

# Proceedings

ASPE 2004 Annual Meeting

October 24-29, 2004



***Proceedings of:***

*The Nineteenth Annual Meeting*

*The American Society for Precision Engineering*

*October 24-29, 2004*

*Wyndham Palace Resort & Spa at Walt Disney World  
Orlando, Florida*

*The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.*

*Founded in 1986, ASPE provides a new focus for a diverse but important community. Other professional organizations have covered aspects of precision engineering, always as a sideline to their principal goals. ASPE is based on the core of generic concepts necessary to achieve precision in any application; independent of discipline, ASPE intends to be the focus for precision technology — and to represent all facets from research to application.*

*ASPE — The American Society for Precision Engineering  
301 Glenwood Avenue, Suite 205, Raleigh, NC 27603  
P.O. Box 10826, Raleigh, NC 27605  
Telephone: (919) 839-8444 Fax (919) 839-8039*

# *Preface*

*This book comprises the proceedings of the 2004 Annual Meeting. The contributions reflect the authors' opinions and are published as presented to ASPE, without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE, or its editorial staff.*

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*2004*

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## Welcome Note

*Welcome to Orlando for the Nineteenth Annual Meeting of The American Society for Precision Engineering, co-sponsored by the Japan Society for Precision Engineering. The growth and success of the Society reflects the increasing importance of precision engineering in a wide variety of fields of endeavor, from manufacturing to microelectronics to basic science. The Society serves as a focus for precision engineers across all of these fields. The Annual Meeting has evolved into a premier international forum for the exchange of ideas and presentation of research results relating to precision engineering, metrology, controls, and system integration. Precision engineers and scientists from private industry, government laboratories, and universities meet to learn about the latest developments and to exchange ideas about the future directions of these technologies.*

*This year's meeting continues the tradition of offering two full days of tutorials presented by some of the foremost precision engineers and scientists in the world. The technical sessions and poster presentations offer the latest research results in the areas of ultraprecision machining, metrology, controls, precision grinding, micro-positioning, material processing, design, precision transducers, surface profilometry, machine tool metrology, and error compensation. The commercial exhibit will provide attendees with the opportunity to view and discuss the latest precision engineering equipment, products, and services that are commercially available.*

*The conference organizing committee is proud to present the program for the Nineteenth Annual Meeting of the ASPE. We welcome your participation and your feedback on how to make next year's meeting even better.*

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# Program

## 2004 ASPE Annual Meeting

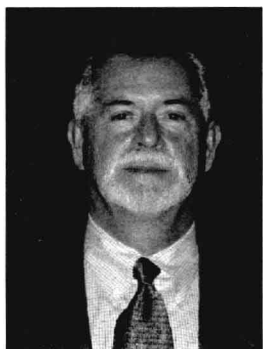
Time	Sun., Oct. 24	Mon., Oct. 25	Tues., Oct. 26	Wed., Oct. 27	Thurs., Oct. 28	Fri., Oct. 29
8:00	Registration	Registration	Registration			
9:00	Tutorials	Tutorials	Technical Session I	Technical Session III	Technical Session VI	Technical Tours
10:00			Break	Break	Break	
11:00			Technical Session II	Technical Session IV	Technical Session VII	
12:00			Lunch and Committee Meetings	Awards Lunch and Business Meeting	Lunch and Roundtable Discussions	
1:00			Commercial Session	Technical Session V	Technical Session VIII	
2:00	Tutorials	Tutorials	Break and Poster Session I	Break and Poster Session II		
3:00			Hospitality Hour	Hospitality Hour		
4:00						
5:00						
6:00		Keynote Address	Science Center Dinner Banquet			
7:00						
8:00		Welcome Reception				
9:00						

# Keynote Address

E. Clayton Teague

Monday, October 25, 2004 – 6:30 p.m.

Session Chair: Vivek G. Badami (Corning Tropol Corporation)



## E. Clayton Teague

Clayton Teague is Director of the Federal National Nanotechnology Coordination Office (NNCO), being appointed in April 2003. As Director of the NNCO, he is the agency representative to the National Science and Technology Council from his position as Chief of the Manufacturing Metrology Division of the National Institute of Standards and Technology (NIST). Beginning with his quantum mechanical tunneling work, since 1967 he has been working in some of the fields now known as nanotechnology. His work has included designing, constructing, and using STMs, AFMs, and interferometers for ultra-high accuracy dimensional metrology of surfaces and micrometer to nanometer-scale features.

Dr. Teague is a member of the American Society for Precision Engineering, has served twice as the Society's president, and is a fellow of the UK Institute of Physics. He served as Editor-in-Chief of the international journal *Nanotechnology* for ten years and is currently a member of the Editorial Board of the journal. He holds a B.S. and M.S. in physics from the Georgia Institute of Technology and a Ph.D. in physics from the University of North Texas. He has been active in the metrology and standards communities for most of his career and has been privileged to receive a number of honors and awards from the government as well as industrial and private organizations for his work.

## Nanotechnology: Hype or the Next Big Thing?

"Now nanotechnology had made nearly anything possible, ..." This quote from an almost ten-year old science fiction novel is indicative of the hype now surrounding nanotechnology. It is being featured in local newspapers as the cure for cancer, in alumni magazines as producing Superman soldiers, in the AARP Bulletin as leading to lifetimes averaging 120 years, and in a large number of investment newsletters being touted as a great investment opportunity. On the other hand, there is an increasing flood of scientific and engineering papers and patents in this field of science, engineering, and technology collectively known as nanotechnology that portend realization of modest progress toward fulfilling the hype. The long-term promise lies in exciting research discoveries and innovations based on new nanoscale processes, phenomena, materials, devices, and systems. Dr. Teague will share his perspectives on the historical development of the field, give an assessment of its current state, argue why he thinks it is the next big thing, and present examples of research, business, and professional opportunities posed by the revolutionary advances in the fundamental understanding and control of matter at the nanometer to atomic level.

\* *The Diamond Age*, Neal Stephenson, p.37

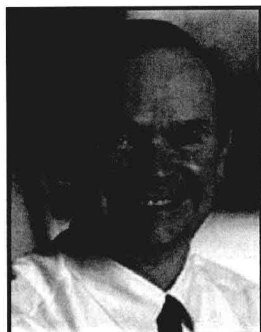
## Commercial Session

Tuesday, October 26, 1:45 - 3:30 p.m.

Session Co-Chairs: Michele H. Miller (Michigan Technological University)  
and David D. Gill (Sandia National Laboratories)

The Commercial Session will take place early in the week on Tuesday afternoon. This is a special session where companies and participants are free to open discussions on a less-formal basis and to promote interaction on a variety of topics. In the first part of this session, company representatives are invited to make brief presentations (five minutes) on new products associated with precision engineering. This provides participants with the opportunity to receive timely information on new technologies that have been commercialized into products and services, as well as information on advances that can be expected in the near future.

## 2004 ASPE Lifetime Achievement Award



### **John H. Bruning**

*The 2004 ASPE Lifetime Achievement Award is presented to Dr. John H. Bruning in recognition of his many contributions to the art and science of precision engineering. John Bruning has been involved in advancing the state-of-the-art of photolithography and has contributed significantly to many of the key events in the history of this key technology.*

*John Bruning received a bachelor's degree from Penn State University and a master's and doctorate from the University of Illinois, all in electrical engineering. His doctoral work, completed in 1969 dealt with multiple scattering of electromagnetic and acoustic waves by spheres. Upon graduation, John started at Bell Laboratories in Murray Hill as a member of the technical staff in the optical group. Early work involved the development of high accuracy interferometry for testing precision optical surfaces and lenses. Out of this work came a fundamentally new approach to interferometry known as phase measuring interferometry (PMI), which is the basis of most modern digital interferometers. This development has enabled 10-100 times greater accuracy in manufactured lens components for optical lithography and other precision optics applications.*

*From 1973-1979 he supervised several groups involved in developing mask inspection systems for photolithography and the exploration of new packaging techniques for integrated circuits and reliability testing methods for these new packaging systems. From 1979 to 1984, he directed several activities within the New Lithographic Systems Group including the mechanical design of EBES-IV, an advanced e-beam mask pattern generator. He initiated and managed the Bell Labs Deep-UV Photolithography Program working with Tropel as optics supplier and authored the fundamental patent for line-narrowed excimer laser photolithography. During this period, he was also involved in optical thin-film filter design, design of uniformers and diffusers, alignment systems and optical design.*

*In 1984, Bruning left Bell Laboratories to become vice president and general manager of Tropel, a division of GCA Corporation. In 1986, he assumed the additional responsibilities as executive vice president and chief technical officer of GCA. In 1994, Bruning led a management buyout of Tropel. Tropel was acquired by Corning Inc. in March 2001. John is currently the President and CEO of Corning Tropel where he remains involved in developing technical strategy.*

*John has published extensively and holds 12 patents. He is a recipient of the Distinguished Alumnus Awards from both his alma maters. He is a Fellow of the IEEE and the OSA and in 1993 received the OSA Richardson Medal. In 1996 he received the SEMI Award for developments in Deep-UV photolithography and was elected to the National Academy of Engineering in 1998. John has served as President of the American Society for Precision Engineering and was responsible for starting the Business Forum at the Annual Meeting. He has served as an editor for the Precision Pointers section of the Precision Engineering journal and is also a recipient of the Society's Distinguished Service Award. John continues to be a strong supporter of the Society and is currently a Sustaining Member.*

# 2004 ASPE Lifetime Achievement Award



## **Ted Arneson**

*Ted is best known as the founder of Professional Instruments Company and as a pioneer in the development of air bearing spindles. Besides his support of ASPE, Ted has also found time for leadership roles in many volunteer activities, concentrating in the areas of mental health, workplace safety, and watching out for the interests of small manufacturers.*

*Both sides of Ted's family contained inventive, intuitive individuals with gifts for music, mathematics, and mechanics. His boyhood home was a place where knowledge was valued, points were argued, and books and tools were ever-present. At age 12, his innate mechanical skills led him to open a bicycle shop in his parents' basement. Later he was heavily involved in the family business of building vision-training instruments invented by his father.*

*Ted worked for General Mills in 1942 and 1943; this major precision-manufacturing plant produced analog-computer torpedo directors, three-dimensional cams, precision gears, and 8" gun sights. He was mentored by several brilliant engineering and manufacturing people, and was given wide exposure to ultra-precision manufacturing processes at a very high level.*

*After the war, Ted and his brother Harold started a small shop, adopting the "Professional Instruments Company" name. When the Korean War put the economy on a war footing, Ted and Harold decided to subcontract for the defense industries. They bought used machinery, fixed it up, and started to make rather difficult precision parts. They were good enough at it to attract the attention of some executives at Honeywell, who admired them for their pluck and their ability to get really excellent work out of miscellaneous machinery.*

*Ted and Harold worked 70 hours a week and came up with one fantastic development after another for projects varying from bag-making machines, to magnetic printing of checks, to spherical electrostatic gyroscopes, to 17-inch spherical air bearings for Apollo program space simulators. The P. I. crew was built from scratch, using a training program devised by Ted, featuring on-the-job mentoring, class work, and after-hours self-education. Ted created the culture of hands-on precision and attention to detail that enabled the success of air bearing work at P.I. by creating world-class experts in the fields of metallurgy, dimensional stability, bolted interfaces, metrology and quality control. Ted's vision, guidance, and support enabled advances in navigational devices, ultra-precision grinding, microlithography, diamond-turned optics, computer memory disks, spindle metrology, and measurement of the gravitational constant.*

# *2004 Annual Meeting*

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# Technical and Poster Sessions Index

*The technical program of the 2004 ASPE Annual Meeting contains 186 papers on precision engineering advances. Papers that lent themselves to significant verbal interaction, concise but important discoveries, or strongly visual or tactile subjects have been selected for the poster presentation. Authors will be in attendance to discuss their work on Tuesday, October 26, and Wednesday, October 27, from 3:30 to 5:15 p.m.*

## Session I Metrology

*Tuesday, October 26, 2004, 8:15 AM - 10:00 AM*

*Session Chair: Vivek G. Badami (Corning Tropel Corporation), and Eric R. Marsh (The Pennsylvania State University)*

- 1. Optical Engineering for Biomedical Optics (Invited Paper)\*\***  
Zavislan, J. (University of Rochester) ..... page 15
- 2. Realizing and Disseminating the SI Micronewton with the Next Generation NIST Electrostatic Force Balance**  
Pratt, J. R.; Newell, D.; Kramar, J. A.; Seugling, R. M. (National Institute of Standards and Technology). .... page 16
- 3. High-resolution Retinal Microscopy Using MEMS-based Adaptive Optics**  
Zhou, Y.; Bifano, T. G. (Boston University) ..... page 20
- 4. Fiber Deflection Probe for Small Hole Measurements**  
Muralikrishnan, B. (University of North Carolina at Charlotte); Stone, J. A.; Stoup, J. R. (National Institute of Standards and Technology); and Vemuri, S. C.; Sahay, C.; Potluri, A. (University of Hartford). .... page 24
- 5. Design, Manufacture and Performance Evaluation of a Rapid Probing Machine**  
Bauza, M.; Smith, S. T.; Hocken, R. J. (University of North Carolina at Charlotte) and  
Woody, S. C.; Jain, P. (InstituTec Inc.) ..... page 28

## Session II Machine Tools

*Tuesday, October 26, 2004, 10:30 AM - 12:15 PM*

*Session Chair: Kenneth P. Garrard (North Carolina State University), and Byron R. Knapp (Olympic Precision, Inc.)*

- 1. Agile Assembly Architecture: A Platform Technology for Microassembly (Invited Paper)**  
Hollis, R. L.; Rizzi, A. A. (Carnegie Mellon University) ..... page 32
- 2. Active Vibration Isolation of an Unbalanced Machine Tool Spindle**  
Hopkins, D. J.; Geraghty, P. (Lawrence Livermore National Laboratory) ..... page 36
- 3. The Effects of Asymmetrical Radial Stiffness in Precision Rotating Machines: The Duality of Fixed and Rotating Sensitive Directions**  
Dalrymple, T. M. (University of Florida) ..... page 40

*\*\* Extended abstract unavailable at press time*

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#### 4. **A 10 kHz Short-stroke Rotary Fast Tool Servo**

Montesanti, R. C. (Lawrence Livermore National Laboratory); and Trumper, D. L. (Massachusetts Institute of Technology) . . . . . page 44

#### 5. **Two-axis Force-feedback Deflection Compensation of Miniature Ball End Mills**

Freitag, K.; Dow, T. A. (North Carolina State University) . . . . . page 48

### Session III

## Nano Positioning

Wednesday, October 27, 2004, 8:15 AM - 10:00 AM

Session Chair: Hisayuki Aoyama (University of Electro-Communications), and Georg Aigeldinger (Sandia National Laboratories)

#### 1. **Manufacturing Technologies for Polymer Microsystem (Invited Paper)**

Saile, V. (Karlsruhe University) . . . . . page 52

#### 2. **Design of a Passive Micro-mechanism Chuck to Minimize the Effect of Backside Particles on Semiconductor Wafer Planarity**

Nimmakayala, P. K.; Sreenivasan, S. V. (The University of Texas at Austin) . . . . . page 56

#### 3. **Design of a Next Generation 6 DoF Stage for Scanning Application in Vacuum with Nanometer Accuracy and mGauss Magnetic Stray Field**

de Klerk, A. C. P.; Angelis, G. Z.; van Eijk, J. (Philips, CFT) . . . . . page 60

#### 4. **A Planar Nano-positioning Table System for Advanced Machine Tools**

Yoshioka, H.; Komatsu, K.; Hashizume, H.; Shinno, H.; Shinshi, T.; Sato, K. (Tokyo Institute of Technology) . . . . . page 64

#### 5. **Design of a Scanning Stage System with Nanometer Resolution for a X-ray Nanoprobe Instrument**

Shu, D.; Maser, J.; Lai, B.; Vogt, S.; Han, Y.; Tieman, B.; Winarski, R.; Roehrig, C.; Smolyanitskiy, A.; Stephenson, G. B. (Argonne National Laboratory) . . . . . page 68

### Session IV

## Precision Machining I

Wednesday, October 27, 2004, 10:30 AM - 12:15 PM

Session Chair: Hiroshi Hashimoto (Kanagawa Institute of Technology), and Tony L. Schmitz (University of Florida)

#### 1. **Ultra-Precision Float Polishing of Optical Materials (Invited Paper)**

Namba, Y. (Chubu University) . . . . . page 72

#### 2. **Tunable Ultrasonic Vibration-assisted Diamond Turning of Steel**

Overcash, J. L.; Cuttino, J. F. (University of North Carolina at Charlotte) . . . . . page 76

#### 3. **Micro-machining Using Elliptical Vibration Assisted Machining**

Brocato, B. C.; Dow, T. A.; Sohn, A. (North Carolina State University) . . . . . page 80

#### 4. **Force Analysis for Segmental Grinding**

Fan, X.; Miller, M. H. (Michigan Technological University) . . . . . page 84

#### 5. **Ball-end Milling of Free-form Surfaces for Optical Mold Inserts**

Brinksmeier, E.; Autschbach, L. (Bremen University) . . . . . page 88

### Session V

## Interferometry

Wednesday, October 27, 2004, 1:45 PM - 3:30 PM

Session Chair: Daniel E. Thompson (Olympic Precision, Inc.), and John C. Ziegert (University of Florida)

#### 1. **Block Regression Phase Digitizing with application to Nonlinearity Measurement and Correction (Invited Paper)\*\***

Chu, D. (Agilent Technologies) . . . . . page 92

#### 2. **Recent Developments in Homodyne Interferometry**

Lee, W. (Renishaw plc) . . . . . page 93

\*\* Extended abstract unavailable at press time



3. **Challenges in Interferometric Measurements of MEMS and Semiconductor Devices**  
Schmit, J.; Novak, E. L. (Veeco Instruments, Inc.) ..... page 97
4. **The Effect of Phase Change on Reflection on Optical Measurements**  
Medicus, K. M.; Fricke, L. R.; Brodziak, J. E.; Carnevale, S.; Chaney, M. A.; Wolff, R.; Davies, A. D.  
(University of North Carolina at Charlotte) ..... page 101

## Session VI

### Novel Systems

Thursday, October 28, 2004, 8:15 AM - 10:00 AM

Session Chair: Alex Sohn (North Carolina State University), and Keith Carlisle (Lawrence Livermore National Laboratory)

1. **A Comparison of Force and Acoustic Emission Sensors in Monitoring Precision Cylindrical Grinding**  
Couey, J. A.; Marsh, E. R. (The Pennsylvania State University); Knapp, B. R. (Olympic Precision, Inc.);  
and Vallance, R. R. (The George Washington University) ..... page 105
2. **Indoor GPS Metrology System with 3D Probe for Precision Applications**  
Kang, S.; Tesar, D. (University of Texas at Austin) ..... page 109
3. **Active Compliant Fixtures for Nanomanufacturing**  
Varadarajan, K. M.; Culpepper, M. L. (Massachusetts Institute of Technology) ..... page 113
4. **Manufacture of a 150x150 Reflective Spatial Light Modulator Integrated Directly onto CMOS Electronics**  
Kim, J.-H.; Bifano, T. G. (Boston University) ..... page 117
5. **Fabrication of Atom Trap Chip for Quantum Information Processing**  
Nagato, K.; Ohsige, K.; Ooi, T.; Tsuchiya, K.; Hamaguchi, T.; Nakao, M. (The University of Tokyo) ..... page 121

## Session VII

### Precision Machining II

Thursday, October 28, 2004, 10:30 AM - 12:15 PM

Session Chair: Thomas A. Dow (North Carolina State University), and Bradley N. Damazo (National Institute of Standards and Technology)

1. **IR Telescope (Invited Paper)\***  
Eikenberry, S. (University of Florida)
2. **Shape Control in Ultra-precision Finishing for the Femoral Head of the Artificial Hip Joint by Means of Abrasive Waterjet**  
Sawano, H.; Warisawa, S.; Mitsuishi, M. (The University of Tokyo); and Kuramoto, K. (Nakashima Propeller Co., Ltd.) ..... page 125
3. **Grinding Simulation with Diamond Pellets and Optimization of its Grinding Conditions**  
Uneda, M.; Suwabe, H.; Ishikawa, K. (Kanazawa Institute of Technology) ..... page 129
4. **Viscoelastic Stress Analysis of Precision Aspherical Glass Lens Forming Process Using Finite Element Method**  
Jain, A.; Yi, A. Y. (Ohio State University) ..... page 133
5. **In-Situ Infrared (IR) Detection of the High Pressure Phase Transformation of Silicon During Scratching Test**  
Dong, L.; Miller, J. A. (University of North Carolina at Charlotte); and Patten, J. A. (Western Michigan University) ..... page 137

## Session VIII

### Micro/Nano Devices

Thursday, October 28, 2004, 1:45 PM - 3:30 PM

Session Chair: Martin L. Culpepper (Massachusetts Institute of Technology), and Stephen J. Ludwick (Aerotech, Inc.)

1. **The Nanostructured Origami™ 3D Fabrication and Assembly Process (Invited Paper)**  
Barbastathis, G.; In, H. J.; Arora, W.; Buchner, T.; Smith, H. I. (Massachusetts Institute of Technology) ..... page 141

\* Abstract unavailable at press time



2. **Optical Fibre Coupled Miniature Interferometers Designed for Application in Micro and Nano Devices**  
Jäger, G.; Manske, E.; Hausotte, T.; Füll, R.; Grünwald, R.; Büchner, H.-J. (Technical University of Ilmenau);  
and Schott, W. (SIOS Meßtechnik GmbH) ..... page 145
3. **Study of Nano-Stereolithography Using Evanescent Light**  
Kajihara, Y.; Inazuki, Y.; Takahashi, S.; Takamasu, K. (The University of Tokyo) ..... page 149
4. **An Experiment Towards Establishing the Tolerance of Micro-scale Interference Fits**  
Jones, J. F.; Aigeldinger, G. (Sandia National Laboratories) ..... page 153
5. **Micro-Turbo Charger for A Palmtop Gas Turbine Generator**  
Tanaka, S.; Esashi, M. (Tohoku University); Isomura, K. (Ishikawajima-Harima Heavy Industries); and  
Togo, S.; Hikichi, K.; Goto, S. (Tohoku Gakuin University) ..... page 157

## Poster Session I

Tuesday, October 26, 2004, 3:30 PM - 5:15 PM

Session Chair: Bradley H. Jared (3M Precision Optics)

## BIOMEDICAL

### Biomedical

1. **Phase Plate Correction of Ocular Aberrations**  
Raasch, T. W.; Yi, A. Y. (Ohio State University); and Roblee, J. W. (Precitech, Inc.) ..... page 161

## EQUIPMENT, MACHINES & INSTRUMENTS

### Analysis & Modeling

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Kato, S.; Nakamura, H. (Nippon Institute of Technology); Ono, M. (Tokyo Metropolitan College of Technology);  
and Saito, N. (Hitachi High-Technologies Corp.) ..... page 165
2. **Stiffness Analysis and Kinematic Modeling of Stewart Platform for Machining Applications**  
Kumar, S. G.; Bikshapathi, M.; Nagarajan, T.; Srinivasa, Y. G. (Indian Institute of Technology - Madras) ..... page 169
3. **Compensation for Distortion of Dynamic Sensor Data Using Receptance Coupling**  
Schmitz, T. L. (University of Florida) ..... page 173
4. **A Precision Active Aerostatic Spindle with an Axial Positioning Actuator**  
Shinshi, T.; Hayashi, T.; Inami, Y.; Hashizume, H.; Sato, K.; Shimokohbe, A. (Tokyo Institute of Technology) ..... page 177
5. **Design of an Efficient Active Cooled Meso-scale Heat Exchanger Using Functionally Gradient Materials**  
Subramanian, R.; Kwon, P.Y. (Michigan State University) ..... page 181

### Controls

1. **Configuration and Control Aspects of High-Precision Planar Multi-Coordinate Drive Systems**  
Kallenbach, E. K.; Kireev, V.; Volkert, R.; Zentner, J.; Bertram, T. (Technical University of Ilmenau) ..... page 185
2. **Identification of Friction Elements Through Limit Cycle Analysis**  
Kim, M.-S.; Kim, M.-Z.; Chung, S.-C. (Hanyang University) ..... page 189
3. **Verification of Precision-limit Positioning of a Direct Drive System with the Existence of Friction**  
Liu, B.-Y.; Hsieh, C. (National Cheng Kung University) ..... page 193
4. **The Development of the NC Method of Eliminating Machining Point Errors Caused by Machining Centers - First Report (Theory) -**  
Nakayabu, T. (Industrial Research Institute of Ishikawa); Hirao, M. (Kanazawa University); Inamura, T.  
(Nagoya Institute of Technology); Yasui, T. (Industrial Exchange Institute of Kanazawa); Imai, H.; Okaji, M.  
(National Institute of Advanced Science and Technology); and Kawara, H. (Tsudakoma Corporation) ..... page 197
5. **Error Compensation via Command Signal Deconvolution**  
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### Design & Testing

1. **Low Cost Flexure Alignment Features**  
Abu Ibrahim, F.; Awtar, S.; Sutin, J.; Slocum, A. H. (Massachusetts Institute of Technology) ..... page 205
2. **Thin Optic Constraint**  
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(Massachusetts Institute of Technology) ..... page 209