

Bibliography

- Ahmad, A., *Handbook of Optomechanical Engineering*, CRC Press, Boca Raton, FL (1997).
- Baiocchi, D., “Design and Control of Lightweight, Active Space Mirrors,” Ph.D. Thesis, Univ. of Arizona (2004).
- Barnes, W. P., “Optical Windows,” in *Optomechanical Design*, P. R. Yoder, Ed., pp. 232–253, SPIE Press, Bellingham, WA (1992).
- Baumeister, T., A. M. Sadegh, and E. A. Avallone, *Marks’ Standard Handbook for Mechanical Engineers*, McGraw-Hill, New York (2007).
- Bäumer, S., *Handbook of Plastic Optics*, pp. 7–34, Weinheim: Wiley-VCH, Berlin (2005).
- Bayar, M., “Lens barrel optomechanical design principles,” *Opt. Eng.* **20**(2), 181–186 (1981).
- Birch, K. P. and Downs, M. J., “An updated Edlen equation for the refractive index of air,” *Metrologia* **30**, 155–162 (1993).
- Blanding, D. L., *Principles of Exact Constraint Mechanical Design*, Eastman Kodak, Rochester, NY (1992).
- Burge, J. H., “An easy way to relate optical element motion to system pointing stability,” *Proc. SPIE* **6288**, 628801 (2006) [doi:10.1117/12.677917].
- Chen, W. T. and C. W. Nelson, “Thermal stress in bonded joints,” *IBM J. Res. Develop.* **23**(2) 179–188 (1979).
- Ciddor, P. E., “Refractive index of air: new equations for the visible and near infrared,” *Appl. Optics* **35**, 1566–1573 (1996).
- Culpepper, M. L., “Design of quasi-kinematic couplings,” *Precision Engineering* **28**, 338–357 (2004).
- Doremus, R. H., “Fracture statistics: A comparison of the normal, Weibull, and Type I extreme value distributions,” *J. App. Phy.* **54**(1), 193–198 (1983).

Bibliography

Doyle, K. B. and M. A. Kahan, “Design strength of optical glass,” *Proc. SPIE* **5176**, 14–25 (2003) [doi:10.1117/12.506610].

Ealey, M., R. Paquin, and T. Parsonage, eds., *Advanced Materials for Optics and Precision Structures*, SPIE Press, Bellingham, WA (1997).

Fischer, R. E., “Optimization of lens designer to manufacturer communications,” *Proc. SPIE* **1354**, 506–522 (1991) [doi:10.1117/12.47955].

Gibbons, R. C., “Athermal infrared optics,” Equipment Group, Texas Instruments, Inc., 1–12 (Feb. 1976).

Hale, L. C., “Principles and Techniques for Designing Precision Machines,” Ph.D. Thesis, MIT, LLNL (1999).

Hibbard, D. L., “Electroless nickel for optical applications,” Chapter 9 in *Advanced Materials for Optics and Precision Structures*, Ealey, M., R. Paquin, and T. Parsonage, eds., SPIE Press, Bellingham, WA (1997).

Jamieson, T. H., “Athermalization of optical instruments from the optomechanical viewpoint” (Critical Review Vol CR43, (1992).

Jones, G. E., “High-performance lens mounting,” *SPIE Proc.* **73**, 9–17 (1975).

Mehta, P. K., “Flexural rigidity characteristics of light-weighted mirrors,” *Proc. SPIE* **748**, 158–171 (1987).

“Military standard environmental test methods for aerospace and ground equipment,” MIL-STD-810, United States Air Force, <http://www.dtc.army.mil/publications/810June1962.pdf> (1962).

Monti, C. L., “Athermal bonded mounts: incorporating aspect ratio into a closed-form solution,” *Proc. SPIE* **6665**, 666503 (2007) [doi:10.1117/12.730275].

Bibliography

Nelson, J. E., J. Lubliner, and T. S. Mast, "Telescope mirror supports: plate deflections on point supports," *Proc. SPIE* **332**, 212–228 (1982).

"Optical components for fire control instruments; general specification governing the manufacture, assembly, and inspection of," MIL-PREF-13830B, United States Army, <http://snebulos.mit.edu/projects/reference/MIL.../MIL-PRF-13830B.pdf> (1963).

Povey, V., "Athermalisation techniques in infrared systems," *Proc. SPIE* **655**, 142–153 (1986).

"Preparation of drawings for optical elements and systems," ISO 10110, International Organization for Standardization, http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=35991 (2006).

Schwartz, K., "Cost and performance trade-offs for commercially available linear stages," *Proc. SPIE* **7793**, 77930Q (2010) [doi:10.1117/12.868245].

Schwartz, K. and J. H. Burge, "Relating axial motion of optical elements to focal shift," *Proc. SPIE* **7793**, 779306 (2010) [doi:10.1117/12.868244].

Sheridan, P. M., F. O. James, and T. S. Miller, "Design of Components," in *Engineering with Rubber: How to Design Rubber Components*, Second Edition, A. N. Gent, Ed., Hanser Gardner Publications, Cincinnati, OH (2001).

Singh, S. P., G. J. Burgess, J. Singh, and M. Kremer, "Measurement and analysis of the next-day air shipping environment for mid-sized and lightweight packages for DHL, FedEx, and United Parcel Service," *Packing Technology and Science* **19**(4), 227–235 (2006).

Singh, S. P., J. Singh, K. C. Chiang, and K. Saha, "Measurement and analysis of small packages in next-day air shipments," *Packing Technology and Science* **23**(1), 1–9 (2010).

Slocum, A. H., *Precision Machine Design*, Society of Manufacturing, Dearborn, MI (1992).

Bibliography

Smith, S. T., *Flexures: Elements of Elastic Mechanisms*, Gordon & Breach, Amsterdam (2000).

Smith, W. J., *Modern Optical Engineering*, Third Edition, McGraw-Hill, New York (2000).

Stachiw, J. D., "Design parameters for germanium windows under uniform pressure loading," *Proc. SPIE* **131**, 57–72 (1978).

Stone, R., "FEA Presentation: Common pitfalls/problems, tips, and examples," Lecture at the Univ. of Arizona, Tucson, AZ (6 Nov 2009).

Valente, T. M., "Scaling laws for lightweight optics," *Proc. SPIE* **1340**, 47–66 (1990) [doi:10.1117/12.23035].

Valente, T. M. and D. Vukobratovich, "A comparison of the merits of open-back, symmetric sandwich, and contoured back mirrors as light-weighted optics," *Proc. SPIE* **1167**, 20–36 (1989).

Vukobratovich, D. and R. Richard, "Flexure mounts for high-resolution optical elements," *Proc. SPIE* **959**, 18–36 (1988).

Weber, M. J., *Handbook of Optical Materials*, CRC Press, Boca Raton, FL (2003).

Yoder, P. R., *Mounting Optics in Optical Instruments*, Second Edition, SPIE Press, Bellingham, WA (2008) [doi:10.1117/3.785236].

Yoder, P. R., *Design and Mounting of Prisms and Mirrors in Optical Instruments*, SPIE Press, Bellingham, WA (1998).

Yoder, P. R., *Opto-mechanical Systems Design*, CRC Press, Boca Raton, FL (2006).

Young, W. C., *Roark's Formulas for Stress and Strain*, McGraw-Hill, New York (2000).

References

1. NIST/SEMATECH, *e-Handbook of Statistical Methods*, <http://www.itl.nist.gov/div898/handbook/index.htm>.
2. Schott - Technical Note. *TIE-33: Design strength of optical glass and Zerodur* (2004).
3. <http://outgassing.nasa.gov>
4. Nelson, J. E., Lubliner, J., and Mast, T. S., "Telescope mirror supports: plate deflection on point supports," *Proc. SPIE* **332** (1982).
5. Park, W. H., "Parametric modeling of self-weighted distortion for plane optical mirrors," (2010).
6. Valente, T. M., Vukobratovich, D., "Comparison of the merits of open-back, symmetric sandwich, and contoured back mirrors as lightweight optics," *Proc. SPIE* **1167** (1989).
7. Kimmel, R. K. and Parks, R. E., *ISO 10110 Optics and Optical Instruments: Preparation of Drawings for Optical Elements and Systems: A User's Guide*. Washington, DC: Optical Society of America (1995).

Index

- 180-deg deviation, 63
- 180-deg rotation, 8
- 90-deg beam deviation, 63

- Abbe error, 31
- absolute dn/dT , 101
- acceleration, 97
- accuracy, 28
- active athermalization, 105
- active optics, 82
- actuators, 27, 82
- adaptive optics, 82
- adhesion, 46
- adhesive properties, 47
- adhesive strength, 46
- adhesives, 46, 75
- adjustable-diameter mount, 52
- adjusters, 37
- alignment telescope, 108
- all-one-material design, 104
- Amici roof prism, 63
- analysis, 93
- anamorphic prism pair, 68
- angular deviation, 28
- aspect ratio, 80
- athermal doublet, 103
- athermalization, 103
- autocollimator, 109
- autostigmatic microscope, 109
- axial motion of a lens, 2
- axial runout, 30

- backlash, 31
- baffle threading, 56
- baffles, 56

- ball in seat, 23
- ball-and-socket stage, 30
- ball-bearing stages, 29
- basic dimensions, 110
- Bayar equation, 55
- beam splitters, 67
- Biot number, 101
- bonding, 53, 66
- bonding materials, 50
- bulge effect, 15
- bulk modulus, 15

- cell, 53
- cell and set screw, 51, 74
- cell and threaded retaining ring, 51
- cellular-core mirror, 87
- cemented doublets, 50
- Ciddor equation, 102
- circle, 107
- circular/elliptical hinge, 45
- clamp forces, 75
- clamp load, 36
- clamping, 53
- clamps, 67
- clean room, 117
- clear aperture, 5
- clearance, 54
- closed-loop-control, 40
- coefficient of thermal expansion (CTE), 98
- cohesion, 46
- cohesive strength, 46
- commercial off-the-shelf (COTS), 51
- compliance, 47
- compressive, 14
- concentricity, 30

Index

- confidence value, 7
- contoured-back mirror, 86
- convergence test, 93
- counterweight supports, 82
- critical damping, 94
- cross-coupling, 31
- cross-strip pivots, 44
- crossed-roller bearings, 29
- cube corner prism, 63
- cyanoacrylates, 46
- cylinder, 26

- damping, 94
- damping factor, 94, 95
- datum, 110
- datum reference frame, 110
- degrees of freedom, 22, 23
- differential screw, 38
- dome, 72
- dome stress, 73
- double Dove prism, 64
- Dove prism, 64
- dovetail stages, 29

- eccentricity, 30
- edge bands, 80
- Edlén equation, 102
- elastomeric adhesive, 55
- elastomers, 46
- electroless nickel, 77
- electronic drivers, 40
- ellipse, 107
- encoder, 27
- envelope principle, 111

- feature control frame, 112
- features of size, 111

- Federal Standard 209, 117
- filters, 67
- finite element analysis (FEA), 90
- finite element method (FEM), 90
- flange retainer, 56
- flexural rigidity, 86, 88
- flexure mounts, 74
- flexures, 29, 41, 67
- focus-adjusting wedge system, 68
- fused core, 87

- galling, 35
- general image-motion equations, 4
- geometric dimensioning and tolerancing (GD&T), 110, 112
- gimble mounts, 74
- goniometer, 30
- gothic-arch, 29
- grade, 34

- heat flow, 100, 101
- Hindle mounts, 81
- hollow cube corner, 63
- hub mounted, 76
- hyperhemispheres, 72
- hysteresis, 31
- h*-adaptive, 91

- image motion, 5
- image space, 1
- inverted, 8
- ISO 10110 standard, 113
- ISO 14644, 117

Index

- isolation, 96
- jitter, 1
- K prism, 64
- kinematic design, 22
- kinematic mirror mount, 74
- Lamé pressure vessel
 - equations, 73
- lateral adjustment, 59
- lateral motion of a lens, 2
- lateral motion of a mirror, 2
- lateral supports, 80
- law of reflection, 10
- leaf flexure, 41
- leaf hinge, 45
- least material condition (LMC), 111
- left-handed, 8
- lens, 108
- lightweight, 86
- limit dimensions, 110
- line-of-sight (LOS) error, 1
- linear stages, 29
- liquid pinning, 39
- load capacity, 28
- lock, 27
- logarithmic decrement, 95
- low-order curvature (power), 85
- machined seats, 58
- manual drivers, 37
- margin of safety, 17
- maximum amplification
 - at resonance, 95
- maximum compressive
 - axial stress, 60
- maximum material
 - condition (MMC), 111
- mechanical axis, 108
- mesh, 91
- metal barrel, 57
- metering rods, 104
- micrometers, 37
- microsteppers, 40
- Miles equation, 97
- mirror matrix, 10
- mirror motion, 2
- mirror mounted axially
 - (axis vertical), 83
- mirror mounted laterally
 - (axis horizontal), 82
- mirror substrate, 77
- Muench equation, 55
- National Institute of Standards and Technology (NIST), 102
- natural frequency, 94
- nodal points, 91
- notch hinge, 45
- object space, 1
- off-the-shelf mounts, 74
- open-back mirror, 88
- open-loop-control, 40
- optical adhesives, 46
- optical axis, 1, 91, 108
- optimizing, 93
- orientation, 8
- outgassing, 47
- overconstraint, 22
- parabola, 107

Index

- parallel leaf strips, 43
- parallel spring guide, 43
- parametric model, 85
- parity, 8
- Pascals, 14
- peak-to-valley (P–V), 89
- peak-to-valley deflection, 85
- Pechan prism, 64
- Pechan–Schmidt prism, 65
- Pechan–Schmidt roof, 65
- pencil bounce trick, 8
- penta prism, 63
- percent collected volatile condensable material (%CVCMM), 47
- percent total mass lost (%TML), 47
- piezoelectric actuators, 40
- pip generator, 109
- plane parallel plate, 3
- point contacts, 25
- point supports, 81
- Poisson effect, 15
- Poisson ratio, 15
- Porro erecting system, 65
- Porro prism, 63
- Porro prism pair, 65
- positioner, 31
- postprocessing, 93
- potted, 70, 75
- potting a lens, 55
- power spectral density (PSD), 95
- ppm, 16
- precise motions, 27
- precision, 28
- precision elastic limit, 16
- preload, 36
- preload force, 22, 67
- preload torque, 54
- preprocessing, 91
- prism matrix formalism, 65
- prism mount, 66
- prisms, 62
- property class, 34
- proportional limit, 16
- psi, 14
- push-pull screws, 37
- p*-adapative, 91
- rectilinear spring guide, 43
- reduced tensile modulus, 41
- reduced thickness, 9
- relative dn/dT , 101
- repeatability, 26, 28
- resolution, 28
- retaining ring, 52, 58
- reversion, 64
- reverted, 8
- rhomboid prism, 62
- right-angle prism, 63
- right-handed, 8
- rigid body, 6
- Risley wedge-prism system, 68
- rms deflection, 85
- roll, 9
- roller chains, 80
- roof, 62
- root-mean-square (rms), 89
- rotation, 6
- rotation matrices, 12

Index

- rotation stages, 30
- Rule #1, 111
- safety factor, 17
- sandwich mirror, 88
- sapphire, 70
- Schmidt prism, 64
- screws, 32
- sealed, 57
- self-weight deflection, 82
- semi-kinematic design, 24
- sensitivity, 28
- servos, 40
- set, 16
- shape factor, 48
- sharp-corner contact, 60
- shims, 38
- single-strip flexure, 41
- sling supports, 80
- snap ring, 52
- solver, 93
- spacers, 58
- spacing adjustments, 59
- sphere, 107
- spherical contact, 61
- spring and locating pins, 67
- stages, 27, 28
- stepped-barrel, 58
- stepper motors, 40
- Stewart platform, 31
- stiffness, 25, 47
- stiffness relations, 42, 44
- stiffness-to-weight ratio, 86
- straight-barrel design, 58
- strain, 14
- strap mounts, 80
- stray light, 56
- strength of the fastener, 34
- stress, 14, 25
- stress-versus-strain curve, 16
- structural adhesives, 46
- subcell mounting, 59
- supports, 75
- system of constraints, 27
- table and clamp, 67
- tangent flexure mounts, 76
- tangential contact, 61
- tapping, 33
- temperature coefficient of the refractive index, 101
- temperature stabilization, 100
- tensile, 14
- thermal conductivity, 99
- thermal diffusivity, 100
- thermal effects, 98
- thermal gradients, 99
- thermal strain, 98
- thermal stress, 98
- thermal time constant, 100
- thin dome, 73
- thin-wedge prism, 68
- thread classes, 32
- threaded inserts, 35
- threaded retaining ring, 53
- three-pronged lens mount, 52
- thumbscrews, 37
- tightening torque, 36

Index

- tilt stages, 30
- tip/tilt stages, 30
- tolerance zone, 110
- toroidal contact, 60
- toroidal hinges, 45
- transient heat flux, 100
- translation, 6
- transmissibility, 96
- travel range, 28
- tunnel diagram, 9

- ultimate strength, 16
- UNC, 32
- underconstrained, 22
- UNF, 32
- Unified Thread Standard (UTS), 32

- V-groove clamp mounts, 52
- V-mount, 80
- van Bezooijen, 55
- vibration isolators, 96

- washers, 36, 38
- wedge, 108
- whiffle tree mounts, 81
- windows, 69
- wobble, 30

- yaw, 9
- yield strength, 16
- Young's modulus, 15

- z axis, 91



Katie Schwertz received her BS in Optics from the University of Rochester Institute of Optics in 2008 and an MS in Optical Sciences from the University of Arizona in 2010. Her graduate work focused on optomechanics, during which she completed the report *Useful Estimations and Rules of Thumb for Optomechanics* under the guidance of Jim Burge. She currently works

as an optomechanical designer for Edmund Optics at their Tucson Design Center.



Jim Burge is a Professor of Optical Sciences and Astronomy at the University of Arizona, leading research and curriculum development in the areas of optomechanical engineering, optical-systems engineering, and optical manufacturing. Dr. Burge has a BS degree from Ohio State University in Engineering Physics with Mechanical Engineering, and MS and PhD degrees in

Optical Sciences from the University of Arizona.