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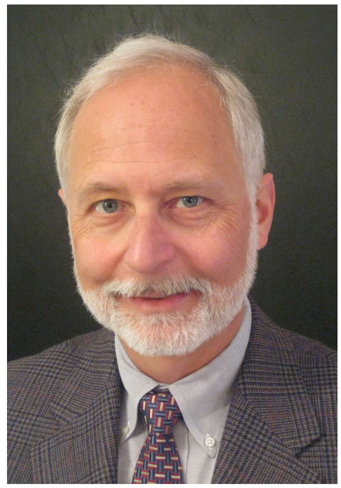

John S. Taylor retired from an extensive career in precision engineering at Lawrence Livermore National Laboratory. He served in lead roles in Precision Systems & Manufacturing, the EUV Lithography Program, NIF Target Fabrication, and NIF Optics. He led a multi-national-lab team who designed and constructed the world's first full-field diffraction-limited imaging systems for EUV lithography in support of the chip industry's evolution to next generation technologies. In recent years, Dr. Taylor is an adjunct professor and member of the graduate faculty at the Center for Precision Metrology at the University of North Carolina at Charlotte. He co-chairs an international conference series on *Advancing Precision in Additive Manufacturing*, a partnership between ASPE and euspen. He is a member of the ASTM F42 Committee on additive manufacturing, ASME, Optica, SME, euspen, Past President of ASPE, Fellow of SPIE and received the ASPE Distinguished Service Award in 2016 and the ASPE Lifetime Achievement Award in 2020. He received his PhD in mechanical engineering from Purdue University. He is the Chairman of the 2025 Annual Meeting of the ASPE in San Diego.

Abstract

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Introduction: Perspective on Determinism and Precision Engineering

In the context of precision engineering, *determinism* usually denotes that all errors in precision systems, machine tools, measurement instruments, etc., are causally linked to a knowable physical source, i.e. there are no unknowable random sources for errors. This perspective was strongly espoused by several founders of the American Society for Precision Engineering and has proven invaluable for several generations of our technical advancement. The origins of the perspective of *cause-and-effect* date back to antiquity, most famously with Aristotle. Jumping forward, Laplace embraced a view that a rigorous application of Newton's Laws to known positions and momenta of all particles would demonstrate a causal deterministic relationship with future events. But, taken to ever finer scales, increasingly consistent with current nanotechnology and semi-conductor manufacturing, fundamental limits on non-random causality in executing precision engineering may be challenged in levels of instrument sensitivity and positional control by thermal noise and quantum considerations. But, even in the context of a deterministic universe, our incomplete knowledge of initial conditions would place limits on our ability to predict some categories of errors with a high level of precision.

The authors will share their own perspective on applying deterministic principles that were first learned from senior mentors, but then broadened into a rubric that has proven useful while developing precision processes, equipment, and metrology, as well as for trouble-shooting when performance did not meet requirements. Here, determinism is considered as a *commitment to ensuring results with a high certainty or known uncertainty*. Results could include making a measurement or performing a design or a fabrication process, with a focus on tolerances, such as those on a technical drawing.

Specifically, four pillars of determinism are presented: 1) Predictability of errors from a first-principles basis, 2) Repeatability, 3) Quantifiability, and 4) Measurability. Each of these pillars will be discussed, and shown to be consistent with cause-and-effect, the perspectives of our ASPE founders, and the scientific method. These thoughts on determinism can be extended to a broader systems perspective and may be restated in terms of a controls-architecture. The authors' personal experience and also examples from the literature will be used for illustration.

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Alex Slocum is the Walter M. and A. Hazel May Prof. of Mech. Eng. at MIT, a MacVicar Faculty Teaching Fellow, a Fellow of ASME, and member of the National Academy of Engineering. He has 200+ patents and has helped develop 11 products that have received R&D 100 awards. He served on the DoE Science Team for the Gulf Oil Spill, and in 2013 was President Obama's Assistant Director for Advanced Manufacturing. Alex has 200+ patents and numerous design awards for translating research into products.

For his research, Alex was the recipient of the Society of Manufacturing Engineer's Frederick W. Taylor Research Medal, and the ASME Leonardo da Vinci, Machine Design, and Thar Energy Design Awards. His current interests focus on the development of precision machines from medical devices and instruments to energy harvesting and storage machines. He has helped start several successful precision instrument and manufacturing equipment companies and has a passion for working with industry to solve real problems and identify fundamental research topics.

Alex is passionate about teaching and mentoring and received the 1999 Martin Luther King Jr. Leadership Award and was the Massachusetts Professor of the Year in 2000. In 2018 he was awarded the ASME Ruth and Joel Spira Outstanding Design Educator Award. At MIT in addition to being a he has been awarded the 2010 Arthur Smith Faculty Achievement Award and the 2017 Capers and Marion MacDonald Award for Excellence in Mentoring and Advising.

Abstract

Determinism Catalyst for Creative Precision Design (CPD)

ASPE Annual Meeting 2025

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"Precision" means repeatability, and repeatability implies in full that a system in addition to meeting quality targets when new, it will maintain quality with use. This implies it will not break or wear out. History has shown that ever greater precision is the key to ever greater quality, which is a catalyst for ever more creative design and productive manufacturing. But what is the catalyst for achieving ever greater precision? It is hypothesized here that catalyst is determinism which itself is governed by the laws of nature and best practices of human experience. Just as CAD and FEA catalyzed ever more creative and productive design and manufacturing, will AI do the same or will it also do more and replace us? AI tools already can accomplish inductive, deductive, and abductive reasoning; and when asked, Google AI explains inductive reasoning takes specific inputs to create generalized outputs, deductive reasoning inputs general principles to output specific conclusions, and abductive reasoning generates the most plausible explanation for a specific set of data. Oops, just as automation has changed the field of "blue collar" work, AI is rapidly changing the field of "white collar" work.

So what hope is there for the future of humans as engineers or any other profession? It is postulated here that precision engineers at least seeking another decimal place to the right or left of the period may succeed by their enthusiasm, imagination, and embracing of AI to relieve us of "tedious" tasks such as detailed analysis associated with uncertainty, error budgets, reliability, and tribology and as the database grows, it can help generate ideas and evaluate in a broad sense concepts we create. This talk will explore these ideas in the context of how Artificial Intelligence Advisors could work with humans to develop a new precision machine starting with initial allocation of resources to lay the foundation for idea generation, and then use FUNdaMENTAL principles and ever more detailed analysis to select, frame and detail the most likely to succeed idea. The final step of the design process would realize a digital twin of the machine which can be virtually operated over its intended life to help ensure quality goals will be met. Continual Precision Development, a great goal for machines and people ☺.

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Dr. Stuart Smith is a Professor of Mechanical Engineering in the Center for Precision Metrology (1994 – present) at UNC Charlotte and was cofounder of North Carolina companies Albany Instruments Inc., 2000, Motus Mechanical Inc., 2014 (now Motus Dynamics Inc., 2016) and was involved in the origination of InsituTec Inc. in 2002 (now IST Precision). These research and manufacturing companies specialize in eddy current sensing technologies, mechanism construction kits and fine motion control metrology systems respectively. He started his career in 1977 with a factory maintenance apprenticeship with Miles Redfern Ltd (UK), a manufacturing industry producing rubber and plastic components for the auto industry.

Throughout his forty-eight year career Dr. Smith's major focus has been the development of instrumentation and sensor technologies, including advanced signal processing techniques, for measurement of surface profile, micro-geometry, and displacements, primarily aimed towards the challenges of atomic scale discrimination and modifications. Development of these systems has required the innovation of many high bandwidth, precision positioning and translation systems. This work has resulted in 20 patents, over 100 journal publications, 100 conference proceedings and the authorship of five books. This work has been recognized with a lifetime achievement award from the American Society for Precision Engineering is 2016. He has also worked to develop the ASPE student Challenge competition since 2015 and was the recipient of a distinguished service award in 2020 and serves as president in 2025.

Abstract

Instrumentation and Mechanisms:
Finding the Ceiling

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All processes are subject to thermal noise and many respond chaotically. These fundamental characteristics limit deterministic behavior. For processes of sufficient simplicity, the various limitations can be evaluated and, when independent, the combined effect of all fundamental limitations determined through superposition or, for random events, quadrature summation.

Taking as an example a simple beam intended for use as a tapping mode atomic force microscope probe measured using either a strain gage, capacitance probe or laser interferometer. Each of these is considered in turn from both a fundamental quantum perspective as well as the practical limitations of detectors.

As well as detector noise there is also thermal noise of the mechanical system and the presence of impulsive forces at the tip (free end of the beam). Thermal noise can be determined directly using Einstein's equipartition principle with the states of the beam expressed in terms of its independent modal coordinates. Another fundamental source of uncertainty arises from the biharmonic governing equation from which all eigenvalues of the beam are irrational multiples of one another. This results in two issues; one being the resulting chaotic response to an input and, second, the resulting problem of determining continuum-based eigen solutions. This talk will determine the magnitudes and dynamics of these sources with calculated numeric examples for different probe designs.

Jelm Franse

Friedrich Franse Settels Savenije

ASML (retired)

Jelm Franse recently retired from ASML where he led various development departments since 2010. He has been working for 40 + years in various companies on the development of High Tech Systems and consumer products. He is now active as Managing Partner and Co-Founder of FFSS B.V. focusing on helping professionals to develop their technical leadership by providing courses and mentoring. Jelm obtained an MSc from Technical University Delft and a PhD from Technical University Eindhoven.

Abstract

The best recipe for developing complex mechatronics systems with world-class performance

Jelm Franse

Friedrich Franse Settels Savenije

The approach to design systems based on total determinism is of course a very sound basic principle. It does however require a complete understanding of the physical cause and effect relations to be viable.

This is feasible for relatively simple systems, where simple means a limited number of movements with a range resolution ratio of +/- 10^6, not too many well-known, physical effects and a performance level that is within the comfort zone of similar existing systems. Design teams for such systems are relatively small, and a “chief engineer” typically has a complete system oversight and is in control of balancing aspects of the design by his/her team members.

When the level is performance of a system has to be extremely high, surpassing the comfort zone of previous systems by an order of magnitude, the complexity of the design, the amount of known and yet unknown/not understood/not expected physical effects, interactions, non-linearities and the amount of engineers of different disciplines involved typically increases more than linear.

For successful development of such systems, of course the basics of determinism are still essential, for every discipline involved, you need the best of the best know-how in your design team. In addition, a more rigorous system engineering approach is needed, covering requirements engineering, modularity of the design both functional and physical, and especially if time to complete is short, concurrent engineering also becomes necessary. The main SE tools will be presented shortly in the talk.

The chief engineer becomes a systems engineer, and maintaining oversight and balancing aspects of the design becomes a teams effort. Communication skills and orchestration and alignment of work methods also has to become world class. Since we are designing now for performance beyond the comfort zone, everyone in the team has to be curious and paranoia about unexpected or incomprehensible effects, interactions etc. That requires objective observations, challenging data and correlations, accepting that we sometimes do not understand, and the system is sometimes non-deterministic.

Quite some debate has been going on about the acceptance of not-physically based mathematical modelling of experimental data, statistical models and recently machine-based learning techniques, sometimes referred to as “Voodoo Engineering”.

Sometimes, it is better to accept the “non deterministic: models or even design rules based solely on tribal knowledge that seems irrational if they produce repeatable performance than to stall progress. Curiosity, attention to the why of “outlier results”, physical effect modelling, doing experiments on the side may over time help to develop more insight and make the system more deterministic. The art of accepting some valuable info that seems non-deterministic and rejecting other conclusions is a skill that grows with experience, leading to improving the intuition of a system engineer. Some examples from system design practice and history will also be discussed in the presentation.

Jeff Roblee

AMETEK Precitech Inc.

Jeffrey Roblee joined Ametek Precitech in February, 2002 and is now a Divisional Vice-President of Technology. Dr. Roblee began his engineering career at Lawrence Livermore National Laboratory in 1977. There he developed ultra-precision machine tools and measuring instruments for use in optics fabrication. His research work continued at Philips Research Laboratory in Holland in 1986 and at Carl Zeiss in Germany in 1990.

In late 1993 Dr. Roblee joined the Optical Engineering Department at Polaroid where he led a program to develop a laser print head for medical images and was involved in many optical fabrication projects. By 2001 he was a Technical Director leading 4 departments.

Dr. Roblee has presented numerous papers on temperature control, machine dynamics, air bearings, and optics fabrication. From 2007 to 2009, he served as a member of the Board of ASPE and as President in 2008. He has an MS and PhD, both in mechanical engineering, from the University of California at Berkeley.

Mark Stocker

Cranfield Precision
Division of Fives Landis Ltd

Mark Stocker is the CTO of Fives' Grinding - Ultra Precision's R&D group, which was formed in 2019 out of Cranfield Precision, a world leader in the design and manufacture of ultra precision machine systems. He has 48 years of professional engineering experience, with over 34 years in the precision engineering field. In 1989, he received his MSc in Machine System Design from Cranfield University and following graduation joined Cranfield Precision. In 2000 Mark joined Corning Incorporated's Precision Machine Systems Group. In 2006, he was promoted to Development Associate. In 2007, Mark re-joined Cranfield Precision and in 2010 became Division Manager. Mark has been an active member of ASPE since 1999 and in 2021, he was elected to ASPE's College of Fellows in recognition of his 'contribution to the advancement of the art and practice of precision engineering by significant, original research and innovations'. In 2022 he was elected to the role of President of ASPE. Mark's designs have resulted in 150+ granted patents worldwide for around 45 independent inventions.

Abstract

Applying the Principles of Precision Engineering to Enhance the Repeatability of Machine Tools

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As will have already been discussed in this session, there are no random machine error motions.
For example, if the motion of a rolling element linear bearing slide were measured and the carriage is returned to its start position for a repeat run:
With every ball in exactly the same start position, with an identical distribution of the grease, with an identical thermal distribution in the carriage, motors, drives, with the external disturbance forces (thermal, vibration etc) at exactly the same cycle start point…etc, etc…
The resulting repeated motion would be *identical* to the first, but it never is, because we cannot replicate precisely the same start conditions or disturbances during motion. Too many of the start conditions are *indeterminate* and cannot practically be repeated. These are the primary sources of what are often, incorrectly labelled: 'Random' errors.

With that in mind, we have to determine early in the design process whether to target the ultimate level of intrinsic machine precision, or to aim to achieve the highest possible level of repeatability. The latter is typically less costly than the former.

At this point we deploy error budgets combining the error motions that can reasonably be determined and those that whilst deterministic, it is not feasible or cost effective to actually determine.

We also use precision design principles such as the Eleven Principles and Techniques of High Precision Machines, proposed by Prof Pat McKeown to minimize the expected errors and to make them less sensitive to initial conditions and disturbances and thus more repeatable.

Furthermore, in the case of machine tools, a test workpiece can be made and then measured on a highly accurate, independent measurement system. If all of the form error is completely repeatable and without any knowledge of the error sources, a perfect workpiece can be made simply with a corrected toolpath program.

The talk will cover the principles and examples behind the selection of repeatability over precision, error budgeting techniques and some of the most relevant of the Eleven Principles/techniques.

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Brigid Mullany is both a professor in Mechanical Engineering and Engineering Science, and the Associate Dean for Research for the William States Lee College of Engineering at the University of North Carolina at Charlotte. She received her BE and PhD in mechanical engineering from the University College Dublin in Ireland. After graduation, she held two-year EU Marie Curie postdoctoral research position at Carl Zeiss in Germany. In 2004 she joined the University of North Carolina at Charlotte where she is currently working in the areas of additive manufacturing (metal and ceramic), surface finishing, robust multi-class surface discrimination machine learning frameworks. Mullany received in the SME Kuo K. Wang Outstanding Young Manufacturing Engineer Award in 2007, and the NSF CAREER Award in 2008. She is the Past President for SME's North American Manufacturing Research Institute (NAMRI), a fellow of the International Academy of Production Engineering (CIRP), and a past Chair of CIRP's Scientific Technical Committee on Surfaces (STC-S). From January 2017 to November 2019 she was a program director in the Advanced Manufacturing program at the National Science Foundation (NSF) in Alexandria, VA.

DETERMINISM IN MANUFACTURING; A SURFACE SCAN CAN REVEAL A MULTITUDE

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INTRODUCTION

The process used to generate a component, be it additive, subtractive or deformation based, plays a pivotal role in the component's overall surface integrity, and frequently, its functional capabilities. Surface integrity includes the chemical and physical states of both the surface and near subsurface [1], and final functionalities encompass mechanical, electrochemical, optical and cosmetic considerations [2]. 'Process Signatures', a term introduced by Brinksmeier et al. [3] in 2011, considers the tool-workpiece interactions from an energy perspective, and how energy dissipation within a process affects the resulting surface morphology. Changing processing conditions, intentionally or unintentionally, will change the process signature imparted on the workpiece. This abstract illustrates how surface metrology, which measures just geometric topographies, if utilized with clear intent, can be an effective tool in capturing process physics and assist in manufacturing determinism.

SURFACE AREAL MAPS AND DETERMINISM

Over the past few decades there has been an increased number of available metrology options suitable for the fast, non-contact measurement of surfaces [4] produced by conventional additive, subtractive, deformation based manufacturing processes. With sub nanometer vertical resolving capabilities, lateral resolutions ranging from sub-micron upwards, [5] and the ability to stitch multiple adjacent images to increase the field of view (FoV), instruments such as coherent scanning interferometers (CSI), focus variation, and confocal systems are all capable of capturing many aspects of the process signature, i.e. the tool-workpiece interaction. If intending to leverage areal measurements for such purposes, consideration should be given to the following as they all contribute to the integrity and relevance of the measurement, and hence its ability to contribute to the determinism of the manufacturing process:

- Metrology system constraints
- Length scale of relevance
- Quantification parameter of relevance

A clear statement of what information is sought from the measurement must also be available; without this optimal measurement and data processing is, at best, challenging.

Metrology System Contraints

In addition to understanding the usual system resolving capabilities (vertical and lateral resolutions, instrument transfer function), consideration should also be given to any surface topographical characteristics (specular versus diffuse textures, local slopes, overhangs), and material constraints (transparent versus opaque, homogeneous versus heterogeneous composition) that may influence the measurements. With knowledge of the chosen system's limitations and factors contributing to measurement uncertainty, areal surface maps can facilitate the examination of micro and meso scale tool-workpiece interactions and underlying process physics. Figures 1(a), (b) and (c) illustrate areal maps with different magnifications of IN625 surfaces produced via laser powder bed fusion (LPBF). Both the 10× with 0.5 zoom, Fig. 1(a), and the 20× measurements, Fig. 1(b), capture the expected laser raster path and spatter. Both images show some data drop out (black pixels in the images) due to the slope limitations of the objectives. The 50× with its much smaller FoV (~170 μm × 170 μm) and higher lateral sampling, enables examination of individual laser tracks. Which measurement is most useful? It depends on the measurement intent. Figure 1(d) illustrates a surface produced via a digital light projection (DLP) additive process. Even with only a rudimentary knowledge of the underlying process physics, the surfaces generated by LPBF and DLP are distinguishable, with each capturing key process drivers: the LPBF laser raster path, and the DLP's light projection pixel size (~ 50 μm).

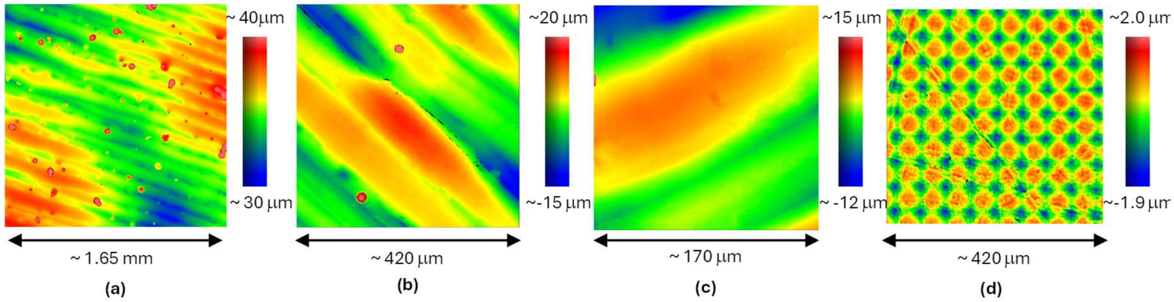

FIGURE 1: *CSI measurements of LPBF and DLP surfaces. Best fit plane removed from all. LPBF of IN625; measurements with magnification of (a) 10×, 0.5 zoom, (b) 20× , and (c) 50×. DLP of a resin (d) 20×.*

Length Scale of Relevance

The feature(s) of interest will dictate the required lateral resolutions and FoV, but they will also strongly dictate the data processing choices, i.e. form removal and filter cut offs. In many cases, the default cut-offs, as outlined in standards, will not be appropriate. Figure 2(a) and (b) illustrate the same stitched CSI measurement of the last printed layer on nominally planar alumina sample fabricated via a stereolithography (SLA) printing process. In Figure 2(a) only the best fit plane is removed from the raw data. The deviation from a nominally planar surface is evident. In Fig. 2(b) a 10th order polynomial is removed from the same; this removes lower order waviness and reveals the local periodic textures related to the laser scanning strategy and polymer curing kinetics.

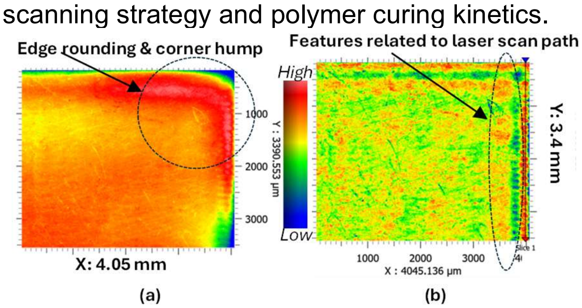

FIGURE 2: Alumina SLA surface;(a) best fit plane removed, (b) 10^{th} order polynomial removed.

Quantification Metrics of Relevance

While the human eye is very good at detecting patterns and anomalies, its non-linear response to stimuli results in unreliable evaluations with difficult to quantify levels of uncertainty [2]. Appropriate quantitative metrics, with emphasis on 'appropriate', are required to facilitate either enhanced understanding of process fundamentals, or for process control. For example, the ubiquitous the root mean square roughness parameter, *Sq*, is a statistically based value that captures surface height distributions. It does not capture any information regarding the spatial distributions of the surface heights. Conceivably, the dissimilar surfaces shown in Fig 1(a) and (d) could have similar *Sq* values; thus making *Sq* inappropriate for differentiation. While not discounting *Sq*'s use in detecting process drift, other ISO25178-2 defined parameters, i.e. 'spatial', 'hybrid' or 'volume' parameters, offer more opportunities for understanding tool-workpiece interactions and classification. Never the less, it is appreciated that selection of the relevant parameter may not always be obvious.

CONCLUSIONS

Areal surface maps, when processed judiciously can deterministically capture aspects of a manufacturing process. Research opportunities still exist to expediate optimal metric and processing route selection. For manufacturing determinism, measurement interpretation must incorporate processing and metrolgy knowledge.

REFERENCES

[1] Jawahir I S, Brinksmeier E, M'Saoubi R, Aspinwall D K, Outeiro JC, Meyer D, Umbrello D; Jayal A D. Surface Integrity in Material Removal Processes. Recent Advances. Annals of the CIRP 60/2; 2011: 603-626.

[2] Mullany B, Savio E, Haitjema H, Leach R, The implication and evaluation of geometrical imperfections on manufactured surfaces ", Annals of the CIRP, Vol. 71 (2), 2022, pp. 717-739.

[3] Brinksmeier E, Gläbe R, Klocke F, Lucca D.A., Process Signatures – an Alternative Approach to Predicting Functional Workpiece Properties, Procedia Engineering, 2011, Vol. 19, pp. 44-52.

[4] Leach R, editor. Optical measurement of surface topography. Berlin, Heidelberg: Springer Berlin Heidelberg; 2011 Mar 31.

[5] Rosén S, Thomas TR, Rosén BG. The Stedman diagram revisited. Surface Topography: Metrology and Properties. 2013 Dec 23;2(1):014005.

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Determinism and Documentary Standards

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The Lede

In a world of uncertainty and errors, documentary standards form a bulwark against which the waves of randomness are broken and dispersed.

Abstract

Precision Engineering begins with precision of expression – what exactly is the quantity that we are attempting to measure or control and under what conditions will this activity be performed? The VIM succinctly captures these ideas in the definition of a measurand as the *quantity intended to be measured*. The careful specification of what is to be made or measured is a prerequisite to achieving precision in the subsequent steps. This paper describes how documentary standards achieve uniformity by unambiguously establishing the characteristics used to evaluate instruments and artifacts. Current national and international standards for measuring instruments will be used as examples to highlight the interaction between the instrument specification, the rated operating conditions, and the test value uncertainty. The paper concludes with a perspective on how well-formed documentary standards reduce ambiguity (and hence support determinism) in precision engineering.