Precision engineering is a relatively new name for a technology with roots going back over a thousand years; those roots span astronomy, metrology, fundamental standards, manufacturing and money-making (literally). Throughout that history, precision engineers have created links across disparate disciplines to generate innovative responses to society’s needs and wants. This review combines historical and technological perspectives to illuminate precision engineering’s current character and directions. It first provides us a working definition of precision engineering and then reviews the subject’s roots. Examples will be given showing the contributions of the technology to society, while simultaneously showing the creative tension between the technological convergence that spurs new directions and the vertical disintegration that optimizes manufacturing economics.

**Keywords:** precision engineering; history; technological convergence; vertical disintegration

1. Introduction

A quarter century ago, I had the impudence to suggest to my senior co-authors of a conference keynote paper [1] that the driving forces in precision engineering had always been:

— fear;
— greed;
— pride; and
— inquisitiveness,

with the implication that defence spending was a more important driver than trade, and that these two drivers dominated. The laudable goals of basic research spur working scientists and technologists (inquisitiveness), but we need to couch our requests for support to non-technical budget appropriators in economic or

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One contribution of 16 to a Discussion Meeting Issue ‘Ultra-precision engineering: from physics to manufacturing’.
Today, it is clear that precision engineering is still driven by the same four forces, although economic forces probably dominate. One notable example of a transition from military to commercial emphasis is single point diamond turning, or ‘micro-machining’ [2], of optical components. Opticians\textsuperscript{1} have long used lathes to produce spherical ‘tools’ used in grinding and polishing operations. As early as 1648, Maignan (figure 1) described a polar coordinate tracer lathe for producing concave and convex metal optics; there is no evidence, however, that such a machine was built. Diamond tools were routinely used by scientific instrument makers, for decorative work on watch cases, and in the first half of the twentieth century, there are numerous references ([4,5] and others cited in Evans [6]) to piston turning, boring and other operations on non-optical components.

\textsuperscript{1}‘Optician’ is frequently used—and is used here—to describe a fabricator of optical elements or systems rather than ‘people who are trained to fill prescriptions for eye correction in the field of medicine’ (source: Wikipedia).
The emergence of modern single point diamond turning for optics fabrication can probably be attributed to parallel efforts during World War II at Polaroid Corp., in the USA, and Philips in Holland to fabricate Schmidt correctors for infrared optical systems. Much of the leading work for the next three decades or so was driven by military imperatives.

Precision machining is a key technology in nuclear weapons manufacturing; in the early 1960s, engineers at Oak Ridge’s Y-12 plant implemented single point diamond turning initially to take the process effects out of their studies of machine tool performance, using polished single crystal diamond microtome knives as their original tools. They rapidly recognized the potential for fabricating reflective optics for use in the infrared and for high power, cooled laser optics. Other US national laboratories (Lawrence Livermore, Los Alamos, Batelle Northwest, Rocky Flats) and defence contractors (e.g. Bell and Howell, Perkin Elmer) built or commissioned custom machines. ‘Standard’ commercial machines emerged in the late 1970s–1980s and with them commercial applications. Custom machines continued to be developed for scientific [7] and military applications [8,9].

Early commercial applications were for high-speed polygon scanner mirrors (bar code readers, laser printers, etc.) and rolls for producing structured films, such as high reflectivity road signs (reviewed in Evans & Bryan [10]). Over the past two decades, commercial applications have exploded, largely through the fabrication of moulds for replicated optics, including contact lenses, illumination systems, micro-optic arrays, brightness enhancement films for flat panel displays of all sizes, Fresnels for solar concentrators, camera lenses, DVD pick-ups, etc. Military applications remain, but they are no longer the dominant driver.

2. What is precision engineering?

It seems, a priori, that any discussion of the history and evolution of precision engineering requires the historian to have a clear definition of the topic. Precision, apparently, is relative as one can locate ‘precision plumbing’ in every state in the USA! Some definitions simply suggest that precision engineering focuses on the highest performing systems, for example:

- Precision engineering covers precision machine tool and measuring machine design and their construction, accuracy evaluation, and operation;
- Research and development, design, manufacture and measurement of high accuracy components and systems.

(American Society for Precision Engineering 2011, www.aspe.net)

Or

Work at the forefront of technology.

(K. J. Poulter 1985, personal communication)

The design and building of complicated tools and instruments whose parts must be exactly right in size and position.


Precision engineering is a multi-disciplinary range of technologies, based heavily on the application of metrology (dimensional and thermal) to manufacturing and covers materials, machining and fabrication processes, design and build of high-precision
machines, micro-sensors, actuators, displacement measuring devices and control systems, etc.

(McKeown [11]; P. A. McKeown 2011, personal communication)

Such definitions are seemingly correct, but clearly do not help the professional historian. A more promising avenue is definitions based on the ratio of dimension to tolerance (or measurement uncertainty). For example, Jones [12] in the first editorial of the journal *Precision Engineering*, suggested:

> Precision engineering...defined by the ratio of dimensions to uncertainty...in the region $10^4$–$10^5$...embraces a wide range of activities...the common feature being that it always demands abnormal care and trouble.

Over the three decades or so since Jones wrote that editorial, we have tried to make that ratio larger, and at the same time have perhaps treated the definition with too much reverence. Consider a single axis measurement—for example of a ‘long block’ such as a 100 mm gauge block. Interferometry in air limits us to about 1 ppm K$^{-1}$, while wringing films, contact conditions, uncertainty in the coefficient of thermal expansion, etc., all conspire to further limit measurement uncertainty. In the end, 10 nm expanded uncertainty (one part in $10^7$) is good work.

When we apply the same definition in other regimes, we sometimes stumble. At least two active projects to develop large ground-based telescopes will use segmented, primary mirrors comprising hundreds of approximately hexagonal segments which, when appropriately phased, form the desired shape [13]. The proposed US Thirty Meter Telescope (TMT), for example, has a structure function definition on the surface errors of the individual, 1.5 m (approximately) primary mirror segments. The specification can be converted to a bandwidth limited 15 nm r.m.s. specification on the surface errors with respect to the design equation. The simple ratiometric approach suggests a ratio of 30 m to 15 nm, or $2 \times 10^{10}$ if we consider the full shape of the primary; restricting ourselves to a single segment (1.5 m) reduces the ratio of dimension to tolerance to $10^8$. This logic seems flawed as the tolerance and dimension involved are orthogonal. The tolerance applies to the deviation of the aspheric shape from nominal, with the error in the best-fit radius of curvature separately controlled. Effectively, the tolerated dimension is the departure of the mirror surface shape from a best-fit spherical cap, which is essentially perpendicular to the 1.5 m size of the segment. For TMT, the worst case aspheric departure over a segment is approximately 0.8 mm, reducing the ratio of dimension to tolerance by over three orders of magnitude, but that does not make the segments easy to make.

Another example from optical testing underlines the difficulty in the ratiometric definition. The Laser Interferometric Gravitational Observatory is developing a new generation of optics to push the sensitivity of the observatory. To a first approximation, the requirement is to deliver 400 mm aperture optics with approximately 2 km radii of curvature. The departure from a plane is of order 10 $\mu$m and the tolerance approximately 1 nm, leading to the rather pedestrian ratio of $10^4$. In reality, these are extremely difficult optics to make and measure.

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2It is my understanding that this ratio-based approach arose in a discussion between R. V. Jones and P. A. McKeown.
The historian, therefore, is in trouble; evocative phrasing defines nothing and ratiometric approaches, while indicative, are subject to interpretation. The practitioner, however, is spared these difficulties, saved by the wisdom of Steward [14], who served on the US Supreme Court from 1954 to 1977. To his reported chagrin, his most often quoted aphorism is

I shall not today attempt further to define the kinds of material I understand to be embraced within the term … and perhaps I could never succeed in intelligibly doing so. But I know it when I see it.

He wrote of pornography, but the definition applies to precision engineering. Practitioners know it when they see it. This allows us to consider the history and evolution of the subject in a number of contexts, including the primary traditions in precision engineering, the intellectual tool kit of modern precision engineers and studies of archetypical applications. The current issue indicates the range of such applications; their individual histories are beyond the scope (or space) of this discussion, although those histories tend to drive towards similar conclusions.

3. Primary historic traditions

Precision engineering has been described as a ‘new grouping of scientific and engineering skills’ [15], but this new grouping has a millennium of traditions. Figure 2 attempts to show those traditions, their evolution and some sense of the major interactions; naturally, the complexity of such evolution cannot be fully captured in this simple two-dimensional representation that shows, very approximately, the passage of time from top to bottom.

Astronomy and time-keeping have deep roots. King [16] notes that

Astronomical observation has its roots deep in remote antiquity … the apparent regularity underlying the celestial panorama was the only sure way of noting the passage of time.

A broad range of archaeological sites of varying ages—such as Stonehenge and Brodgar to the Big Horn Medicine Wheel—variously provide remarkable definition of the solstices and equinoxes, invaluable information for agriculture (ignoring the likely spiritual functions). Chaco Canyon, in northern New Mexico, has solar and lunar markings [17,18] as well as pictographs apparently recording the Crab Nebula supernova of 1054 [19] and Halley’s comet a few years later (centuries before Halley).

One can argue that the early observers practiced what today we would call astrology rather than astronomy. Were they driven by the systematic acquisition of knowledge or by the desire for some basis for predicting auspicious dates on which rulers should act?

There is clear evidence, however, of the interplay between astronomy and surveying [20]: the same instruments were used. The first Greek sighting instrument with a graduated scale, the staff of Archimedes, appeared around AD 300. An important instrumental development was Hero’s dioptra (figure 3) from the first century AD. This instrument is a clear precursor of the modern theodolite, and may well be the earliest documented use of precision screws as measuring devices [21]. Notably, such surveying techniques (in the form of

An easily accessible summary can be found at http://suneartday.nasa.gov/2005/locations.
so-called ‘laser trackers’) are being applied, increasingly it seems, to metrology of large-scale modern precision engineered products. Perhaps the most interesting recent application is the use of a laser tracker both to align the elements of the test tower being used in the fabrication of the elements of the primary mirror for the Giant Magellan Telescope and to provide alternative metrology to interferometry, especially in the early stage of figuring [22].

The history of astronomy has a massive primary—and extensive secondary—literature and will not be addressed here. It is, however, pertinent to emphasize some points often lost in ‘heroic’ treatments of the history of technology in general and precision instrumentation in particular. First, the Western astronomer’s perspective tends to focus on developments in instrumentation and observation with the generally unstated assumption that developments were driven by intellectual curiosity. It is salutary to recall that the Royal Observatory was founded with the explicit aim of improving navigation; better astronomical data would minimize mercantile losses at sea.

A second point, commonly missed in history written by practitioners rather than historians, is that the evolution of technology is not a clean, linear process. Rarely is ‘widget A invented by Joe Bloggs and commercialized by Fred’s Fabrication Company’. Like other strands of technology, precision engineering is plagued with painful and wasteful reinvention and repetition of past errors. This, Hocken [23] argued, was due to the absence, until recently, of a well-defined community (in contrast to physics, for example). The emergence in the past quarter century of the American Society for Precision Engineering and, more recently, the European Society for Precision Engineering and Nanotechnology and collaborations between them have started to build an international community, but that community is far from exhibiting a common culture4 with a shared history. A documented history should reduce the wasteful reinvention.

4The Japan Society for Precision Engineering predates these exemplars of emerging professional societies by more than 50 years, although its scope has been much broader, including much that might be described as production engineering [24] as well as activities that easily fit the descriptions in §2. The Dutch Society for Precision Engineering (DSPE) evolved from NVFT, a society for fine mechanism founded in 1957. Other emerging groups include the Korean Society for Precision Engineering, the Asian Society for Precision Engineering and Nanotechnology, and the VDI/VDE sponsored Society Microelectronics, Microsystems and Precision Engineering (GMM).
Another, perhaps greater, benefit of studying the history of precision engineering is that it emphasizes the reality that invention ahead of demand will be forgotten, not commercialized. The leadscrew error corrector cam, for example, was invented many times before (and after) Society Genevoise d’Instrumente de Physique found a market for Thury’s version (figures 4 and 5) of the device in dividing engines and measuring machines in the late nineteenth and first half of the twentieth century (summarized in Evans [6]).

Another key point is that rapid evolution of precision engineering occurs in environments where common technological solutions can be applied to diverse products. A good example of this is the interplay between three strands of early development in fine mechanism—astronomy, navigation and horology. Central to that interplay was the graduation of scientific instruments, and in particular the art of circular division.

(a) Horology and the foundation of instrument making

To the common man, brought up before the ‘quartz revolution’, a Swiss watch once epitomized precision. The confusion of small with accurate notwithstanding, this view reflects reasonably well a strand of influence in the development of precision engineering, most easily seen by switching briefly to considering archetypical applications. Diffraction grating manufacturing was, for at least two centuries, one of the pinnacles of precision engineering practice. Rittenhouse, a trained clockmaker, produced the first-documented diffraction grating. Nobert and Fasoldt, key producers over a century or so, were both initially trained as clockmakers. Nobert’s ruling engine (figure 6) is clearly a modified clockmaker’s gear cutter.

In a different domain, Brown and Sharpe was a dominant name in engineering metrology in the USA for about 150 years. David Brown and his son Joseph were clockmakers, and in the early days of the company, they built a number of tower clocks. Their dividing engines clearly show their roots in horological gear cutters [6].

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Modern precision engineers recognize that every instrument is—in addition to its intended function—a thermometer (and often a barometer and a hygrometer). The foundation for athermal design is the thermally compensated pendulum such as Graham’s mercury bob and Harrison’s gridiron pendulum.

The influence of the clockmakers in the early development of precision instrumentation is clear. Horology has an ample historical literature, mostly written by and for collectors and antiquarians. The evolution of time and its interaction with the emergence of modern civilization is less well documented [26]. Bedini [27], however, is clear in his opinion:

The art of the clockmaker also had a strong influence in the 17th century on the development of tools and apparatus for the scientist…(and the) advent of precision timekeeping was also responsible for the birth of precision scientific instrumentation.

The requirement for more accurate clocks led to investigations of properties of metals, springs, etc. More and better tools had to be devised, and these developments applied equally to scientific instrument making. Note, however,
that the dominant market for early scientific apparatus was not for precise measurement; rather the purpose was to demonstrate theories, to model behaviour, and particularly to grace the ‘cabinets’ of the wealthy.

The drive for more accurate clocks seems obvious when viewed from a modern perspective, but that was not the perspective of the developers of early clocks.

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Landes’ study of the history of time-keeping provides us graphic examples of the interaction of society and technology. It provides us an important lesson to remember when trying to understand the history of specific application areas within precision engineering.

By AD 1000, the Chinese had produced a series of water clocks, or clepsydra, that set them well ahead of Europe and Islam in horological sophistication. They had developed adequate escapements and indeed had an impressive technological lead in many areas. They had undoubtedly encountered the problems caused by cold weather and there are reports of the use of a heated water bath to avoid them. Why then was the mechanical clock developed in Europe? Why, centuries later when mechanical clocks and watches were introduced by missionaries, did the Chinese take so long to copy them? The answers, Landes suggests, lie in a lack of demand. There was no requirement for a more precise measure of the passage of time. In rural areas, the natural cycle determined what needed to be done; where the land was farmed collectively, drums or other signals summoned the workers when they were needed. In urban areas, in the craftsman’s workshop, the concept of productivity was unknown; ‘the great virtue was busyness, unremitting diligence to one’s tasks’ [26]. The only group within China who, in principle, would be interested in increased precision was the court astronomer–astrologers.

Like China, mediaeval Europe had water clocks and sundials, cloudy days and freezing temperatures: it also had monastic Christianity which, Landes argues, provided the essential driving force for the development of the mechanical clock. The development of monastic orders stimulated a drive to uniformity of practice and observance. But why would punctuality be so important? According to Landes

One reason was that lateness…might make it necessary to abridge an office. Another…that simultaneity was thought to enhance the potency of prayer…the whole was greater than the sum of the parts. Multiplication of simultaneous devotions—this was the way of salvation for all. The performance of such a demanding sequence, in particular…the nocturnal office after a period of sleep, imposed a new and special kind of temporal servitude…the medieval church would learn to make alarm mechanisms. Otherwise no one would have got any sleep, for fear of failing in his duty and jeopardizing not only his own salvation, but that of others.

While the clergy developed this new technology, they hardly represent a large market; the spread and development of mechanical clocks were stimulated by other markets; first the numerous courts and then the rich and powerful of the growing urban centres. By the mid-fourteenth century, tower clocks, particularly when combined with costly automata, became a clear symbol of urban pride, whereas miniaturization, the ‘privatization’ of time, generated a huge market potential for these original precision engineers.

The ethos of fine mechanism was born of the clockmakers—but the gestation period was significant. Men such as Graham and Tompion were equally at home in either trade. From there emerged a new community, scientific mechanicians who applied their skills to more than scientific instruments. With the rapid mechanization that came with the industrial revolution came also the first true ‘community’ of precision engineers. It came first to the UK, the nation to have the first industrial revolution; the community comprised not only instrument
makers, but also men such as Bryan Donkin, who commercialized the Fourdrinier process for paper making and built dividing engines; the multi-talented Henry Maudslay; and John Barton, comptroller of the mint, who built a differential screw micrometer (the ‘Atometer’) and a mechanism with 0.25 μm resolution for adjusting rolling machines.

(b) Machine tools and interchangeable manufacturing

The industrial revolution wrought major change in the means of production. Metal working changed dramatically, and machine tools evolved quickly. A parallel change, in the methods of production, also had a significant impact; the increasing replacement of fitting by assembly is one of the widely touted benefits of increasing precision. Thus, a new cadre of precision engineers was born of the machine tool builders and the pioneers of interchangeable manufacturing.

American-made light goods took the 1851 Crystal Palace exhibition by storm; Whitworth led a group of England’s best engineers to study manufacturing methods. Their report coined the phrase ‘the American system of manufactures’ and gave a major stimulus, in the UK at least, to the development of interchangeable manufacturing. As is commonly known, Eli Whitney ‘invented’, or at least pioneered interchangeable manufacturing in his production of muskets under US Government contract from 1798 until his death in 1825. His methods spread though New England, and the Robbins and Lawrence armoury in Windsor, VT, is today viewed as the birthplace of the American system. Unfortunately, the first part of that ‘common knowledge’ has little basis in fact. Woodbury, among others, showed that Whitney’s muskets were hand finished and the parts often not interchangeable [28]. Current scholarship suggests that interchangeable musket parts were first produced in France, and that the first US firearms with interchangeable parts were produced by Simeon North in Springfield, MA, just 25 miles north of Whitney’s plant.

While the American system may have stimulated rapid growth of the use of interchangeable manufacturing, it certainly was not the only stimulus. At the beginning of the nineteenth century, the Royal Navy needed about 100 000 pulley blocks each year. They were supplied by private contractors using labour intensive methods—until the whole process was revolutionized by Marc Isambard Brunel, Sir Samuel Bentham and Henry Maudslay [29].

Prior to his appointment as inspector general of naval works (he was the first, and only, holder of that position), Bentham had spent most of his working life in Russia. There he had invented woodworking machinery for use by unskilled peasants. He subsequently built similar machines for use in English prisons—in both cases aiming to ‘deskill’ manufacturing operations. Once installed in his naval position, Bentham attempted to improve dockyard productivity, eliminate fraud and introduce mechanization as far as possible.

Brunel, a French émigré, had spent 6 years in the USA in a number of posts, including that of chief engineer of New York City. In 1798, he learnt of the problems of block making, and devised and patented a new system of specialized machines. He went to the UK and, eventually, showed his ideas to Bentham. By this time, Maudslay had completed 8 years of service with Bramah, building the machinery to produce Bramah’s patented locks. He had recently set up his own shop, and built machines for Bentham who, in collaboration with his more
famous economist–politician brother Jeremy, had his own workshop. Bentham persuaded the Lords of the Admiralty to support the introduction of mechanized block making. Maudslay made the machines to Brunel’s designs, while Brunel supervised their installation and operation at Portsmouth. It seems a testament to the designs and manufacture of these machines that, as recently as 1984, four were still being used, for other purposes, at Portsmouth (figure 7).

By 1805, three independent sets of machines had been installed, each set capable of handling a family of parts. In total, 72 standard sizes, plus 48 sizes of ‘thin sheaved’ blocks and a number of specialized block designs could be produced. The machines were not, however, synchronized, although it appears that Brunel had designed the machines to produce approximately the same number of parts per hour; this was not a production line. Individual machines ran at their own pace, some handling several parts at a time; wheeled bin storage between machines smoothed the flow of parts and each machine operator was required to be able to operate (in the modern sense of a machine operator rather than as a craftsman) more than one class of machine. This appears to have been the first ‘flexible manufacturing system’; by 1805, the navy was able to dispense with the outside contracts and, in 1808, to produce 130 000 blocks. Those blocks had interchangeable parts. The system paid for itself in 4 years.

4. The precision engineer’s tool kit

As indicated in §2, one can look at the history of precision engineering from a number of perspectives. One is through the ‘tool kit’, the collection of design concepts and machine elements that are commonly found in archetypical applications. In many ways, the design of precision machines and systems is the same as the design of any other system; the fundamentals are identical.

Figure 7. Inside the block-making mill at Portsmouth naval dockyard in around 1900; the world’s first flexible manufacturing system? Image courtesy of the Science Museum/Science and Society Picture Library.
However, the ‘abnormal care and trouble’ that Jones [12] used to characterize precision engineering tends to result in particular emphasis on certain aspects of design. The contents of the tool kit have been widely discussed, among precision engineers [30–32]. Consider one example, ‘determinism’ and the concept of systematic error correction.

\[ (a) \] Determinism

Since the mid-1980s, the phrases ‘deterministic metrology’ and ‘determinism’ have been accepted in the precision engineering community. The principle they embody is simple, almost self-evident, and has been described as ‘central to precision machine design’: perhaps the most interesting aspect is the need to teach it to conventionally educated engineers and scientists, and the difficulty apparently encountered in so doing.

Loxham [33] expressed the basic concept as

... an automatic machine may be classified as operating perfectly. It may not be doing what is required and if this is so it is because it has not been suitably arranged.

Donaldson [34] was more specific:

A basic finding from our experience in dealing with machining accuracy is that machine tools are deterministic. By this we mean that machine tool errors obey cause-and-effect relationships, and do not vary randomly for no reason. Further the causes are not esoteric and uncontrollable, but can be explained in terms of familiar engineering principles.

Implicit in these statements, and others like them, is the concept that since machines, workpieces and the vast majority of precision engineering activity are on a physical scale where probabilistic explanations of physical phenomena are not required, then truly random behaviour cannot occur. Thus, statistics are (T. Charlton 1985, personal communication):

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or, put another way [34]:

... at best an unwarranted distraction and at worst a cloak of respectability for bad metrology.

Bryan [35] takes a slightly less trenchant tone, suggesting that

... the probabilistic approach to a problem is only a tool to allow us to deal with variables that are too numerous, or expensive to properly sort out by common sense and good metrology.

He then ascribes to Portas the now widely quoted observation that

Random results are the consequence of random procedures.

‘Determinism’, therefore, is both emotive of ‘abnormal care and trouble’ and the antithesis of probabilistic treatments. The opprobrium aimed at probabilistic methods seems to be, mainly, a response to the perceived ‘damage’ performed by
modern management’s emphasis on the techniques of statistical process control. This, it is argued, breeds unwarranted assumptions [35], particularly that there is some inherently statistical element in, for example, non-repeatable positioning of machine slides. Practical application of determinism requires acceptance of the idea that the level of apparent non-repeatability is controlled by the equipment, facilities, personnel, time and money available. Directly related to, although not necessarily derivative of the concept of determinism is the common effort to separate, as far as possible, variables influencing machine accuracy and repeatability. Use of three point supports and kinematic design ensures that a machine or sub-system does not suffer strains as a result of motions or deformations in its ‘foundation’; metrology frames isolate measurement systems from machine deformations: compound motions are avoided wherever possible [31].

Determinism states that all process variations are due to assignable, quantifiable causes; decoupling likely causes will ease the subsequent process of assigning observed process variations. Further, this decoupling based on kinematic design principles makes it easier to describe the machine system in closed form equations, and hence easier to analyse and optimize (A. Slocum 1987, personal communication).

Once the ideas of determinism are accepted, one can define three basic approaches to improving machine accuracy:

— error reduction: the brute strength approach of isolating error sources and then eliminating them to the degree required by the application;

— error correction: calibrate the machine or part errors and then provide a corrective action. Examples of this approach are leadscrew error correction cams and software-based correctors, using either look-up tables or parametric models of machine motions; and

— error compensation: measuring either error causes (e.g. thermal drifts) or effects (e.g. part shape) in real time and, through an appropriate model, compensating for the perturbation. Examples are the Harrison gridiron pendulum and adaptively controlled grinders.

The first approach does not appear to have any traceable evolution, other than the broad history of machine design. Error correction, dubbed ‘gadgeteering’ by Bryan [36] naturally leaves traces for the historian; the modern ‘gadgeteer’ clearly wishes his or her skill to be recognized by peers, and therefore publishes descriptions of the techniques developed, while design details of older machines reveal earlier approaches.

The earliest error map, or look-up table, located so far was used by Edward Troughton on a linear dividing engine in the early nineteenth century. Troughton’s original division scheme, for both his circular and linear dividing engines, was based on the idea of first making a reasonably accurate attempt at division, then measuring all the individual errors. On the circular dividing engine, Troughton then made corrections; on the linear engine, however, he stored the errors in, literally, a look-up table. When he needed to use the engine, he simply applied the appropriate corrections to the nominal values, interpolating as necessary. Such an approach is, of course, cumbersome and provokes mechanicians to simply build better machines that do not need correction.
It is, perhaps, worth noting a subtle evolution in error correction and its impact on precision machine design. The better machine still has systematic errors, which another generation of ‘gadgeteers’ can fix with appropriate error corrections—to the limit of the signal to noise in the machine control system (typically no better than 10:1). The alternative approach is to focus on making the machine repeatable, not accurate, to ensure that the errors have spatial frequency content compatible with a designed-in calibration method, and that machine metrology has the necessary bandwidth.

The examples discussed in this section indicate applications of the different error-reduction approaches, but do not allow any deductions about the emergence of explicit understanding of the different philosophies. Engineers and machine designers publishing papers describing design philosophies is a relatively recent phenomenon, making this particular area of historical research somewhat unproductive. The extant artefacts allow interpretation by current practitioners, at the risk of their interpretation being coloured by current perceptions. Despite this caveat, a broad exploration of the precision engineer’s tool kit [6] leads to the same conclusions as studying the historical traditions (§3) or archetypical applications. There is a continuous tightening of tolerances within any given application area; there is a slowly evolving set of core design principles that enable ultra-precision machines to be developed in any particular application area; and there is a continuing tradition of reinvention. Why is this?

5. The cyclic nature of precision engineering and the educational challenge

A simple model of the cyclic nature of precision engineering builds on the work of Rosenberg and Stigler. Rosenberg coined the term ‘Technological Convergence’ to explain the growth of the American machine tool industry in the nineteenth century at a faster rate than any accepted economic model would predict [37]. Simply, a core set of machine elements and design concepts can be applied to a range of applications: gear cutters, milling machines, dividing engines and so on all have a common set of elements. The organization that understands them all diversifies and can serve many markets.

Growth of these individual market sectors proceeds until they are large enough to support their own specialist suppliers. Now ‘vertical disintegration’ [38] promotes specialization, introducing barriers to the cross-disciplinary communication that provided the conditions for technological convergence. New recruits into these specialized industries learn the speciality, not the underlying principles. Designs may be scaled without understanding the fundamentals—until the limits of the design are reached.

The simple model [6] suggested that the ‘new technology’ of the 1970s and 1980s was a reversion to ‘technological convergence’. A new generation of scientific mechanicians, mostly unknowingly, adopted the mantle of the Troughtons and Donkins of the nineteenth century. They understood the broad principles and applied them.

In the twenty-first century, this temporal cycle can no longer apply in application areas at the current limits, for example in the development of lithography tools. These systems require simultaneously the personification of both technological convergence and vertical disintegration—posing a major
educational challenge for the future. These complex systems require ‘systems architects’ who understand the entire system and the interactions between components and sub-systems; they also require discipline specialists. Individual organizations will need a continuous creative tension between technological convergence and vertical disintegration.

Modern postgraduate education is well designed to produce specialists. System architects must be able to convert applications requirements to machine requirements, understand entire systems, communicate requirements to specialists and evaluate their designs, and communicate design to customers and understand their responses. Conventional education systems are, for the most part, not optimized to produce or value such skills. This will be a serious challenge for the future evolution of precision engineering.

P. A. McKeown, D. J. Whitehouse, R. J. Hocken, J. B. Bryan and the late K. J. Stout were severally responsible for sparking my interest in precision engineering in the late 1970s and, together with J. Dinsdale, opening the door to my being both a practitioner and a historian. Colleagues and friends too numerous to mention here have provided input to my understanding of the continuing evolution of precision engineering. The credit is theirs; the errors are entirely mine.

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