Industrial Revolution [22] developed from the much earlier water-powered wood turning lathe [23]. Accuracy capability improvement of the turning process can be linked to numerous machines and cutting tool advancements, many of which are twentieth century in origin. The diamond turning process is presently at the pinnacle of turning processes with regard to machining accuracy capability and surface finish.

Single-point diamond machining employs an ultra-sharp high-purity diamond tool used with ultra-precision lathes and milling machines. These have smooth, precise motions founded on stiff guideways and fluid film bearings that control the relative movement of the workpiece and tool to nanometre levels of control and achievable component part accuracy [24]. Diamond turning was initially developed using modified measuring machines such as those made by Moore Special Tool (figure 4) in the USA and Taylor Hobson in the UK. In the 1960s and 1970s, the US Lawrence Livermore National Laboratory (LLNL) built dedicated large-scale diamond turning machines (LDTM) such as the Large Optics Diamond Turning Machine (LODTM), under defence programmes [25,26]. Similarly in the UK, the Science and Engineering Research Council commissioned the Cranfield Institute of Technology (later, Cranfield University) to design and build a LDTM (figure 4) [27] although this was for astronomy purposes. The machine established the UK capability to fabricate X-ray grazing incidence space mirrors [28]. Through the development of the LLNL and Cranfield machines, a number of high-precision machine techniques were firmly established. Further refinement for ultra-precision applications has improved these technologies, which include: pressurized oil and air bearings, smooth drive actuation, active thermal stabilization methods, application of laser interferometers for machine tool motion control, laser interferometer-referenced metrology frames, vibration isolation and
responsive numerical control. Such techniques ensured that these large machines had a form machining accuracy capability in the range 50–1000 nm on components up to 1 m scale or more.

Of the many concepts shared between the contemporary LLNL LODTM and Cranfield LDTM, perhaps the most important was the application of laser interferometers operating at 10 nm resolution, referenced to a master straight edge. Error data collected through the lasers were used to modify motional tool paths. In 1982, the Rosat space telescope wide-field camera mirrors, of metre scale, having circularity and axial profile accuracies significantly better than 1 μm total error envelope, were made using LDTM.

By the mid-1980s, Cranfield had produced several classified high-precision and ultra-precision diamond turning machines for the defence sector. Through the UK’s National Initiative on Nanotechnology (NION, figure 4), new diamond turning machines were also built having 1 nm resolution-controlled motions, using active laser interferometer-referenced metrology frames, with highly sophisticated thermal control systems operating at milli-kelvin resolution. The approach to thermal stabilization advanced the earlier work by Bryan at LLNL. By the mid-1980s, commercial ultra-precision aspheric generator machines were produced.
in the USA, UK, Germany and Japan. These machines firmly established conventional diamond turning machines having approximately 100 nm machining accuracy capability for 350 mm sized parts.

The ability to fabricate natural and synthetic diamonds into cutting tools with near atomically sharp edges was finessed. Understanding of the effects of diamond type, crystal orientation, edge preparation and trace elements on the cutting performance was greatly advanced [29]. Important research into the diamond machining of hard and brittle materials such as silicon and germanium was undertaken by many [30–33]. Collectively, their work established today’s production methods for the fabrication of infrared (IR) optics as applied in missile guidance systems, heat-seeking detection cameras and night vision sights [34]. Materials ostensibly considered brittle, such as silicon, can today readily be turned without brittle fracture owing to the quality of control of the cut chip thickness using high-quality lathes. The resultant surfaces approach 1 nm r.m.s. roughness with a limited amount of subsurface atomic bond dislocation, typically approximately 200 nm deep.

Recent technical advancements of commercial diamond turning machines relate to the development of high-frequency response motions and additional axes. Technically speaking, in general application, linear motor technology and higher-resolution Moiré fringe gratings have replaced capstan or ballscrew drives and laser interferometers, respectively. Additionally, high-frequency piezo-actuated tool holders providing kilohertz bandwidth position control of the tool enabling complex structured surface generation with small feature size at realistic production rates.

(b) Abrasive machining technologies

Abrasive machining has long been established. Assyrian ground optics nearly 3000 years old have been found [35]. Abrasive machining of optics in the form of grinding and polishing were the concern of many leading scientists from Galileo and Huygens forward [36].

Today’s major science programmes continue to fund abrasive processing research [37]. The development of precision grinding and precision polishing machines followed quite distinct routes as they depend on different technologies. Grinding is fundamentally a position-controlled process (akin to diamond turning), where the motions of the machine dictate the quality of the part produced through a direct influence on its accuracy, since the abrasives are fixed into a tool; whereas polishing is a force-controlled process, where abrasives are free to move within a fluid between the part and a moving tool. In the case of polishing, the applied pressure between tool and part, and the duration of engagement, are the dominant controlling material removal parameters, although there are others, in what is often a multi-step iterative process to converge on the desired component shape, as with the oldest manual craft processes.

The development of ultra-precision grinding machines closely followed the technical progression of single-point diamond turning machines. In the early 1980s, IBM funded the development of the so-called lap-grinding machines for grinding ceramic read/write heads, where roughnesses of 10 nm r.m.s. were demanded. This lap-grinding process removed the need for ‘messy’ polishing processes. The lap-grinding machines employed air bearing spindles and linear
slideways and provided greater accuracy in read/write head fabrication, thereby enabling lower flying heights that provide faster data exchange rates and higher data density, this technology being later applied directly to optical grinding [38]. The US company Pneumo produced aspheric optics grinding machines adapted from their successful aspheric optics diamond turning machines from the mid-1980s (figure 5). These machines also incorporated air bearing grinding spindles and permitted aspheric shape glass optics to be ground to form an accuracy level of 200–300 nm peak to valley. They enabled effective fabrication of aspheric optics since their output quality permitted much shorter subsequent polishing operations than previously possible.

A large special-purpose grinding machine sold to Eastman Kodak in 1988 and made by Cranfield Precision Engineering Limited embodies an ultra-precision grinding machine possessing many technologies refined from earlier LDTM projects. The OAGM 2500 was purchased to deliver numbers of large mirror segments for US astronomy projects such as the Keck telescopes.

This large-scale Cartesian machine (figure 5) has a working volume of $2.5 \times 2.5 \times 0.6 \mu \text{m}$ with a claimed volumetric accuracy in the range 3–5 mm [39]. This unprecedented accuracy level and scale combination, beyond that of commercial CMMs of similar size, even today, was achieved through application of a full three-dimensional metrology frame operating at 1 nm resolution through multiple laser interferometers. By incorporating a coordinate measuring capability, also
laser referenced to the metrology frame, the opportunity exists to measure and compensate for grinding process issues such as tool wear and force variations.

Ultra-precision grinding machines were developed to support silicon wafer processing. As the size of silicon wafers increased up to 300 mm by the year 2000, the grinding machines became larger and demanded improved relative accuracy to ensure subsequent post-grinding processes would be effective on larger size wafers. Many ultra-precision silicon wafer grinding machines employ the technologies found in diamond turning machines.

In contrast to the scale-up of silicon wafers, many precision automotive components such as fuel injectors and bearings have decreased in size. However, their accuracy demands have also become ever more stringent. The driver for higher accuracy in these automotive components is a requirement for reduced emissions and improved efficiency from internal combustion engines, through reduced friction and longer life from bearing systems. This is an example of how environmental and sustainability issues are becoming increasingly significant in requiring ultra-precision technologies.

The Nanogrinder developed by Lidköping Machine Tools in Sweden represents an important technical indicator of future small-scale ultra-precision machines (figure 5). This machine [40] was under development at the end of the millennium. The Nanogrinder employed large air bearings with integrated direct drive motions held within the main rotary systems. This approach significantly reduced machine size and energy demands, while delivering high accuracy capability and increased output. The approach was made possible through adopting air bearings, high-power density direct drive motors (linear and rotary) and sub-nanometre resolution cylindrical Moiré fringe gratings, technologies similar to those in modern diamond turning machines.

Free abrasive glass polishing has been researched by many leading scientists during the late nineteenth and twentieth centuries. This list includes key contributions that advanced the purely abrasive Newtonian model [41] to the partial ‘flow’ model [42–46]. Rayleigh considered the grinding process to be dominated by microfracturing, whereas he considered polishing to be dominated by molecular or near molecular flow. These scientists had differing views as to the contribution of material flow mechanisms, debating the likely flow layer depth to be between 25 and 1000 nm. Understanding of both the physics and chemistry of free abrasive processes remains a major research area [47] to advance production efficiency in the microelectronics and optics sectors alike [48].

Whereas the progress of fixed abrasive grinding can be traced through machine tool technology developments, the progress of polishing should be charted against process and measuring technology developments. The range of modern polishing processes includes: magnetorheological finishing (MRF), which carries abrasives in a fluid that can be stiffened using electromagnetic influence [49]; elastic emission finishing [50], which drives very fine abrasives into surfaces using a high-speed moving tool; and variants of sub-aperture polishing [51,52], examples of which are shown in figure 6. Many of these free abrasive polishing techniques are applied using sub-aperture tools. Tool path calculations are derived from error measurement maps of the component surface. An iterative convergence process from measurement to polishing to measurement and so on is applied. The error maps allow a time dwell tool path to be calculated so that the tool resides longer...
on high regions and less so on relatively low regions of the surface. In so doing, the desired surface shape is approached through a series of process–measurement iterations.

There is no doubt that the capability of sub-aperture grinding and polishing has advanced through numerous projects; however, the astronomy demand for a leading high-performance X-ray space telescope can be identified as stimulating the achievement of exceptional accuracy in large and delicate mirror optics.

The NASA Chandra X-ray space telescope was launched in 1999 and is the most sensitive X-ray space telescope ever deployed. It provides an 800 cm$^2$ collecting area (equivalent to a 0.3 m diameter optical telescope) and provides a resolution of 0.5 arcsec (compared with the earlier Rosat telescope at 3 arcsec). The largest Chandra (AXAF) mirror element is 1.2 m in diameter and 0.83 m long; a man can stand inside it, cleaning its surface (figure 7).

The Chandra mirrors were made in the glass ceramic Zerodur and produced to exacting quality by Hughes Danbury in the USA. Chandra’s mirrors were processed using small tool (sub-aperture) grinding and polishing techniques. The mirrors were carefully supported on aluminium rings fitted at each end of the tube-like mirrors during processing. These support rings were removed during post-grind and post-polish measurements so that their distortion influence did not affect the measurements of the freely supported mirrors.
Hughes Danbury achieved significantly greater accuracy and at a larger scale on the Chandra mirrors compared with earlier X-ray space telescopes. This higher accuracy capability was principally achieved through the development of improved measurement applied during manufacture. This improved measuring capability required new special-purpose measuring machines. Data from these measuring machines ensured that subsequent polishing runs were effective in converging towards required final shape. The special-purpose measuring machines included a Precision Metrology Station (PMS) and a Circularity and Inner Diameter Station (CIDS). PMS provided axial figure errors, at specific azimuthal positions, by interferometrically measuring the separation between the mirror surface and a calibrated reference surface. CIDS, built at Cranfield in the UK (figure 7), determined the inner diameters and roundness at the near-end regions.
of the mirrors. CIDS also used interferometers to collect data from the mirror surface with respect to known reference artefacts. In operation, the Chandra mirrors were loaded over the top of CIDS.

CIDS rotated inside the Chandra mirror carrying two sets of opposed measuring probes [57]. By fusing the data from the PMS and CIDS instruments, Hughes Danbury could create low-frequency error maps to drive their time dwell sub-aperture polishing process. Typically, it took four polishing cycles per element to achieve an axial form error of 5 nm r.m.s. It was necessary to use polishing tools of differing size to reduce profile error features of differing wavelength. Roughness of the Chandra mirrors was 1.8–3.4 Å r.m.s. as measured over distances of 0.01–1 mm.

Other polishing techniques employ a chemical mechanism and these are referred to as chemical–mechanical polishing or CMP. CMP has been widely developed especially within the microelectronic sector [58].

(c) Ion beam technologies

The most precise surfaces produced at the turn of the twentieth century were undoubtedly finalized using ion beam figuring (IBF). These surfaces include the optical surfaces for telescopes and perhaps most significantly, at least in a commercial sense, the lenses that form the optical towers of lithography steppers: these being the machine tools that in fact enable compliance with Moore’s law.

IBF, as employed for optical surface figure correction, was pioneered by Wilson & McNeill [59]. The process uses a beam of accelerated ions operating in a vacuum environment, causing the ions to bombard previously polished surfaces. The kinetic energy causes atoms within the optical substrate to be ‘knocked out’ in a process often called sputtering. In IBF, the ion beam is formed so that it offers a Gaussian-shaped removal ‘footprint’. IBF is used with a time dwell strategy akin to that employed with sub-aperture computer-controlled polishing, where slower transit of the IBF ‘head’ over the surface causes more material to be removed, thus allowing controlled change of surface shape through controlled speed variations. The significant advantage of IBF over abrasive-based polishing is in the realization of atomic levels of material removal sensitivity of this non-contact process. The IBF process offers nanometre levels of fabrication finesse without the need for ultra-precise machine motions, although costly vacuum-based operation is required (figure 8).

Realization of IBF was perhaps most significantly demonstrated through the creation of 2.5 m scale IBF systems at Eastman Kodak and their application to the final shaping of the Keck telescopes’ primary mirror components; a combined total of 72 mirror segments of 1.8 m scale. It was reported that each mirror was figured in approximately 80 h with a material removal rate in the region of 0.1 mm³ min⁻¹, improving form accuracy from approximately 500 nm r.m.s. to 10–30 nm r.m.s. [64]. Production data for lithography optics fabrication are commercially sensitive and in the most part unpublished. However, the IBF systems are identifiable and claims of reliable sub-nanometre form accuracy production are in evidence [63]. Representative systems and outputs are shown in figure 9.

At the conclusion of the twentieth century, it remained clear that the demands of science projects remained a key driver of ultra-precision manufacturing
technology advancement and that these provided enormous benefit in high-technology sectors.

3. Twenty-first-century ultra-precision demands

At the start of the twenty-first century, the requirement for ultra-precision processing has broader significance. The demands of astronomy programmes for larger, more accurate mirrors, fabricated much more quickly, nevertheless remain fully aligned with another pressing demand: for lithography optics required to ensure future adherence to Moore’s law.

This point is most clearly illustrated by comparing the optical demands of the European Extremely Large Telescope (E-ELT) with those proposed for the future extreme ultraviolet (EUV) lithography steppers, operating at increasingly shorter optical wavelengths, in order to achieve 13 nm (even 6 nm) feature size creation capability; final figure accuracy and physical scale demands of individual mirrors are similar (and extremely challenging), despite the different applications (figure 9).

The broader importance of ultra-precision technologies at the start of the twenty-first century is driven by a number of pressing requirements, including: sustainable or ideal energy generation, energy efficiency in manufacture/
consumption and the demand for advanced products. Example products include displays, animated packaging, programmable plastic newspapers and wall coverings.

For much of the twentieth century, the promise of a clean, almost carbon-free, energy supply based on the principle of nuclear fusion was simply a science ideal. At the start of the twenty-first century, the prospect of a fusion energy source has been transformed into arguably the most important engineering challenge for the long-term sustainability of the human population on the planet. The National Ignition Facility at the Lawrence Livermore National Laboratories [69] and the Laser Mega Joule facility in Bordeaux [70] represent pinnacle science facilities for laser-induced inertial fusion confinement. These essentially defence-driven facilities are yielding results that will gain support for key fusion energy-producing research facilities such as the US LIFE project [71] and the European HiPER programmes [72]. These laser-induced fusion confinement research facilities represent enormous ultra-precision machines in that the key enabling components in themselves are feats of ultra-precision engineering. Example challenges include: the manufacture of the high-fluence damage threshold large optics (these are wear components requiring regular replacement) and the target fuel pellets, together with the numerous demands of the control, steerage and tracking of multiple high-power laser beams (figure 9).

The surface and subsurface requirements of high-power laser optics pose demands beyond those driven previously by astronomy projects and the micro-electronics sector. As at the beginning of the seventeenth century, for
the twenty-first century, new surface creation capabilities are required to enable science understanding and economic wealth and energy generation, with the added constraint of environmental sustainability. New ultra-precision machine tools are being established for rapid manufacture of optics for fusion energy systems.

The Cranfield BoX ultra-precision free-form grinding machine was created to produce E-ELT mirror segments in 10 h [73]. Another next-generation machine tool for large optics fabrication is the Helios 1200. It is a joint development between Cranfield University and a spin-out from LLNL, RAPT Industries. Helios is a rapid plasma beam surface figuring system capable of reducing the final figuring time (and cost) of large-scale ultra-precision optics for fusion, astronomy and lithography applications [74]. These machines are shown in figure 10.

A microengineering next-generation ultra-precision machine tool under development is the Cranfield μ4 machine. It is an advanced mass-production compliant multi-axis diamond machining system for rapid fabrication of fusion fuel pellets [76]. This highly compact ultra-precision six-axes diamond micromachining machine (figure 10) will offer rapid fabrication of fusion fuel shape components through high-response dynamic motions of nanometre accuracy.

Manufacture of large optical surfaces is a demand for solar energy systems. For concentrated solar thermal (CST) systems such as those of Southwest Solar Technologies (figure 9), the optical demand is rather obvious. Mirror quality is a parameter influencing energy efficiency. Less obvious but more
demanding is the required accuracy of optical surfaces within concentrated solar photovoltaic (CSP) systems. Here, ultra-precision diamond turning is a key enabling technology for high energy efficiency and low manufacturing cost. In order to concentrate solar light onto the photovoltaic (PV) junction, diffractive optical elements can be employed. The cost-effective mass production of large-scale high-quality concentrating diffractive films/lenses demands a reel-to-reel production process. Although these diffractive optical parts need to be produced in huge quantity and at low cost, they require ultra-precision diffractive features typically seen in high-end IR systems as used in missile guidance systems.

It is perhaps therefore not surprising that the diamond turning process used for making IR optics for the defence sector is the core enabling technology for the mass production of CSP diffractive film mould tools. The diamond turning process is used to fabricate large embossing drums that are employed within a reel-to-reel process producing low-cost high-quality diffractive optics. The capacity and technology base for the diamond turning machines used to manufacture these large-scale ultra-precision structured drums are very similar to the machines used previously to fabricate X-ray space optics. The machine tool suppliers who previously delivered machine tools for astronomy and defence programmes during the twentieth century are, in the twenty-first century, producing ultra-precision machine tools for machining diffractive film embossing tools—an example of machine, process and output is shown in figure 11.

The complexity of the surface structures is driven by the need for very complex-shaped features to avoid light loss/absorption together with the need for features to have sub-micrometre placement accuracy or registration over distances up to 2 m or more. The machining duration to cut a structured diffractive drum of such size having 10–50 μm features can be as much as 100–200 h. Any significant untreated thermal distortion of the machine tool during this processing time would cause a failure to produce useful product. Consequently, the most advanced structured drum diamond turning machines employ active temperature control operating in the milli-kelvin range and use metrology frames as developed previously for the large machines for astronomy optics manufacture.

The economic importance of display technologies has become ever more significant; displays are now a main feature of our daily lives, and provide product differentiation spanning children’s toys, mobile phones, computers, TVs and large advertising displays. The fabrication of advanced displays is enabled by ultra-precision fabrication technologies, for example, reel-to-reel fabrication of brightness enhancement films for displays. These reduce energy consumption while providing greater illumination and longer battery life. Such optical films can also provide greater quality viewing, three-dimensional and security features. The manufacture of active elements for flat panel displays represents complex ultra-precision manufacture where accretion, removal and joining processes must work in combination for effective mass production of these hard (non-flexible) panel items.

The future of displays, and potentially cost-effective large-area solar energy production, is associated with low-cost organic (plastic)-based substrates and their reel-to-reel fabrication. Significant progress in plastic-based displays has already been made through a combination of innovations in ultra-precision engineering and chemistry (arguably nanotechnology). Active organic-based substrate manufacture demands new ultra-precision processes operating
over large areas at high accuracy and with high speed. By moving away from inorganic (metal conductive)-based electronics on non-flexible material substrates, a significant opportunity exists to reduce the capital costs of establishing manufacturing facilities for electronics-based products. As such, the manufacture of next-generation organic-based electronics can be made more accessible to manufacturing companies. Organic electronics and ultra-precision engineering provide a key opportunity for companies, and even countries, to re-engage in high-technology product fabrication, avoiding prohibitive capital barriers.

4. Conclusions

This paper has introduced the historical drivers of increasing manufacturing accuracy exemplified by the long-established demands of science programmes. The authors have attempted to illustrate that the ultra-precision engineering created in support of many large-scale science projects has subsequently translated into core manufacturing processes (or product systems) of today’s advanced processes and products. The paper also highlights the changing focus
of the major science (and engineering) programmes in the twenty-first century compared with those of the twentieth century. We have also sought to highlight sustainable energy creation (along with wealth creation) as the major drivers of ultra-precision engineering for the future.

In conclusion, we emphasize that ultra-precision engineers enable major science successes. In the twenty-first century, it is ultra-precision engineers who hold a practical responsibility for the continued sustainability of the human population.

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