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Challenges to NIST in Dimensional Metrology: The Impact of Tightening Tolerances in the U.S. Discrete-Part Manufacturing Industry

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Introduction

Dimensioned geometry is one of the most critical attributes of a host of manufactured goods including airplanes, automobiles, VCRs, communications systems, and computers. These and the other discrete-part products are able to function because the individual physical parts of which they are made have specified dimensions. With Japan as pacesetter, global competition in manufacturing of such products has lead to dramatically tighter tolerances on these dimensions. Tighter tolerances require greater accuracy, in both the measurements which industry must make to control production and the measurements which NIST must make to support industry. This report looks at some recent changes in dimensional tolerances in a number of U.S. discrete-parts manufacturing industries and the measurement challenges to NIST they pose.

The Discrete-Parts Industry

Contrasted with continuous-process industries (which produce materials in bulk), discrete-parts manufacturing industries produce individual products, such as complete aircraft, automobiles, computers and microelectronic chips and all the individual parts of which they are made.

The discrete-parts industry is large: the more than \$500B (10^9) in durable goods alone it produces represents 52% of all manufacturing and 10% of the GNP [1]. As indicated in Table 1, discrete-parts manufacturing includes: the \$241B automotive industry (including \$205B in motor vehicles and \$36B in closely allied farm-and-construction equipment); the \$146B fabricated-metal products industry; the \$104B for the aerospace industry (including \$78B in aircraft and \$26B in missiles and spacecraft); and the \$108B instrumentation, \$96B communications equipment, \$62B computer, and \$50B electronic-components industries [2].

Dimensions in Discrete-Parts Manufacture

For discrete-part products, it is their dimensioned geometry which determines how and how well they function. Whether aircraft, automobiles, computers or integrated circuits, it is because the components of these products have specific geometrical shapes, sizes, and related dimensions that they have, for example, the strength, weight, electrical, and other physical properties, as well as the ability to be assembled, that are required.

There are numerous aspects of dimensioned geometry of discrete parts. For those manufactured in simple prismatic shapes (such as blocks, spheres, cylinders, and cones), dimensioned geometry includes: features of size (such as the length and width of rectangular features and diameter of

Table 1 Value of Shipments ($B) of Key Sectors of Overall U.S. Discrete-Parts Manufacturing Industry

Discrete-Parts Industry Sector	*Shipments*
Automotive	$ 241 B
Motor Vehicles	$ 205 B
Farm and Construction Equipment	$ 36 B
Fabricated Metal Products	$ 146 B
Aerospace	$ 104 B
Commercial/Military Aircraft	$ 78 B
Spacecraft/Missiles	$ 26 B
Instrumentation, Measurement/Control	$ 108 B
Computer/Communications	$ 96 B
Electronic Components	$ 50 B
Total for Industries Shown	*$ 649 B*

circular features); positional relations (such as true position of a feature with respect to a specified coordinate system within the part and the distance between any two features); form (including circularity, cylindricity and sphericity of rotationally symmetric features); finish (or roughness of surfaces); and, finally, angular relation of features (including orientation, parallelism and perpendicularity). For discrete parts manufactured in non-prismatic shapes, dimensioned geometry also includes curvatures. Dimensional tolerances include not only geometrical tolerances, such as allowable deviation on, for example, lengths of objects and positions of holes, but also include surface tolerances, the allowable deviations of surface peaks and valleys from the nominal surface. As surface tolerances, flatness represents the overall allowable deviation of the overall form of the surface from the ideal while roughness represents fine scale deviations.

Critical dimensions specified for particular discrete parts during their manufacture include: the length, width and height of an automobile engine block; the locations of its oil-pan planes and reference holes; and the diameter, position, orientation, and surface roughness of its cylinder bores. Similarly, for a microelectronic wafer being processed, specified dimensions include: the diameter, thickness, flatness and roughness of the wafer; the linewidth, spacing, positioning, and overlay of features in multiple layers variously exposed, deposited or etched during device fabrication; and the number and size of particles on the wafer which can produce defects during those multiple processes. Critical dimensions specified for the complex forms include the aerodynamic contours of automobile bodies and the aspherical surfaces of x-ray lithography mirrors.

The Economic Significance of Tighter Tolerances

For competitiveness in the global market, the ability to manufacture goods to increasingly precise dimensional tolerances is a simple necessity. As evidenced by Japan's success, it is a major factor in achieving dominance of markets. In automobiles, machine tools, video recorders, microelectronic devices and other super-precision products, Japan has become the pacesetter in precision manufacturing.

The logical links between market-dominating product quality and tighter manufacturing tolerances are exemplified by the following account by Taguchi, describing one aspect of Japanese automobile manufacture [3]. According to the account, quality in the operation of an automobile door as perceived by customers correlates with variations in the force required to open the door and a comparison showed that to open them U.S. cars required forces of 76 ± 58 N (17 ± 13 lbs) while

Japanese cars required 31 ± 9 N (7 ± 2 lbs), the Japanese companies thus holding a six-to-one advantage over U.S. companies. The variations in force correspond to variations in the dimensions of door-assemblies which correspond to variations in dimensions of panels from which doors are assembled which in turn correspond to variations in the dimensions of the dies from which panels are stamped. With a 3σ norm of 1 mm on door assemblies, Japanese cars have half the variation in such dimensions as US-made cars [4].

Table 2 Absolute and Relative Tolerances of Dimensioned Features of High-Precision Discrete Parts Made By Techniques From Stamping and Diamond-Slicing to X-Ray Lithography and Molecular-Beam-Epitaxy Combined With Tunneling Microscopy

High-Precision Discrete Part	*Manufacturing Technique*	*Part Geometric Feature*	*Dimension D*	*Tolerance T*	*Ratio T/D*
Auto Door Ass'y	Die Stamping	Panel Size/Position	1 m	1 mm	1000 ppm
Auto Piston	MT Machining	Piston Cylindricity	100 mm	7-8 µm	75 ppm
Mag R/W Heads	Diamond Slicing	Cutter Position	125 mm	2.5 µm	20 ppm
TC Optical Fibers	Die Drawing	Fiber Diameter	125 µm	0.2 µm	0.16 %
Wafer Micropattern	e-Beam Lithography	Pattern Position	250 mm	20 nm	0.08 ppm
Integrated Circuit	X-ray Lithography	Device Linewidth	0.5 µm	50 nm	10 %
Quantum Devices	MBE with STM/Other	Device Size	0.01 µm	0.5 nm	5 %

Similar situations of tighter tolerances required by a competitive market are occurring in other domestic industries as well. For example, the largest U.S. manufacturer of photographic film reports that in order to continue to serve the motion-picture industry — which records images on film, digitally processes and superimposes multiple images, and rerecords on film for high-quality projection in theaters — it must reduce film flutter by producing film with a tolerance on spacings of sprocket holes of 5 μm, half that of the US-industry standard [5]. And a U.S. producer of world-class slicing/slotting machines used in magnetic head production reports that to maintain leadership it must increase the cutting accuracy of its best machines from 2.5 μm to 0.25 μm [6].

Manufacturing Tolerances

Formally defined by ANSI Standard Y14.5 on "Dimensioning and Tolerancing", a tolerance is a number given in an engineering drawing which specifies the total amount by which a dimension is permitted to vary [7]. Represented here by $\pm T$, a tolerance defines a range of acceptability of the magnitude of the difference between the dimension of a part-as-made (D_M) and the dimension of the part-as-designed (D_D), that is, $|D_M - D_D| \leq T$.

Figure 1 shows graphically and Table 2 numerically tolerance-versus-dimension for selected examples of the wide variety of outputs of the discrete-parts manufacturing industry, spanning a range of dimensions from 1 meter to 10 nanometers and a range of tolerances from 1 millimeter to 0.5 nm.

At the large-dimension end of the precision-manufacturing spectrum is the state-of-the-art in automobile manufacture where a 1 mm tolerance on the fit of 1m-size passenger-car doors assemblies is achieved only by the Japanese. Next, also in state-of-the-art automobile manufacturing, is the 7-8 μm tolerance on metal-matrix composite pistons for a new-generation engine under development by a leading Japanese car company [8]. In the intermediate-dimension range is the 0.25 μm accuracy of a slotting/slicing machine for use in the fabrication of the new-generation thin-film magnetic read/write heads for computer memory systems under development by a U.S. company in head-to-head competition with Japanese counterparts [6]. Toward the lower dimensions, are the 0.025 μm (25 nm) tolerances on 125 μm diameter optical fibers for telecommunications systems [9] and the 0.010 μm (10 nm) tolerances representing current demands in electron-beam micropatterning equipment in Japan [10]. Finally at the smallest-dimension end of the precision-manufacturing spectrum shown are 0.0005 μm (0.5 nm) variations on the 10-nm size dimensions of devices such as quantum-well lasers as well as quantum-wire and quantum-dot devices under development [11].

As Table 2 makes explicit, tight tolerances and high precision in discrete parts manufacture of Figure 1 are relative terms that apply to a wide span of products, technologies, dimensions, tolerances, and relative tolerances, the latter ranging from the order of ten parts per hundred ($\sim 10^{-1}$) to the order of ten of parts per billion ($\sim 10^{-8}$).

Trends in Tolerances

The demand for dramatically tighter dimensional tolerances in manufactured goods is, however, pervasive. For example, according to an assessment of the state-of-the-art of conventional machining by the National Center for Manufacturing Sciences, within the last decade, tolerances have decreased by a factor of five. While in 1980 5 μm was the limit of best practice in normal production machining, at present a Cross Company machining system for automotive components is designed

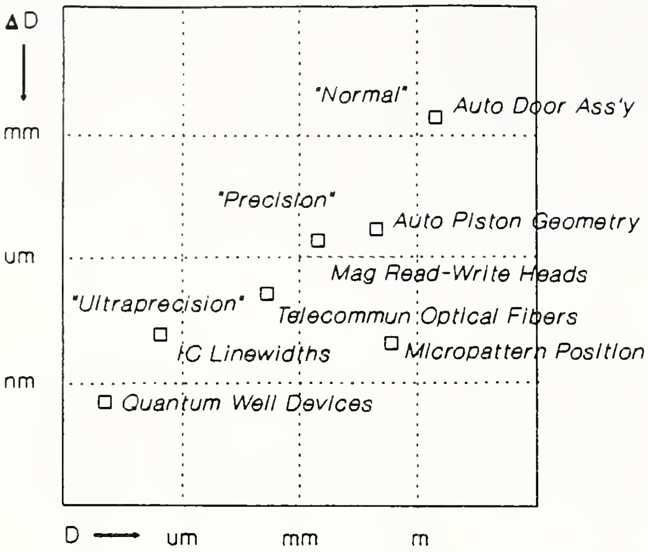

Figure 1 Log-Log Plot of Tolerance versus Dimension for Discrete-Part Products in Normal, Precision, and Ultraprecision Regimes

to hold a bore dimension 1.5 μm. Similarly, in the aerospace industry, Texas Instruments reports its expectation that 1.25 μm tolerances are imminent [12].

Such tightening of tolerances, which transcends conventional machine-tool-based manufacturing and affects all discrete-parts manufacture from automobiles to microelectronics, are part of a major trend shown in Figure 2 and first reported to the international production community in the early 1980s [13]. The trend involves manufacturing in each of three "machining" regimes:

Normal Machining, as done by conventional machine tools, verified by coordinate measuring machines, and used to produce aircraft and automobiles;

Precision Machining, as done by diamond turning machines, measured by special laser interferometer systems, and used to produce optical discs and x-ray mirrors; and

Ultraprecision "Machining", as done by various types of atom, ion, electron, optical-photon, and x-ray systems, measured by electron and tunneling microscopy, and used to produce structures such as micro- and nano-electronic devices.

As indicated in Figure 2 and summarized in Table 3, the overall trend to tighter manufacturing tolerances affects each of these three regimes; the general trend corresponds to roughly factor-of-three decrease in the size of tolerances every ten years.

According to this projection, between 1980 and 2000 state-of-the-art tolerances will decrease: from 7.5μm to 1 μm in the most-demanding "normal" machine-tool-based production; from 0.075 μm to 0.01 μm in the most-demanding "precision", e.g., diamond turning machine production; and from 0.005 μm (5 nm) to < 0.001 μm (< 1 nm) in the most-demanding atom-, electron-, or x-ray "machining"-based production.

Also shown on the trend lines of Figure 2 are examples of the state-of-the-art of each of the three regimes today. In the "normal" regime, there is the 7-8 μm tolerance on the metal-matrix pistons of a Japanese automobile engine noted above [8]. In the "precision" regime there is the 0.025 μm accuracy of the aspheric-optics machining system which has been developed by Lawrence Livermore [14]. In the "ultraprecision" regime there is the roughly 3-nm variation in 30-nm features of prototype "nanolithographic" devices which have been fabricated in laboratories [15].

Trends to tighter surface tolerances follow those of Figure 2, but at values one or two orders of magnitude smaller than those of ordinary dimensional tolerances. For example, in 1990 while the

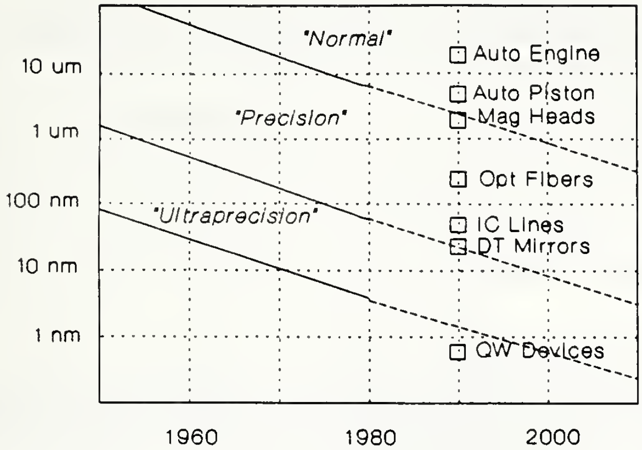

Figure 2 Semilog Plot of Trends in Limiting Values of Tolerances in Normal, Precision and Ultraprecision Regimes with Examples of State-of-Art Today

geometric tolerances of parts manufactured at the limit of the precision regime were of the order of 20 nm, the surface roughnesses of such parts were typically subnanometer with the extreme case being the RMS (root-mean-square) roughness specification of 0.05 nm for laser gyro mirrors.

Impact of Tightening Tolerances on NIST

Tighter part tolerances has a major effect on measurement accuracies due to: 1) the multiples by which production-control measurements are expected to be better than tolerances; and 2) the multiples by which the reference standards are expected to be better than production measurements.

Table 3 Tightening of Realizable Dimensional Tolerances In Normal, Precision and Ultraprecision Tolerance Regimes of Machining From 1980 to 2000.

Machining Regime	*Production and Measuring Machines*	*Accuracy 1980*	*Accuracy 2000*
Normal	Conventional Milling and Turning Coordinate Measuring Machines	7.5 μm	1 μm
Precision	Diamond Turning Machines Interferometer Systems	0.075 μm	0.01 μm
Ultraprecision	Atom and Ion-Beam Machining Scanning Tunneling Microscopes	0.005 μm	< 0.001 μm

Table 4 shows the ratios of inspection-accuracy-to-tolerances and expected-NIST-accuracy- to-inspection-accuracy for two widely used bases. The first basis is the customary "Gage Maker's Rule", which requires that reference measurements, whether inspection-to-manufacturing or NIST-to-inspection, be at least ten times better. According to a CMM supplier, both GM and Ford apply the gage-maker rule for functionally specifying production-measurement CMMs [16]. The second basis is the most-widely used minimum ratio — specified, for example, in Military Standards [17] — which requires a factor of four. Thus by the minimum ratio, the accuracy of NIST reference measurements should be better than tolerances by a factor of 16 and by the Gage Maker's Rule they should be better by a factor of 100.

Impact of Tightening Tolerances in the "Normal" Regime

Table 4 Effect of Two of the Most Commonly Used Ratios on Accuracies of Inspection and Reference Measurements: 1) the Gage Maker's Rule (Factor of 10); and 2) the Minimum Ratio (Factor of 4).

	Gage Maker's Rule	*Minimum Ratio*
Manufacturing Tolerance	T	T
Inspection Accuracy	M = T/10	M = T/4
Expected NIST Accuracy	N = M/10 = T/100	N = M/4 = T/16

Table 5, based on the minimum "factor of four" ratios of Table 4 and the trend of Figure 1, shows the accuracy NIST realized relative to that required to support manufacturing design tolerances and production-control measurements at the limit of "normal machining" for the period 1970 to 2000. As indicated in the third column of Table 5, at the limit of conventional machine-tool-based manufacturing, manufacturing/design tolerances of 20 μm required production measurement accuracies of 5 μm, which in turn required NIST reference measurements accurate to 1.25 μm; in fact, with an error-compensated state-of-the-art coordinate measuring machine acquired in 1972, by the mid-1970s NIST realized an accuracy on two-dimensional ball plates then estimated to be 1 μm [18]. As indicated in the fourth column of Table 5, by the late 1980s tolerances at the limit of "normal machining" had decreased to below 7.5 μm, calling for production measurement accuracies below 1.75 μm, and an NIST accuracy of the order of 0.5 μm. As indicated, however, with the same system in operation throughout the 1980s, NIST accuracy remained essentially what it had been established in the 1970s and NIST capabilities fell behind industry need.

Table 5 Realized NIST Accuracy Relative to That Required to Support Manufacturing Design Tolerances and Production Measurements at Limit of the Normal-Tolerance Regime Over the Period of 1970 to the Year 2000.

Measurement	*Relations*	*1970s*	*1980s*	*1990s*	*2000*
Manufacturing Design Tolerance	T	20 μm	7.5 μm	2.5 μm	1 μm
Production Measurement Accuracy	M = T/4	5 μm	1.75 μm	0.625 μm	0.25 μm
Req'd NIST Measurement Accuracy	N = M/4 = T/16	1.25 μm	0.5 μm	0.15 μm	0.05 μm
Realized NIST Measurement Accuracy	U	1.0 μm	→ Same	TBD	?

The "future-shock" of such changes in tolerances and required accuracies is illustrated by a leading

U.S. CMM manufacturer's account of development of a new CMM to meet auto industry needs. Consistent with the trend in Figure 2 where the limit of tolerances for the "normal-machining" regime in the 1980s approached 7.5 μm and inspection accuracies approached 1.75 μm, the size tolerances on many features of today's U.S.-made automobile transmission housings, clutch covers, engine blocks, and cylinder heads are of the order 12 μm, corresponding to a production measurement accuracy of about 3 μm by the minimum-ratio rule and 1.2 μm by the gage-maker rule. To meet just such a latter demand by GM for the manufacture of its new Saturn, the Sheffield CMM company has successfully developed its new "Summit" line of CMMs. As Sheffield was startled to learn, the high-accuracy CMMs GM was acquiring for the Saturn facility were not for use in an inspection laboratory but on the factory floor [16].

Formally, the three-dimensional length-measuring accuracy of the Summit CMMs, specified in the form used throughout Europe and Japan, is $M = U_{95}\,(3D) = \{\ 1.5 + L/500\ \}$ μm. For NIST to minimally support this production measurement accuracy, its (factor-of-four) measurements would need be $N = U_{95}\,(3D) = \{\ 0.375 + L/2000\ \}$ μm, corresponding to 0.425 μm at 100mm, that is, slightly less than the 0.5 μm shown in Table 5 as the accuracy required of NIST in the 1980s and a factor-of-two better than the documented accuracy NIST has been able to deliver.

Needs today for such "less-than-0.5 μm" accuracies in the "normal" production regime are reported by other industries as well. For example, the same U.S. photographic film manufacturer mentioned above reports that to achieve cutting of film into precise 16-, 35-, and 70-mm widths involves this chain: final width tolerance, 25 μm; fraction of total tolerance allocated to cutting dies, 30% or 7.5 μm; production-control measurement accuracy with a "test quality index" (TCI) of four, 1.75 μm; reference measurements expected of NIST, "TCI" of 10, i.e., < 0.2 μm.

In the 1990s, as Table 5 shows, the limit of manufacturing tolerances for "normal machining" progresses to 2.5 μm, corresponding to a factor-of-four production-measurement accuracies of about 0.6 μm and a required NIST accuracy of 0.15 μm. At present, with a new state-of-the-art coordinate measuring machine, but operating un-error-mapped, on a single axis, in an unstable temperature environment, NIST's capability has been estimated to be $N = U_{95}\,(1D) = \{\ 0.3 + 0.L/1400\ \}$ μm [19], corresponding to 1 μm at 100mm, that is, an order of magnitude less than required for the 1990s and a factor of twenty below that required for the year 2000. The eventual performance achieved by the system is to be determined.

Impact of Tightening Tolerances in the "Precision" Regime

Parallel to the trend to tightening tolerances and their doubly-ratioed demands on NIST reference measurements in the "normal" regime is that in the "precision" regime, which by 1990 spanned an approximate range from 2 μm down to 0.02 μm (20 nm). An example of the competiveness-driven tightening of tolerances in this regime involves the need of a U.S. manufacturer of the specialized slicing/slotting machines used fabricate the magnetic read-write heads used in computer memories.

As summarized in Table 6, in 1980, magnetic head manufacturers were slicing 50-mm substrates into 200 heads with design/manufacturing tolerances of 50 μm; today they are slicing 125-mm substrates into 4000 heads of half the width and one-fifth the tolerances or 10 μm in ordinary applications and 2.5 μm in critical ones. Because of the continuation of this trend and entry of Japanese companies into the market, by 1995-2000 the U.S. producer of the slicing/slotting machines used to cut those substrates will need to develop a machine capable of slicing 150-250 mm substrates to tolerances of less than 0.5 μm, with 0.25 μm as a design goal [6]. As also shown in Table 6, due to the double-ratioing of such tightened tolerances, the required accuracy of NIST reference measurements for ordinary tolerances in 1980 was 3 μm, by 1990 it was 0.6 μm, and by 1995-2000 it will be 0.15 μm; for the newly-developed critical applications, such as fabrication of thin-film heads, the need in 1990 was 0.15 μm and by 1995-2000 it will be 0.015 μm (15 nm).

Table 6 Impact of Changing Tolerances of Computer Magnetic-Memory Read/Write Heads on Accuracy Required of Slotting/Slicing Machine Tools and NIST Reference Measurements 1980-2000.

	1980	*late 1980s*	*mid-1990s*
Heads/Substrate	200/50mm	4000/125mm	
Rel# Heads/Area	1	4	
Machine Envelope	50mm x 50mm	125mm x 125 mm	150mm x 250 mm
Tolerance: Ordinary	50 μm	10 μm	2.5 μm
Critical		2.5 μm	0.25 μm
Reqd NIST Accuracy	3 μm	0.15-0.6 μm	0.015-0.15 μm

In the magnetic storage industry, surface tolerances have also decreased to levels corresponding to accuracies beyond NIST capabilities. For example, the pole tip of a magnetic head is specified to be recessed from the surrounding shoulders by less than 0.025 μm and the industry requires inspection measurement systems to be calibrated at the Gage-Maker's-Rule factor of ten better, that is, 2.5 nm [20]. Such measurements are normally performed by a profiling microscope, the calibration of which is checked by step-height standards. With a minimum factor of four better expected, the accuracy required of NIST for calibration of step-height standards should thus be 0.6 nm, about a factor of two better than NIST can deliver.

Also representative of the trend in this precision regime are the impact of changing tolerances for registration and widths of features of devices produced by x-ray lithography [21]. As summarized in Table 7, in the early 1990s, the state-of-the-art of microelectronic manufacture involves production of individual circuit elements with 500 nm (0.5 μm) features having design tolerances of 80 nm on registration and 50 nm on linewidths. Under development now are the technologies, including x-ray lithography, to produce 250-nm features with design tolerances on registration of 40 nm and on width of 25 nm. As also indicated in Table 7, the move from 500-nm features now to 250nm features later this decade corresponds to a changes in the accuracy of reference measurements for registration and linewidth from 5 nm to 2.5 nm and from 3 nm to 1.5 nm, respectively.

Impact of Tightening Tolerances in "Ultraprecision" Regime

Finally, parallel to the trend of tightening tolerances and their effect on demands on NIST in the "normal" and "precision" regimes is that in the "ultraprecision", where as indicated in Figure 1, by 1990 both tolerances and dimensions had decreased to a range from 0.02 μm (20 nm) to less than 0.001 μm (i.e., < 1nm).

Table 7 Impact of Changing Tolerances on Registration and Width of Features Produced by X-Ray Lithography on Accuracies of Inspection and NIST Reference Measurements 1990-2000.

		1990	*2000*
Feature Size		500 nm	250 nm
Registration	*Design Tolerance*	80 nm	40 nm
	Inspct Accuracy	20 nm	10 nm
	NIST Accuracy	5 nm	2.5nm
Linewidth	*Design Tolerance*	50 nm	25 nm
	Inspct Accuracy	12 nm	6 nm
	NIST Accuracy	3 nm	1.5 nm

Thus at the extreme low dimension-tolerance limit of discrete-parts manufacture is the emerging technology of quantum optical and electronic devices, being investigated as a potential successor to large-scale integration of conventional transistors and a basis for new non-binary-logic types of computing [22,23]. Based on quantum-mechanical phenomena occurring when electrons are confined in structures smaller than their wavelength, the devices require nanometer-scale dimensions and sub-nanometer tolerances.

Table 8 summarizes for quantum-well, quantum-wire, and quantum-box devices with various applications the characteristic dimensions and associated tolerances of the one-, two- and three-dimensional nanostructures of which they are respectively comprised.

Quantum Wells: Shown in the second row of Table 8 are 2D quantum-well devices, the first quantum devices to enter the commercial market, in use as lasers used in most compact disc players, sources for optical-fiber communication systems, and low-noise amplifiers for direct-broadcast satellite receivers [11]. With well-controlled layer-growth techniques such as molecular beam epitaxy (MBE), it is now possible to fabricate 2D-freedom, 1D-confinement layered structures of quantum-well devices to thickness dimension and uniformity tolerance required. For example, layers with a vertical dimension of 10 nm can now be fabricated with a tolerance of as little as 0.2 nm [24].

Quantum Wires: In the third row of the table are 1D quantum-wire devices being developed as high-speed, high-electron-mobility "ballistic" transistors for applications such as analog-to-digital conversion at multiple-gigahertz rates [22]. Fabrication of 2D-confinement structures begins with 1D confinement layers for vertical nanostructure and uses pattern-transfer lithographic techniques, such as electron- or ion-beam, to produce the other, lateral nanostructure. However, while the one (vertical) dimension can be fabricated to MBE tolerances, fabrication of the other (lateral) dimension by lithographic techniques has limited the overall dimensions of quantum-wire devices has to 30 nm [11].

Quantum Boxes: In the fourth row are 0D quantum-box (or -dot) devices being developed as post-VLSI electronic devices and post-binary-logic computers including novel multi-state logic systems such as cellular automata [22]. With one (vertical) dimension produced by MBE and two lateral produced by conventional lithographic techniques, quantum-box diodes have been fabricated with overall "diameters" of as little of 30 nm [25]. For producing smaller nanostructures, a variety of novel fabrication techniques are being investigated [11], including the use of tunneling microscope systems for writing patterns specifically on III-V semiconductors [26,27].

Tolerances on Quantum Devices: In the last column of Table 8 are shown the tolerances associated by various means with the fabrication of quantum-well, quantum-wire, and quantum-dot devices: the 0.2 nm tolerance on the vertical dimension of 1D quantum-well devices is single-atom-layer limit associated with MBE of such devices; for quantum-wire and quantum-box devices, the 3 nm corresponds to a 10% variation which a theoretical evaluation of 20-nm quantum-boxes [28]. For comparison to the dimensions and tolerances realized in fabrication of actual quantum devices, in the bottom row of the Table 7 are shown the smaller dimensions and tolerances indicated as being required by theoretical modelling of quantum-boxes used as lasers. As indicated in the table, while tolerances on diametral dimensions of 20nm devices need be of the order of 2 nm or 10%, those on 10-nm devices need be proportionately tighter, assumed here to be 5% or 0.5 nm, corresponding to that attainable in 1D structures by MBE.

As has been observed, the manufacture of 2- and 3-D nanostructures to such tolerances poses a major technological challenge [11]. As has been shown throughout this report, because of the minimum factor-of-sixteen expected by industry in the accuracy of NIST reference measurements relative to manufacturing tolerances, the measurement challenge is all the more formidable. For example, with manufacture of a 10-nm quantum-box device to a 5% or 0.5-nm tolerance, the

Table 8 Dimensions and Tolerances of One-, Two- and Three-Dimensional Nanostructures Required to Confine Electrons in Quantum Devices of Respectively Two, One and Zero Degrees of Freedom

Quantum-Device Structure	*Example Application*	*Degrees Freedom*	*Constraining Nanostructure*	*Dimension D*	*Tolerance T*
Quantum Well	Tiny High-Efficiency Lasers On Chips	2D	1D Vertical	10 nm	0.2 nm
Quantum Wire	Ballistic-Transistor Multi-GHz A/D Conversion	1D	2D 1 Vertical, 1 Lateral	30 nm	3 ? nm
Quantum Dot	Diodes, Binary-, Novel Multi-Switch Logic	0D	3D Diametral: 1 Vert / 2 Lateral	30 nm	3 ? nm
	Theoretical			20 nm 10 nm	2 nm 0.5 nm

accuracy ostensibly required of NIST to support the 0.125-nm production-measurement accuracy would be an almost unimaginable 0.03 nm or 30 pm (that is, $30 \cdot 10^{-12}$ m).

Challenges to NIST

As has been shown so far, because of the leveraging effect of tolerance-to-measurement-accuracy ratios, the trend of decreasing dimensional tolerances in manufacture of discrete-part products critical to U.S. economic well-being is presenting major challenges to NIST. Over the last decade, NIST has met a number of such tolerance-driven measurement challenges, particularly those affecting Federal government mission agencies.

For example, when NASA diagnosed the cause of the Space Shuttle Challenger disaster as the catastrophic failure of the O-ring seal on the solid rocket motor due at least in part to out-of-tolerance O-ring grooves, under contract to NASA NIST was able to: evaluate the specialized measuring machines subsequently proposed for their inspection; determine which could realize the 125 μm (34 ppm) measurement accuracy on the 3.7m-diameter rings; and lay the basis for NASA's subsequent revision of its design, procurement and inspection specifications for those critical seals [29].

When DoE undertook development one of the most advanced machine tools in the world, the Large Optics Diamond Turning Machine capable of direct machining mirror-like surfaces of aspheric optical elements greater than 1.5m in diameter, under contract to DoE NIST was able to provide the field validation of the super-precise machine to prove it capable of machining to figure tolerances approaching 25 nm [30].

And when DoD undertook development of the "Stars Wars" Strategic Defense Initiative, which required systems with angular pointing capabilities of 0.2 ppm (corresponding to 1m in 5000 km), far beyond the state-of-the-art of measurement laboratories to support, with funding from SDI NIST was able to advance the state-of-the-art by designing and putting into operation a high-resolution angle measurement system with a current 0.04 ppm accuracy (expected to be improved by error-mapping of the instrument) [31].

However, in non-defense manufacturing — from the seemingly familiar regime of "normal machining" as in automobile manufacture, through the less familiar regime of "precision machining" as in diamond slicing of magnetic heads, to the exotic regime of "ultraprecision machining" as in x-ray lithography of next-generation electronics — there are major measurement challenges to NIST which have been unaddressed.

Unmet Challenges to NIST

For example, NIST has not been able to meet the needs of U.S. manufacturers and users of coordinate measuring machines such as the "Summit" described above. U.S. companies, including Caterpillar, Brown and Sharpe, and Sheffield have made clear the limits of NIST in meeting their needs for laboratory-based measurements and calibration standards to support 3D coordinate measuring machines which are critical to modern inspection in aircraft, automotive and defense production. Representative of these unmet needs is the recent letter from a Vice President of the Caterpillar Company [32], which says:

Five years ago our company embarked a major factory modernization program with the purpose of maintaining, if not increasing the competitive edge that has historically been ours. A vital component of our overall program was modernization of our metrological equipment. Central to the metrology upgrade was increased use of coordinate measuring machines (CMMs) on our factory floor.

Obtaining length standards of adequate accuracy, certified by NIST, for use in certification and ongoing verification of our new CMMs is a problem of on-going concern. For the past three years we have been unable to obtain certification of step gages from NIST... Our current solution is to use PTB (German Standards Bureau) for certification of step gages ...

The current situation is unacceptable. We cannot afford the cost and time of continuing to send reference artifacts to Europe for certification. For both competitive and strategic reasons, we must have a metrologically strong partner at NIST...

Similarly, there are also unmet needs for reference measurements in the "ultraprecision" regime, especially in support of new technology development. Of particular concern are the various competing lithographic techniques — ultraviolet-light, electron-beam and x-ray — being refined or developed to make the coming generations of electronic devices. U.S. semiconductor manufacturers repeatedly indicate their unmet needs, for example, for 2D measurements and standards for microelectronic manufacture [33]. Representative of the unmet needs in this regime is the report from DuPont Photomask [21], which says:

A common thread that seems to exist among all competing (lithographic) techniques is the current capability to measure linewidths and registrations on both masks and wafers... Results indicate that measurement error should be less than one fourth of the specification being measured to provide a reasonable fabrication window ... Our current capabilities are marginal with respect to this standard and we are severely limited in our ability to develop 0.25 μm technology.

In parallel with its inability to meet the most demanding needs of U.S. industry, NIST cannot provide itself with dimensional measurements of sufficient accuracy to satisfy its own needs in the realization of primary standards of SI units other than length. For example, whereas the British National Physical Laboratory realizes the candela, the international standard unit of luminous intensity, to an accuracy of 0.2%, NIST can do so only to 1%, with 0.4% due to uncertainty in the dimensional measurements of the radiometric apertures. Comparable situations exist in NIST's realization of primary standards of pressure, temperature, and microwave impedance where state-of-the-art measurements of dimensions of various other pistons, apertures and cavities are involved.

Benchmarking NIST Capabilities to Support Industry

In other advanced industrial nations, domestic manufacturers have been achieving higher dimensional quality through more direct ties to their respective national standards institutes, the latter providing state-of-the-art dimensional measurement technology and traceability to national and international standards. For example, Nikon of Japan is drawing upon the advanced measurement capabilities of that country's National Research Laboratory of Metrology (NRLM) to achieve the world-class performance of its market-dominating step-and-repeat cameras for semiconductor manufacture [34]. Similarly, Zeiss of Germany is drawing upon the advanced capabilities of that country's Physicalishe-Technische Bundesanstalt (PTB) to achieve such performance in its market-dominating coordinate measuring machines for automated inspection [35].

U.S. companies, in contrast, cannot obtain state-of-the-art dimensional measurement-and-standards support from NIST, which is no longer on a par with NMRL, PTB or even many U.S. companies in terms of capabilities or equipment. Table 9 compares NIST with PTB (an EEC as well as FDR reference laboratory) in terms of the measurements which each can provide to their own domestic CMM and auto makers. As indicated by the table, PTB can calibrate artifacts of two dimensions versus NIST's one, over a range of temperatures instead of at a single value, controlled to 0.01°C degree instead of 1°C, to a well-established accuracy of 0.1 μm instead of a best effort at least five times worse [35]. Such poor capabilities on the part of NIST have made it unable to provide the better-than-industry support required of it as the U.S. standards reference laboratory.

Table 9 Inferiority of NIST Dimensional Accuracy and Reference Temperature Control Relative to PTB (German National Lab), Zeiss (German CMM Manufacturer) and Sheffield (U.S. CMM Manufacturer)

FDR/EEC	*Accuracy*	*T-Control*	*USA*	*Accuracy*	*T-Control*
Zeiss	0.5μm	0.1°C	Sheffield	1.5μm	0.1°C
PTB	0.1μm	0.01°C	NIST	> 0.5μm	> 1°

The Role of NIST in Manufacturing to Precision Tolerances

Under its new charter, NIST now has a technology and a standards responsibility for assisting U.S. industry in achieving technological competitiveness. In terms of support for the dimensions-and-tolerances aspects of discrete-part manufacturing, this dual responsibility involves:

- Provision of practical access to the international standard of length by which such dimensions and tolerances are defined; and
- Assistance in development of the manufacturing technology by which dimensions and tolerances are realized.

Table 10 shows schematically the system by which the dimensions and tolerances of consumer goods are linked through those of producer goods to the international standard of length. As indicated at the bottom of Figure 3, system-type discrete-part *consumer goods* such as automobiles, aircraft and computers are comprised of subsystem-type discrete parts such as reciprocating and turbine engines and integrated-circuits which are in turn comprised of component-type discrete-parts such as pistons, fan blades, and processes wafers. As indicated in the middle of the Figure, such consumer goods and their parts are manufactured by means of discrete-part *producer goods*, including machine-tools

— such as milling machines, diamond-turning machines, and e-beam step-and-repeat lithography systems — and measuring machines — such as coordinate measuring machines and scanning electron and scanning tunneling microscopes. And as indicated toward the top, at the subsystem and component level of the producer goods, both machine tools (which impose dimensioned geometry on material) and measuring machines (which determine the degree to which that dimensioned geometry conforms to design) require measurement subsystems, the most modern of which involve displacement interferometers and optical-wavelength lasers, the latter providing the means to realize the SI unit of length, the meter, indicated at the very top of the figure.

Some Specific Challenges for NIST

Table 11 shows, in terms of the chain of discrete-part producer and consumer goods of Table 10 some of the key measurements-and-standards challenges to NIST which have been recently identified. Horizontally, in log scale each row represents a tolerance band, from > 10 μm through < 1 nm; vertically, each the columns represent the levels of Figure 3, with the three consumer-good levels shown by the single last column.

As indicated by entries in the second, third and fourth rows of Table 11, that is, in the 0.1-10 μm tolerance regime, there are many unmet U.S. industry needs associated with modern high-accuracy coordinate measuring machines. In the documentary standards area, there are different US, German, Japanese and ISO CMM performance-evaluation standards in use in different national markets and there needs to be a means to intercompare the effect of use of these different standards and the reference artifacts specific to each on evaluation of CMMs. There also needs to be developed a means to evaluate the measurement uncertainty (U_T) associated with given CMM measurements of dimensions of actual parts based on the evaluated accuracies of the CMM and probe and the specific number of probed points, substitute-geometry algorithm, and software implementation employed. Also needed in the CMM area are high-accuracy one-, two-, and three-dimensional reference standards and the means to determine the temperature-dependence of the accuracy of CMMs and those reference standards.

As indicated by entries in the fourth and fifth columns of Table 11, there are many unmet needs associated with optical-wavelength lasers and the interferometer systems of which the lasers are part and by which dimensional measurements are tied to the standard unit of length. Because displacement interferometers measure only change in position with movement of a reference mirror and lose track when their laser beam is interrupted, there is a need for multiple-wavelength absolute-distance interferometers, especially operating on synthesized, tunable wavelengths. There is also a need for a widely-available user-friendly iodine-stabilized laser to provide one-part-in-10^{10} reference wavelength accuracy for the most demanding industrial applications. And there needs to be developed diode-laser sources as hardy, compact, solid-state replacements for the bulky, breakable gas-in-glass helium-neon laser.

As indicated by entries in sixth column of Table 11, there are unmet needs in terms of advanced-metrology high-precision machine tools. For example, to achieve the 1 μm accuracies of the normal-tolerance regime, machine tools need metrology at the level of new types of built-in measuring devices to monitor the machines state and the dimensions of parts being fabricated; to achieve 10-nm accuracies of the precision-tolerance regime, they need metrology at the level of new, metrology-driven designs; and to achieve 1-nm accuracies of the ultraprecision regime, they need metrology at the level of understanding of tool-material interactions.

Tightening surface tolerances in semiconductor manufacturing also present difficult challenges for NIST. For example, measurement needs of companies such as Veeco-Sloan — which supplies both the semiconductor and optics industries — is currently for NIST accuracies of 0.6 nm (on 30 nm steps) with 0.1 nm (on 10 nm) anticipated in the near term. Future needs for roughness standards for the optical, semiconductor and magnetic-storage-device industries include standards with well-defined surfaces with roughness values from 1 to 7 nm [36]. To meet these needs it will necessary for NIST to develop roughness and step-height standards with uniformity and smoothness at the atomic level and to develop profiling instruments, such as the atomic force microscope, with the stability required to measure them.

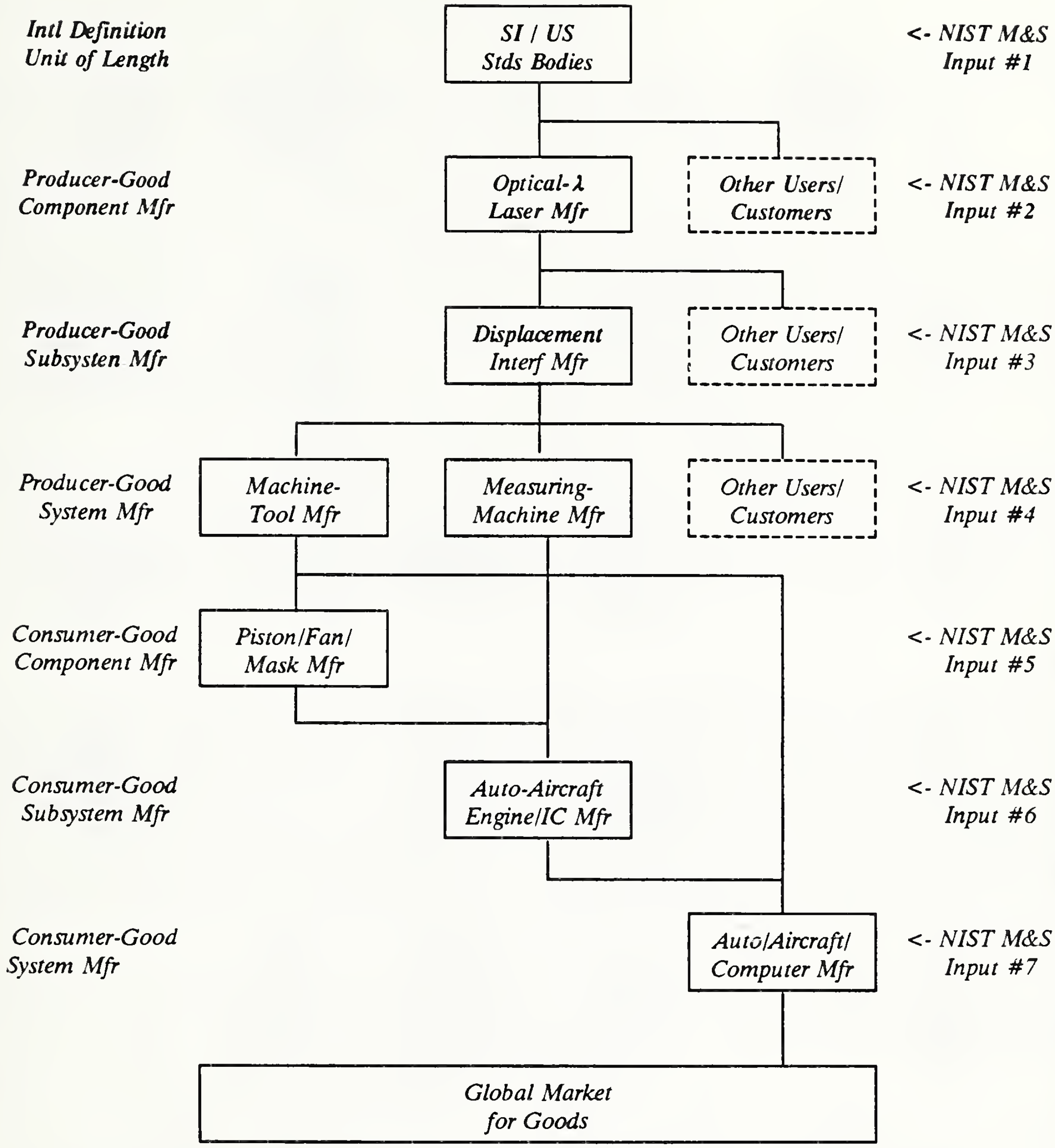

Table 10 NIST Measurement-and-Standards Support Inputs (#1-#7) to Achievement of High-Precision Tolerances in Discrete-Parts Manufacturing Beginning with the International and National Standard of Length and Proceeding Through the Chain of Interdependencies of Producer and Consumer Goods At Their Respective Component, Subsystem and System Levels of Production. The Overall Chain Is Specifically Illustrated for the Manufacture of Autos, Aircraft and Computers By Means of Those Optical Wavelength Laser Interferometer Equipped Machine Tools and Measuring Machines Specific to Manufacture of Those End Products Respectively. Shown Explicitly Only for the Consumer-Good System Manufacturer But True of the Intermediate Products and Producer Goods Is Their Being Produced for Trade in the Global Market for Goods.

Table 11 Challenges to NIST In Matrix of System Element (Documentary Standards, Measuring Machines, Metrology-Incorporating Machine Tools, and Components) and the Magnitude of the Tolerances of the Discrete Part Being Manufactured

	Documentary Standards	*Lasers, Optics, Detectors, etc*	*Interferometers, Probes, etc*	*Measuring Machines*	*Machine Tools*	*Manfactured Parts*
≥ 10 μm	Evaluation U_T of Point-Sample CMM Systems	...	...	...	...	Mfg in Gen'l: Intelligent Vision-Based CMM Systems
1 μm	Evaluation of Multiple Natl/ Intl CMM Stds	Multi-Synthetic-λ Laser Sources	Multi-λ Abs Distance Measurements	Temperature-Dependence CMMs & Stds	Conventional MT: Sensor-Based In-Process Metrology	...
100 nm	...	Diode-Laser Sources for Interferometers	Performance Evaluation of CMM Probes	Calibrated 1,2,3D CMM Artifacts	...	...
10 nm	...	User-Friendly I-Stabilized HeNe Laser	...	Artifacts Stds for Optical and Electron Microscopes	MagHead Slicer: Ultraprecison Metrology-Based Design	Semiconductor Lithography: Cal 250mm 2D Grids
≤ 1 nm	Artifacts for Surface Measurement	...	λ/1000 Fringe-Fractioning Systems	XRO: MMs for X-Ray -Optics and Devices	DTMs: Tool-Matl Interaction Measurement	Nano S&T: Calibrated nm Features Atom-Smooth Planes

Potential NIST Responses to Industry-Need Challenges

Table 12 shows a matrix of potential NIST approaches and laboratory deliverables that could be directed at some of the key dimension-and-tolerance problems of industrial users operating in in each of the normal-, precision-, and ultraprecision-tolerance regimes.

Normal-Tolerance Regime: As indicated in rows two through four of Table 12, in the normal-tolerance regime, the automotive, farm-and-construction equipment, aircraft and defense-aerospace industries need tests of methods used for the evaluation of CMMs in procurement, need calibrated artifacts for CMMs in use in production control, and need data on the performance of CMMs and reference artifacts at temperatures encountered on shop floors. To respond to these needs, NIST needs to develop a state-of-the-art coordinate metrology capability, including the ability to measure, model and calibrate the thermal behavior of CMMs and artifact standards and to implement, by means of software and artifacts, emulations and tests of the various CMM performance tests encountered by U.S. manufacturers in foreign markets. Example deliverables in terms of new NIST laboratory capability in this regime include: a state-of-the-art reference CMM with substantially better than 0.5 µm volumetric accuracy and an absolute, uniform temperature of 20.0 controlled to better than 0.1° C; a thermal-test facility for CMMs and artifacts with uniform, constant temperatures over the range 5°-35° C; and a combined software-artifact implementation on the reference CMM of the various CMM calibration and performance tests such as the German, Japanese, US and ISO standards.

Precision-Tolerance Regime: As indicated in rows five and six of Table 12, in the precision-tolerance regime, both measuring machines and machine tools are involved, both needing absolute-position measurement capability increased by a factor of twenty and both needing a new generation of 2D positioning standards to support their use. Especially critical to this regime is development of new high-resolution, solid-state laser interferometer systems, requiring R&D in the sources, optics, detectors and environmental conditions to allow achievement of single-wavelength displacement measurements and multi-wavelength absolute-distance measurements in industrial applications to accuracies of less than one nanometer. Also critical in this regime is development of new high-resolution grid plate standards to meet the needs of semiconductor electronics manufacturing.

Example deliverables of new NIST capability in this regime include: lab prototype systems for sub-nm displacement and absolute-position measurement based on diode lasers; user-friendly iodine-stabilized HeNe lasers; and a vision-based CMM for measurement of 250mm-by-250mm micropattern grid plates to an overall accuracy of less than 25 nm.

Ultraprecision-Tolerance Regime: Finally, as indicated in the last two rows of Table 12, in the ultraprecision-tolerance regime, there are measurement-intensive manufacturing problems as well as direct measure needs which require addressing. For example, to support realization of next-generation electronic devices, both conventional and quantum-effect, new techniques are required for the fabrication and measurement of x-ray optics, including mirrors and for the direct-writing or mask lithography fabrication of the electronic devices themselves. In addition to those in the nanoelectronics area of the emerging-technology field of nanotechnology, there are also fabrication-and-measurement needs in the areas of materials and biotechnology. Critical needs in this tolerance regime, thus involve development of basic capability to fabricate to large-scale objects such as x-ray mirrors with figures of nanometer tolerances but to fabricate nanometer-scale objects such as quantum-effect device structures to sub-nanometer tolerances. Example deliverables of new NIST capability in this ultraprecision regime include a facility to fabricate and measure diamond-turned,

Table 12 Summary of NIST Approaches and Principal Laboratory Deliverables Directed at the Major Dimensional-Measurement Problems Occurring in the Discrete-Part Manufacturing Industries Involved in the Various Tolerance Regimes

Tolerances	*Industry Users*	*Problem*	*NIST Approach*	*Lab Deliverable*
Normal Regime	Automotive, Farm-and-Construction, Aircraft, Defense-Aerospace	Need Ref Artifacts for CMMs Used in Production Control	Develop State-of-Art 3D Coordinate Metrology Capability	Reference 3D CMM with Accuracy of < 0.5 μm and < 0.1°C T Variation
	Same	Need CMMs and Stds Useable Over Range of Shop Temperatures	Develop Capability to Measure/Model Thermal CMMs and Artifact Stds	Rangeable 5°-35° C Facility for CMM Testing and Artifact Calibration
	CMM Vendors, Users, and Standards-Writing Bodies	Need Tests of Std Methods Used in Evaluating CMMs	Develop Capability to Compare Natl/Intl Stds on Testing of CMMs	Software/Artifact Implementation on Ref CMM of Major Stds
Precision Regime	Machine Tool, Diamond Turning, Micropattern, CMM Users/Producers	Need Absolute Positioning of Machines Improved by Factor of 20	Conduct R&D in Sources, Optics, Detectors, Environment	Single-λ Displacement to <1nm; Synthetic Multi-λ for Absolute Distance
	Semiconductor Mfg, Micropatterning Equipment Producers	Need 2D Position Stds for Micropatterning Eqpmnt Used in Production	Develop State-of-Art System for High-Accuray Grid Plates	Vision-Based 2D CMM with 25nm Accuracy with Range 250mmx250mm
Ultraprecision Regime	Developers of X-Ray Lithography and Space-Based X-Ray Systems	Need Techniques for Manufacturing of X-Ray Optical Components	Develop Capability to Fabricate/Measure/Test X-Ray Optics	Facility for Measurement of Figure of λ/500 X-ray Optics to < 1nm Accuracy
	Industrial R&D in Matls, Biotech, and Nanoelectronics	Need Ref Artifacts of Dimensioned Geometry on Atomic-Scale	Develop State-of-Art of Fabricating and Measuring Nanoscale Artifacts	Lg-Area Atomically-Smooth Substrates with Sub-nm Structures

optical-λ/500 (i.e., 1 nm) substrates as in x-ray optics and calibrated, large-area, atomically-smooth artifacts with nanometer-size two- and three-dimensional structures.

Conclusion

This report has looked at some recent changes in dimensional tolerances in a number of U.S. discrete-parts manufacturing industries and the measurement challenges to NIST they pose. The changes in tolerances have been shown to be part of a long-term trend by which tolerances have been decreasing at the rate of approximately a factor of three every ten years. The report has also shown that whether by the twice-applied Gage-Makers factor-of-ten or Military-Standard factor-of-four relationship of measurement accuracy to manufacturing tolerances, NIST needs to be more accurate than these moving-target tolerances by factors of sixteen to one hundred. Since NIST does not have the current capability to adequately address such needs, it needs to develop new laboratory-based capability in each of the three tolerance regimes: the normal-tolerance regime of metal-cutting machine tools and coordinate measuring machines, the precision-tolerance regime of diamond slicing and advanced interferometers, and the ultraprecision-tolerance regime of scanning tunneling lithography and microscopy. With such new capability, NIST could then meet the ultimate challenge posed by the industry representative who insists that: "For both competitive and strategic reasons, we must have a metrologically strong partner at NIST" [32].

References

1. "Gross National Product, By Industry, in Current and Constant Dollars, 1980 to 1987", Statistical Abstract of the United States 1990: The National Data Book, U.S. Bureau of Census, Washington DC.

2. "Manufactures — Summary by Industry Group: 1980 to 1987"", Statistical Abstract of the United States 1990: The National Data Book, U.S. Bureau of Census, Washington DC.

3. Taguchi, G., "Use of Taguchi Methods in Machine Design", Invited Seminar, Manufacturing Engineering Laboratory, NIST, April 1991.

4. Private Communication, U.S. Auto Body Consortium, Nov 1991. According to the ABC, benchmarking of tolerances on door-in-body fit of U.S., European and Japanese cars indicates 6σ variations of ≥ 3 mm, 2.5 mm, and ≤ 2 mm, respectively.

5. Private Communication, Michael Kehoe, Eastman Kodak Company, Nov. 22, 1991 and American National Standard "Dimensions for 35mm Motion Picture Film", ANSI PH22.93-1974.

6. Private Communication, Senior Manager, Domestic Specialized Machine Tool Company, August 1990.

7. ANSI Y14.5M-1982, "Dimensioning and Tolerancing: American National Standard Engineering Drawings and Related Documentation Practices", The American Society of Mechanical Engineers, NY, NY.

8. Private Communication, J. Matsuda, NRLM, Nov 1991: Tolerances achieved by Honda of Japan on conventional cast-iron pistons and those of metal-matrix composite pistons under development reported in private communication to be 12μm and 7-8 μm respectively.

9. Variations in nominal 125μm diameter optical fibers measured with instrument developed by Theodore Doiron, Dimensional Technology Group, Precision Engineering Division, NIST.

10. Positional accuracy of SEM micropatterning machines of JEOL of Japan reported by Robert Scace, NIST Foreign Trip Report No. 720-42, Oct. 17, 1989.

11. M. Sundaram, et al, "New Quantum Structures", Science, Vol. 254, Nov. 29, 1991.

12. "High Productivity Machining Systems: A State-of-the-Art Assessment", National Center for Manufacturing Sciences, Ann Arbor MI, 1989.

13. Current Status and Future Trends of Ultraprecision Machining and Ultrafine Materials Processing, N. Taniguchi, Annals of the CIRP (International Institute of Production Research), Vol. 2, No. 2, 1983.

14. Estler, W.T., "Calibration and Use of Optical Straightedges in the Metrology of Precision Machines", Optical Engineering, Vol. 24, No. 3, June 1985.

15. H. Smith, "Nanofabrication", Special Issue: Nanoscale and Ultrafast Devices, Physics Today, Feb. 1990.

16. Private Communication, John Bosch, President, Measurement Division, Giddings and Lewis, Nov. 1991.

17. U.S. MIL-STD-45662A, "Calibration System Requirements", U.S. Department of Defense, Washington DC.

18. Based on a single-set 3-σ repeatability of the order of 3 x 6μ" and a systematic error assumed to be of the same order; R. Hocken, et al, "Three Dimensional Metrology", Annals of the International Institute of Production Research, Vol. 26, 1977, p. 403-408.

19. Private Communication, Dennis A. Swyt, Precision Engineering Division, NIST to B.P.Sorel, Vice President, Caterpillar, Peoria, IL, June 7, 1991.

20. Cohen, D.R., Wyko Corporation, Tempe AZ, Private Communication, Jan 1991.

21. G. O. Foss, "Error Component Analysis in the Metrology of X-Ray Photomasks", J.Vac.Sci.Technol., B 8(6), Nov/Dec 1990.

22. Luscombe, et al, "Quantum Dot Diodes", Proc. of IEEE, Vol. 79, No. 8, Aug. 1991, pp. 1117.

23. Weisbuch, C. and Borge Vinter, <u>Quantum Semiconductor Devices</u>, Academic Press, Ny, 1991, p. 207.

24. Corcoran, E., "Diminishing Dimensions", Scientific American, Nov 1990, pp. 122-131.

25. Randall, J.N., et al., "Advances in the Processing of Quantum Coupled Devices," SPIE Proc., Vol. 1284, 1990, p.66.

26. Dagata, J.A., et al, "Integration of STM-Based Nanolithography and Electronics Device Processing", Proc. 38th Nat'l Mtg of American Vacuum Society, Seattle WA, Nov. 11, 1991. to be published in J. Vac. Soc., Jul/Aug 1992.

27. Dagata, J.A., et al, "Nanolithography on III-V Semiconductor Surfaces Using a Scanning Tunneling Microscope in Air", J. App. Phys., 70, 3661, 1991.

28. Valhala, K.J., "Quantum-Box Fabrication Tolerance and Size Limits in Semiconductors and Their Effect on Optical Gain", IEEE Journ. Quantum Electronics, Vol. 24, No. 3, March 1988, pp. 523-530.

29. Estler, W.T., "Accuracy Analysis of the Space Shuttle Solid Rocket Motor Profile Measuring Device", NISTIR 89-4171 (1989).

30. Estler, W.T., and Magrab, M., "Validation of Metrology of the Large Optics Diamond Turning Machine", NBSIR 85-3182(R) (1985).

31. Estler, W.T., et al, "Advanced Angle Metrology at NIST", Proc. ASPE 1991 Annual Conference, Santa Fe, Oct. 1991.

32. Private Communication, B.P. Sorel, Vice President, Caterpillar Corp., Peoria IL, to Dennis Swyt, John Simpson, and John Lyons, NIST, June 7, 1991.

33. IEEE Workshop on Submicrometer Lithography, Solid State Technology, Dec 1991, p. 54.

34. Private Communication, M. Postek of NIST, subsequent to visit to NRLM Japan.

35. Private Communication, PTB to Dr. Steve Phillips, Foreign Trip, Braunschweig Germany, Jun 1-3, 1991.

36. Smythe, R.A., Zygo Corp., Middlefield CT, Private Communication, Jan 1991.

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Toleranced dimensions are a critical attribute of the more than $500B worth of discrete-part products the U.S. produces each year. Global competition in manufacture of these products has lead to dramatically tighter tolerances on part dimensions, with reductions by factors of three in the size of tolerances every 10 years. As a result, today there are tolerances of 1mm in the normal-tolerance regime of assembled automobile car bodies, 2.5 micrometers in the precision-tolerance regime of diamond-sliced magnetic read-write heads, and 0.5 nm in the ultraprecision-tolerance regime of nanofabricated quantum-electronic devices. With the 4-to-10 multiples by which industry's production-control measurements are expected to be better than tolerances and NIST's reference measurements are expected to be better than industry's, NIST is faced with major metrological challenges and unmet industry needs in each of the three tolerance regimes.

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