

Feedback Systems

An Introduction for Scientists and Engineers

SECOND EDITION

Karl Johan Åström
Richard M. Murray

Version v3.0j (2019-08-18)

This is the electronic edition of *Feedback Systems* and is available from
<http://fbsbook.org>. Hardcover editions may be purchased from Princeton
University Press, <http://press.princeton.edu/titles/8701.html>.

This manuscript is for personal use only and may not be reproduced, in whole or
in part, without written consent from the publisher (see
<http://press.princeton.edu/permissions.html>).

Bibliography

- [ÅB00] K. J. Åström and R. D. Bell. Drum-boiler dynamics. *Automatica*, 36:363–378, 2000.
- [Abk69] M. A. Abkowitz. *Stability and Motion Control of Ocean Vehicles*. MIT Press, Cambridge, MA, 1969.
- [Ack72] J. Ackermann. Der Entwurf linearer Regelungssysteme im Zustandsraum. *Regelungstechnik und Prozessdatenverarbeitung*, 7:297–300, 1972.
- [Ack85] J. Ackermann. *Sampled-Data Control Systems*. Springer, Berlin, 1985.
- [AF66] M. Athans and P. Falb. *Optimal Control*. McGraw-Hill, New York, NY, 1966. Dover Reprint 2007.
- [Agn76] C. E. Agnew. Dynamic modeling and control of congestion-prone systems. *Operations Research*, 24(3):400–419, 1976.
- [ÅH86] K. J. Åström and A. Helmersson. Dual control of an integrator with unknown gain. *Comp. & Maths. with Appls.*, 12A(6):653–662, 1986.
- [ÅH06] K. J. Åström and T. Häggglund. *Advanced PID Control*. ISA—The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC, 2006.
- [Ahl66] L. V. Ahlfors. *Complex Analysis*. McGraw-Hill, New York, 1966.
- [ÅHL94] K. J. Åström, C. C. Hang, and B. C. Lim. A new Smith predictor for controlling a process with an integrator and long dead-time. *IEEE Transactions on Automatic Control*, 39:343–345, 1994.
- [AJÅ⁺17] M. Ahrnbom, M. B. Jensen, K. Åström, M. Nilsson, H. Ardö, and T. Moeslund. Improving a real-time object detector with compact temporal information. In *International Conference on Computer Vision Workshops, 2017*, page 190, 2017.
- [ÅK14] K. J. Åström and P. R. Kumar. Control: A perspective. *Automatica*, 50:3–43, 2014.
- [ÅKL05] K. J. Åström, R. E. Klein, and A. Lennartsson. Bicycle dynamics and control. *IEEE Control Systems Magazine*, 25(4):26–47, 2005.
- [Alu15] R. Alur. *Principles of Cyber-Physical Systems*. MIT Press, 2015.
- [AM90] B. D. O. Anderson and J. B. Moore. *Optimal Control Linear Quadratic Methods*. Prentice Hall, Englewood Cliffs, NJ, 1990. Republished by Dover Publications, 2007.
- [AM10] P. Albertos and I. Mareels. *Feedback and Control for Everyone*. Springer, 2010.
- [Ano92] Anon. V-model development standard for it-systems of the federal republic of germany. Technical report, Federal German Armed Forces, 1992.

- [Apo67] T. M. Apostol. *Calculus, Vol. II: Multi-Variable Calculus and Linear Algebra with Applications*. Wiley, New York, 1967.
- [Apo69] T. M. Apostol. *Calculus, Vol. I: One-Variable Calculus with an Introduction to Linear Algebra*. Wiley, New York, 1969.
- [Ari94] R. Aris. *Mathematical Modeling Techniques*. Dover, New York, 1994. Originally published by Pitman, 1978.
- [Arn78] V. I. Arnold. *Mathematical Methods in Classical Mechanics*. Springer, New York, 1978.
- [Arn87] V. I. Arnold. *Ordinary Differential Equations*. MIT Press, Cambridge, MA, 1987. 10th printing 1998.
- [AS82] R. H. Abraham and C. D. Shaw. *Dynamics—The Geometry of Behavior, Part 1: Periodic Behavior*. Aerial Press, Santa Cruz, CA, 1982.
- [ASMN03] M. Atkinson, M. Savageau, J. Myers, and A. Ninfa. Development of genetic circuitry exhibiting toggle switch or oscillatory behavior in *Escherichia coli*. *Cell*, 113(5):597–607, 2003.
- [Åst99] K. J. Åström. Automatic control—The hidden technology. In P. M. Frank, editor, *Advances in Control—Highlights of the ECC '99*, pages 1–29, London, UK, 1999. Springer.
- [Åst00] K. J. Åström. Limitations on control system performance. *European Journal on Control*, 6(1):2–20, 2000.
- [Åst06] K. J. Åström. *Introduction to Stochastic Control Theory*. Dover, New York, 2006. Originally published by Academic Press, New York, 1970.
- [Ath75] D. P. Atherton. *Nonlinear Control Engineering*. Van Nostrand, New York, 1975.
- [AVK87] A. A. Andronov, A. A. Vitt, and S. E. Khaikin. *Theory of Oscillators*. Dover, New York, 1987.
- [ÅW97] K. J. Åström and B. Wittenmark. *Computer-Control Systems: Theory and Design*. Prentice Hall, Englewood Cliffs, NJ, 3rd edition, 1997.
- [ÅW08a] K. J. Åström and B. Wittenmark. *Adaptive Control*. Dover, New York, 2nd edition, 2008. Originally published by Addison Wesley, 1995.
- [ÅW08b] K. J. Åström and B. Wittenmark. *Adaptive Control*. Dover, New York, 2nd edition, 2008. Originally published by Addison Wesley, 1995.
- [BÅ70] R. Bellman and K. J. Åström. On structural identifiability. *Mathematical Biosciences*, 7:329–339, 1970.
- [Bas01] T. Basar, editor. *Control Theory: Twenty-five Seminal Papers (1932–1981)*. IEEE Press, New York, 2001.
- [BB91] T. Basar and P. Bernhard. *H^∞ -Optimal Control and Related Minimax Design Problems: A Dynamic Game Approach*. Birkhauser, Boston, 1991.
- [BBvB⁺01] K. Beck, M. Beedle, A. van Bennekum, A. Cockburn, W. Cunningham, M. Fowler, J. Grenning, J. Highsmith, A. Hunt, R. Jeffries, Jon Kern, Brian Marick, Robert C. Martin, Steve Mallor, Ken Schwaber, and Jeff Sutherland. The Agile Manifesto. Technical report, The Agile Alliance, 2001. Available at <http://agilemanifesto.org>.
- [BC48] G. S. Brown and D. P. Campbell. *Principles of Servomechanisms*. Wiley, New York, 1948.

- [BD04] W. E. Boyce and R. C. DiPrima. *Elementary Differential Equations*. Wiley, New York, 2004.
- [Bec05] J. Bechhoefer. Feedback for physicists: A tutorial essay on control. *Reviews of Modern Physics*, 77:783–836, 2005.
- [Bec19] J. Bechhoefer. *Control Theory for Physicists*. 2019. In press.
- [Bel57] R. Bellman. *Dynamic Programming*. Princeton University Press, Princeton NJ, 1957.
- [Ben79] S. Bennett. *A History of Control Engineering: 1800–1930*. Peter Peregrinus, Stevenage, 1979.
- [Ben93] S. Bennett. *A History of Control Engineering: 1930–1955*. Peter Peregrinus, Stevenage, 1993.
- [Beq12] B. W. Bequette. Challenges and recent progress in the development of a closed-loop artificial pancreas. *Annual Reviews in Control*, 36:255–268, 2012.
- [Beq13] B. W. Bequette. Algorithms for a closed-loop artificial pancreas: The case for model predictive control. *Journal of Diabetes Science and Technology*, 7:6:1632–1643, 2013.
- [Ber54] L. L. Beranek. *Acoustics*. McGraw-Hill, New York, 1954.
- [Ber89] R. N. Bergman. Toward physiological understanding of glucose tolerance: Minimal model approach. *Diabetes*, 38:1512–1527, 1989.
- [Ber01] R. N. Bergman. The minimal model of glucose regulation: A biography. In J. Novotny, M. Green, and R. Boston, editors, *Mathematical Modeling in Nutrition and Health*. Kluwer Academic/Plenum, New York, 2001.
- [BG68] B. Brawn and F. Gustavson. Program behavior in a paging environment. *Proceedings of the AFIPS Fall Joint Computer Conference*, pages 1019–1032, 1968.
- [BG87] D. Bertsekas and R. Gallager. *Data Networks*. Prentice Hall, Englewood Cliffs, 1987.
- [BH75] A. E. Bryson, Jr. and Y.-C. Ho. *Applied Optimal Control: Optimization, Estimation, and Control*. Wiley, New York, 1975.
- [Bia95] B. Bialkowski. Process control sample problems. In N. J. Sell, editor, *Process Control Fundamentals for the Pulp & Paper Industry*. Tappi Press, Norcross, GA, 1995.
- [BK64] R. E. Bellman and R. Kalaba. *Selected Papers on Mathematical Trends in Control Theory*. Dover, New York, 1964.
- [BKLS16] M. Blanke, M. Kinnaert, J. Lunze, and M. Staroswiecki. *Diagnosis and Fault-Tolerant Control*. Springer, 3rd edition, 2016.
- [Bla34] H. S. Black. Stabilized feedback amplifiers. *Bell System Technical Journal*, 13:1–2, 1934.
- [Bla77] H. S. Black. Inventing the negative feedback amplifier. *IEEE Spectrum*, pages 55–60, 1977.
- [Bla91] J. H. Blakelock. *Automatic Control of Aircraft and Missiles*. Addison-Wesley, Cambridge, MA, 2nd edition, 1991.
- [Bli90] G. Blickley. Modern control started with Ziegler-Nichols tuning. *Control Engineering*, 37:72–75, 1990.

- [BM99] A. Bemporad and M. Morari. Control of systems integrating logic, dynamics, and constraints. *Automatica*, 35(3):407 – 427, 1999.
- [Boa16] BKCASE Editorial Board, editor. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*. Stevens Institute of Technology, v. 1.6 edition, 2016. Accessed 27 August 2016, <http://sebokwiki.org>.
- [Bod40] H. W. Bode. Relations between attenuation and phase in feedback amplifier design. *Bell System Technical Journal*, 19:421–454, 1940.
- [Bod45] H. W. Bode. *Network Analysis and Feedback Amplifier Design*. Van Nostrand, New York, 1945.
- [Bod60] H. W. Bode. Feedback—The history of an idea. In *Symposium on Active Networks and Feedback Systems*. Polytechnic Institute of Brooklyn, New York, 1960. Reprinted in [BK64].
- [BP96] M. B. Barron and W. F. Powers. The role of electronic controls for future automotive mechatronic systems. *IEEE Transactions on Mechatronics*, 1(1):80–89, 1996.
- [Bri66] E. H. Bristol. On a new measure of interactions for multivariable process control. *IEEE Transactions on Automatic Control*, 11(1):133–134, 1966.
- [Bro70] R. W. Brockett. *Finite Dimensional Linear Systems*. Wiley, New York, 1970.
- [Bro00] R. W. Brockett. New issues in the mathematics of control. In B. Engquist and W. Schmid, editors, *Mathematics Unlimited—2001 and Beyond*, pages 189–220. Springer-Verlag, Berlin, 2000.
- [BRS60] J. F. Blackburn, G. Reethof, and J. L. Shearer. *Fluid Power Control*. MIT Press, Cambridge, MA, 1960.
- [BSÅH17] J. Berner, K. Soltesz, K. J. Åström, and T. Hägglund. Practical evaluation of a novel multivariable relay autotuner with short and efficient excitation. In *IEEE Conference on Control Technology and Applications*, 2017.
- [BT78] C. Brosilov and M. Tong. Inferential control systems. *AIChE Journal*, 24(3):457–465, 1978.
- [Can03] R. H. Cannon. *Dynamics of Physical Systems*. Dover, New York, 2003. Originally published by McGraw-Hill, 1967.
- [CCG⁺02] A. Cimatti, E. M. Clarke, E. Giunchiglia, F. Giunchiglia, M. Pistore, M. Roveri, R. Sebastiani, and A. Tacchella. Nusmv 2: An opensource tool for symbolic model checking. In *Proceedings of the 14th International Conference on Computer Aided Verification*, pages 359–364. Springer-Verlag, 2002.
- [CCS15] E. Crawley, B. Cameron, and D. Selva. *Architecture: Strategy and Product Development of Complex Systems*. Pearson, New York, NJ, 2015.
- [CD75] R. F. Coughlin and F. F. Driscoll. *Operational Amplifiers and Linear Integrated Circuits*. Prentice Hall, Englewood Cliffs, NJ, 6th edition, 1975.
- [CD91] F. M. Callier and C. A. Desoer. *Linear System Theory*. Springer-Verlag, London, 1991.
- [CFG⁺06] L. B. Cremean, T. B. Foote, J. H. Gillula, G. H. Hines, D. Kogan, K. L. Kriechbaum, J. C. Lamb, J. Leibs, L. Lindzey, C. E. Rasmussen, A. D. Stewart, J. W. Burdick, and R. M. Murray. Alice: An information-rich autonomous vehicle for high-speed desert navigation. *Journal of Field Robotics*, 23(9):777–810, 2006.

- [CJ59] H. S. Carslaw and J. C. Jaeger. *Conduction of Heat in Solids*. Clarendon Press, Oxford, UK, 2nd edition, 1959.
- [CM51] H. Chestnut and R. W. Mayer. *Servomechanisms and Regulating System Design, Vol. 1*. Wiley, New York, 1951.
- [Cor08] J. Cortés. Distributed algorithms for reaching consensus on general functions. *Automatica*, 44(3):726–737, March 2008.
- [CR80] C. R. Cutler and B. C. Ramaker. Dynamic matrix control—A computer control algorithm. In *Proceedings Joint Automatic Control Conference*, San Francisco, CA, 1980.
- [CRK11] C. Cobelli, E. Renard, and B. Kovatchev. Artificial pancreas: Past, present, future. *Diabetes*, 68:11:2672—2682, 2011.
- [Cro93] Crocus. *Systemes d’Exploitation des Ordinateurs*. Dunod, Paris, 1993.
- [CS08] G. C. and K. S. Sin. *Adaptive Filtering Prediction and Control*. Dover, New York, 2008. Originally published by Prentice Hall, 1984.
- [Cul66] W. J. Culver. On the existence and uniqueness of the real logarithm of a matrix. *Proc. American Mathematical Society*, 17(5):1146—1151, 1966.
- [DB04] R. C. Dorf and R. H. Bishop. *Modern Control Systems*. Prentice Hall, Upper Saddle River, NJ, 10th edition, 2004.
- [DFT92] J. C. Doyle, B. A. Francis, and A. R. Tannenbaum. *Feedback Control Theory*. Macmillan, New York, 1992.
- [DGH⁺02] Y. Diao, N. Gandhi, J. L. Hellerstein, S. Parekh, and D. M. Tilbury. Using MIMO feedback control to enforce policies for interrelated metrics with application to the Apache web server. In *Proceedings of the IEEE/IFIP Network Operations and Management Symposium*, pages 219–234, 2002.
- [DGKF89] J. C. Doyle, K. Glover, P. P. Khargonekar, and B. A. Francis. State-space solutions to standard H_2 and H_∞ control problems. *IEEE Transactions on Automatic Control*, 34(8):831–847, 1989.
- [DM02a] L. Desborough and R. Miller. Increasing customer value of industrial control performance monitoring—Honeywell’s experience. In *Sixth International Conference on Chemical Process Control*. AIChE Symposium Series Number 326 (Vol. 98), 2002.
- [DM02b] L. Desborough and R. Miller. Increasing customer value of industrial control performance monitoring - Honeywell’s experience. In *Sixth International Conference on Chemical Process Control*, pages 172–192. AIChE Symposium Series Number 326 (Volume 98), 2002.
- [DM14] D. Del Vecchio and R. M. Murray. *Biomolecular Feedback Systems*. Princeton University Press, 2014.
- [Dos68] F. H. Dost. *Grundlagen der Pharmakokinetik*. Thieme Verlag, Stuttgart, 1968.
- [Doy78] J. C. Doyle. Guaranteed margins for LQG regulators. *IEEE Transactions on Automatic Control*, 23(4):756–757, 1978.
- [Dra55] C. S. Draper. Flight control. *Jorunal Royal Aeronautical Society*, 59(July):451–477, 1955. 45th Wilber Wright Memorial Lecture.
- [Dub57] L. E. Dubins. On curves of minimal length with a constraint on average curvature, and with prescribed initial and terminal positions and tangents. *American Journal of Mathematics*, 79:497–516, 1957.

- [Dys04] F. Dyson. A meeting with Enrico Fermi. *Nature*, 247(6972):297, 2004.
- [EG05] S. P. Ellner and J. Guckenheimer. *Dynamic Models in Biology*. Princeton University Press, Princeton, NJ, 2005.
- [EHBM08] B. Eisenhower, G. Hagen, A. Banaszuk, and I. Mezič. Passive control of limit cycle oscillations in a thermoacoustic system using asymmetry. *Journal of Applied Mechanics*, 75:011021–1–011021–9, 2008.
- [EKR03] E. N. Elnozahy, M. Kistler, and R. Rajamony. Energy-efficient server clusters. In *Power-Aware Computer Systems*, pages 179–197. Springer, 2003.
- [EL00] M. B. Elowitz and S. Leibler. A synthetic oscillatory network of transcriptional regulators. *Nature*, 403(6767):335–338, 2000.
- [Ell94] J. R. Ellis. *Vehicle Handling Dynamics*. Mechanical Engineering Publications, London, 1994.
- [ESGK02] H. El-Samad, J. P. Goff, and M. Khammash. Calcium homeostasis and par-turient hypocalcemia: An integral feedback perspective. *Journal of Theoretical Biology*, 214:17–29, 2002.
- [FCF⁺06] P. G. Fabietti, V. Canonico, M. O. Federici, M. Benedetti, and E. Sarti. Control oriented model of insulin and glucose dynamics in type 1 diabetes. *Medical and Biological Engineering and Computing*, 44:66–78, 2006.
- [Fel65] A. A. Feldbaum. *Optimal Control Theory*. Academic Press, New York, 1965.
- [FLMR92] M. Fliess, J. Levine, P. Martin, and P. Rouchon. On differentially flat nonlinear systems. *Comptes Rendus des Séances de l'Académie des Sciences, Serie I*, 315:619–624, 1992.
- [FLMR95] M. Fliess, J. Levine, P. Martin, and P. Rouchon. Flatness and defect of non-linear systems: Introductory theory and examples. *International Journal of Control*, 61(6):1327–1361, 1995.
- [For61] J. W. Forrester. *Industrial Dynamics*. MIT Press, Cambridge, MA, 1961.
- [Fou07] J. B. J. Fourier. On the propagation of heat in solid bodies. Memoir, read before the Class of the Institut de France, 1807.
- [FPEN05] G. F. Franklin, J. D. Powell, and A. Emami-Naeini. *Feedback Control of Dynamic Systems*. Prentice Hall, Upper Saddle River, NJ, 5th edition, 2005.
- [Fra87] B. A. Francis. *A Course in $\mathcal{H}_\infty$ Control*. Springer-Verlag, Berlin, 1987.
- [Fra07] A. Fradkov. *Cybernetical Physics: From Control of Chaos to Quantum Control*. Springer, Berlin, 2007.
- [Fri04] B. Friedland. *Control System Design: An Introduction to State Space Methods*. Dover, New York, 2004.
- [Fri15] P. Fritzson. *Principles of Object-Oriented Modeling and Simulation with Modelica 3.3: A Cyber-Physical Approach*. IEEE Press. Wiley, 2 edition, 2015.
- [FW76] B. A. Francis and M. W. Wonham. The internal model principle of control theory. *Automatica*, 12(5):492–500, 1976.
- [Gan60] F. R. Gantmacher. *The Theory of Matrices, Vol. 1 and 2*. Chelsea Publishing Company, 1960.
- [GB42] M. A. Gardner and J. L. Barnes. *Transients in Linear Systems*. Wiley, New York, 1942.

- [GF71] L. Gunkel and G. F. Franklin. A general solution for linear sampled data systems. *IEEE Transactions on Automatic Control*, AC-16:767–775, 1971.
- [GGS01] G. C. Goodwin, S. F. Graebe, and M. E. Salgado. *Control System Design*. Prentice Hall, Upper Saddle River, NJ, 2001.
- [GH83] J. Guckenheimer and P. Holmes. *Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields*. Springer-Verlag, Berlin, 1983.
- [Gil63] E. Gilbert. Controllability and observability in multivariable control systems. *SIAM Journal of Control*, 1(1):128–151, 1963.
- [GL95] M. Green and D. J. N. Limebeer. *Linear Robust Control*. Prentice Hall, Englewood Cliffs, NJ, 1995.
- [GL13] T. T. Georgiou and A. Lindquist. The separation principle in stochastic control, redux. *IEEE Transactions on Automatic Control*, 58(10):2481–2494, 2013.
- [GM61] D. Graham and D. McRuer. *Analysis of Nonlinear Control Systems*. Wiley, New York, 1961.
- [GMGM05] A. De Gaetano, D. Di Martino, A. Germani, and C. Manes. Mathematical models and state observation of the glucose-insulin homeostasis. In J. Cagnol and J.-P. Zolesio, editors, *System Modeling and Optimization – Proceedings of the 21st IFIP TC7 Conference*, pages 281–294. Springer, 2005.
- [God83] K. Godfrey. *Compartment Models and Their Application*. Academic Press, New York, 1983.
- [Gol53] H. Goldstein. *Classical Mechanics*. Addison-Wesley, Cambridge, MA, 1953.
- [Gol70] S. W. Golomb. Mathematical models—Uses and limitations. *Simulation*, 4(14):197–198, 1970.
- [GP82] M. Giobaldi and D. Perrier. *Pharmacokinetics*. Marcel Dekker, New York, 2nd edition, 1982.
- [GPD59] J. C. Gille, M. J. Pelegrin, and P. Decaulne. *Feedback Control Systems; Analysis, Synthesis, and Design*. McGraw-Hill, New York, 1959.
- [GQH16] R. Gonzalez, F. Qi, and B. Huang. *Process Control System Fault Diagnosis: A Bayesian Approach*. Wiley, 2016.
- [Gre59] P. C. Gregory, editor. *Proc. Self Adaptive Flight Control Symposium*. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1959.
- [GST12] R. Goebel, R. G. Sanfelice, and A. R. Teel. *Hybrid Dynamical Systems: Modeling, Stability, and Robustness*. Princeton University Press, 2012.
- [Gui63] E. A. Guillemin. *Theory of Linear Physical Systems*. MIT Press, Cambridge, MA, 1963.
- [Hah67] W. Hahn. *Stability of Motion*. Springer, Berlin, 1967.
- [Hås87] J. T. Håstad. *Computational Limitations of Small Depth Circuits*. MIT Press, Cambridge, Massachusetts, 1987.
- [HB90] J. K. Hedrick and T. Batsuen. Invariant properties of automobile suspensions. In *Proceedings of the Institution of Mechanical Engineers*, volume 204, pages 21–27, London, 1990.
- [HC03] C. Hajiyev and F. Caliskan. *Fault Diagnosis and Reconfiguration in Flight Control Systems*. Kluwer, 2003.

- [HD95] M. B. Hoagland and B. Dodson. *The Way Life Works*. Times Books, New York, 1995.
- [HDPT04] J. L. Hellerstein, Y. Diao, S. Parekh, and D. M. Tilbury. *Feedback Control of Computing Systems*. Wiley, New York, 2004.
- [Heb49] D. O. Hebb. *The Organization of Behavior*. Wiley & Sons, New York, 1949.
- [Her04] D. V. Herlihy. *Bicycle—The History*. Yale University Press, New Haven, CT, 2004.
- [HH52] A. L. Hodgkin and A. F. Huxley. A quantitative description of membrane current and its application to conduction and excitation in nerve. *Journal of Physiology*, 117(500–544), 1952.
- [HK83] J. Hammer and P.P. Khargonekar. Decoupling of linear systems by dynamic output feedback. *Mathematical Systems Theory*, 17:135–157, 1983.
- [Hol03] G. J. Holzmann. *The SPIN Model Checker*. Addison-Wesley, 2003.
- [Hor63] I. M. Horowitz. *Synthesis of Feedback Systems*. Academic Press, New York, 1963.
- [Hor75] I. M. Horowitz. Superiority of transfer function over state-variable methods in linear, time-invariant feedback system design. *IEEE Transactions on Automatic Control*, AC-20(1):84–97, 1975.
- [Hor91] I. M. Horowitz. Survey of quantitative feedback theory. *International Journal of Control*, 53:255291, 1991.
- [Hor93] I. M. Horowitz. *Quantitative Feedback Design Theory (QFT)*. QFT Publications, Boulder CO, 1993.
- [HSH15] R. J. Hawkins, J. K. Speakes, and D. E. Hamilton. Monetary policy and PID control. *Journal of Economic Interaction and Coordination*, 10(1):183–197, 2015.
- [Hug93] T. P. Hughes. *Elmer Sperry: Inventor and Engineer*. John Hopkins University Press, Baltimore, MD, 1993.
- [Hun07] J. Y. Hung. Posicast control past and present. *IEEE Multidisciplinary Engineering Education Magazine*, 3:7–11, 2007.
- [HW00] D. Hanahan and R. A. Weinberg. The hallmarks of cancer. *Cell*, 100:57–70, 2000.
- [Isi95] A. Isidori. *Nonlinear Control Systems*. Springer-Verlag, Berlin, 3rd edition, 1995.
- [Ito70] M. Ito. Neurophysiological aspects of the cerebellar motor system. *International Journal of Neurology*, 7:162–178, 1970.
- [Jac65] H. A. Jacobs. *Frank Lloyd Wright: America’s Greatest Architect*. Harcourt, Brace & World., 1965.
- [Jac72] J. A. Jacquez. *Compartment Analysis in Biology and Medicine*. Elsevier, Amsterdam, 1972.
- [Jac95] V. Jacobson. Congestion avoidance and control. *ACM SIGCOMM Computer Communication Review*, 25:157–173, 1995.
- [Jan14] P. K. Janert. *Feedback Control for Computer Systems*. O’Reilly Media, 2014.
- [JBRM99] J. B. J. B Rawlings and D. Q. Mayne. *Model Predictive Control Theory and Design*. Nob Hill Publishing, Madison, WI, 1999.

- [JNP47] H. James, N. Nichols, and R. Phillips. *Theory of Servomechanisms*. McGraw-Hill, New York, 1947.
- [JT61] P. D. Joseph and J. T. Tou. On linear control theory. *Transactions of the AIEE*, 80(18), 1961.
- [Jun02] W. G. Jung, editor. *Op Amp Applications*. Analog Devices, Norwood, MA, 2002.
- [Kal60] R. E. Kalman. Contributions to the theory of optimal control. *Boletín de la Sociedad Matemática Mexicana*, 5:102–119, 1960.
- [Kal61a] R. E. Kalman. New methods and results in linear prediction and filtering theory. Technical Report 61-1, Research Institute for Advanced Studies (RIAS), Baltimore, MD, February 1961.
- [Kal61b] R. E. Kalman. On the general theory of control systems. In *Proceedings of the First IFAC Congress on Automatic Control, Moscow, 1960*, volume 1, pages 481–492. Butterworths, London, 1961.
- [KÅT⁺79] C. G. Källström, K. J. Åström, N. E. Thorell, J. Eriksson, and L. Sten. Adaptive autopilots for tankers. *Automatica*, 15:241–254, 1979.
- [KB61] R. E. Kalman and R. S. Bucy. New results in linear filtering and prediction theory. *Transactions of the ASME (Journal of Basic Engineering)*, 83 D:95–108, 1961.
- [Kel85] F. P. Kelly. Stochastic models of computer communication. *Journal of the Royal Statistical Society*, B47(3):379–395, 1985.
- [Kel94] K. Kelly. *Out of Control*. Addison-Wesley, Reading, MA, 1994. Available at <http://www.kk.org/outofcontrol>.
- [KFA69] R. E. Kalman, P. L. Falb, and M. A. Arbib. *Topics in Mathematical System Theory*. McGraw-Hill, New York, 1969.
- [KG02] B. C. Kuo and F. Golnaraghi. *Automatic Control Systems*. Wiley, New York, 8th edition, 2002.
- [Kha01] H. K. Khalil. *Nonlinear Systems*. Macmillan, New York, 3rd edition, 2001.
- [KHN63] R. E. Kalman, Y. Ho, and K. S. Narendra. *Controllability of Linear Dynamical Systems*, volume 1 of *Contributions to Differential Equations*. Wiley, New York, 1963.
- [Kit95] C. Kittel. *Introduction to Solid State Physics*. Wiley, New York, 1995.
- [Kit04] H. Kitano. Biological robustness. *Nature Reviews Genetics*, 5(11):826–837, 2004.
- [KKK95] M. Krstić, I. Kanellakopoulos, and P. Kokotović. *Nonlinear and Adaptive Control Design*. Wiley, 1995.
- [Kle75] L. Kleinrock. *Queuing Systems, Vols. I and II*. Wiley-Interscience, New York, 2nd edition, 1975.
- [Kle89] R. E. Klein. Using bicycles to teach dynamics. *Control Systems Magazine*, 9(3):4–8, 1989.
- [KN00] U. Kiencke and L. Nielsen. *Automotive Control Systems: For Engine, Driveline, and Vehicle*. Springer, Berlin, 2000.
- [KNP11] M. Kwiatkowska, G. Norman, and D. Parker. PRISM 4.0: Verification of probabilistic real-time systems. In G. Gopalakrishnan and S. Qadeer, edi-

- tors, *Proceedings of the 23rd International Conference on Computer Aided Verification (CAV'11)*, pages 585–591. Springer, 2011.
- [Kol57] A. N. Kolmogorov. On the representations of continuous functions of many variables by superpositions of continuous functions of one variable and addition. *Doklady Akademii Nauk USSR*, 114(5):953–956, 1957.
- [Kow09] A. J. Kowalski. Can we really close the loop and how soon? Accelerating the availability of an artificial pancreas: A roadmap to better diabetes outcomes. *Diabetes Technology & Therapeutics*, 11, Supplement 1:113–119, 2009.
- [Kra63] N. N. Krasovski. *Stability of Motion*. Stanford University Press, Stanford, CA, 1963.
- [Krs03] K. B. Ariyur and M. Krstić. *Real-Time Optimization by Extremum-Seeking Control*. Wiley, 2003.
- [Kru09] Paul Krugman. *The Return of Depression Economics and the Crisis of 2008*. W. W. Norton & Company, New York, 2009.
- [KS08] J. Keener and J. Sneyd. *Mathematical Physiology I: Cellular Physiology*. Springer, 2nd edition, 2008.
- [KS09] J. Keener and J. Sneyd. *Mathematical Physiology II: Systems Physiology*. Springer, 2nd edition, 2009.
- [KSH12] A. Krizhevsky, I. Sutskever, and G. E. Hinton. Imagenet classification with deep convolutional neural networks. In *Advances in neural information processing systems*, pages 1097–1105, 2012.
- [Kum01] P. R. Kumar. New technological vistas for systems and control: The example of wireless networks. *Control Systems Magazine*, 21(1):24–37, 2001.
- [Kun93] P. Kundur. *Power System Stability and Control*. McGraw-Hill, New York, 1993.
- [KV86] P. R. Kumar and P. Varaiya. *Stochastic Systems: Estimation, Identification, and Adaptive Control*. Prentice Hall, Englewood Cliffs, NJ, 1986.
- [Lam03] L. Lamport. *Specifying Systems: The TLA+ Language and Tools for Hardware and Software Engineers*. Pearson Education, 2003.
- [LaS60] J. P. LaSalle. Some extensions of Lyapunov’s second method. *IRE Transactions on Circuit Theory*, CT-7(4):520–527, 1960.
- [LBD⁺89] Y. LeCun, B. Boser, J.S. Denker, D. Henderson, R. E. Howard, W. Hubbrd, and L. D. Jackel. Backpropagation applied to handwritten zip code recognition. *Neural Computation*, 1(4):541–551, 1989.
- [LBSP05] D. Limperich, M. Brown, G. Schmitz, and K. Prölß. System simulation of automotive refrigeration cycles. In *Proceedings of the 4th Modelica Conference*, pages 193–199, 2005.
- [Lew03] A. D. Lewis. A mathematical approach to classical control. Technical report, Queens University, Kingston, Ontario, 2003.
- [Lju99a] L. Ljung. *System Identification—Theory for the User*. Prentice Hall, Upper Saddle River, NJ, 1999. 2nd.
- [Lju99b] L. Ljung. *System Identification – Theory for the User*. Prentice Hall, Upper Saddle River, NJ, 2nd edition, 1999.
- [LLAE⁺17] F. Lamnabhi-Lagarigue, A. Annaswamy, S. Engell, A. Isaksson, P. Khar-gonekar, R. M. Murray, H. Nijmeijer, T. Samad, D. Tilbury, and P. Van den

- Hof. Systems & control for the future of humanity, research agenda: Current and future roles, impact and grand challenges. *Annual Reviews in Control*, 43:1–64, 2017.
- [Low17] S. Low. *Analytical Methods for Network Congestion Control*. Morgan and Claypool, 2017.
- [LP15] A Lindquist and G. Picci. *Linear Stochastic Systems: A Geometric Approach to Modeling, Estimation and Identification*. Springer-Verlag, Berlin, Heidelberg, 2015.
- [LPD02] S. H. Low, F. Paganini, and J. C. Doyle. Internet congestion control. *IEEE Control Systems Magazine*, pages 28–43, February 2002.
- [LPW⁺02] S. H. Low, F. Paganini, J. Wang, S. Adlakha, and J. C. Doyle. Dynamics of TCP/RED and a scalable control. In *Proceedings of IEEE Infocom*, pages 239–248, 2002.
- [LRS12] S. Laxminaryan, J. Reifman, and G. M. Steil. Use of a food and drug administration-approved type 1 diabetes mellitus simulator to evaluate and optimize a proportional-integral-derivative controller. *Journal of Diabetes Science and Technology*, 6:6:1401–1409, 2012.
- [LS06] D. J. N. Limebeer and Sharp R. S. Bicycles, motorcycles and models. *Control Systems Magazine*, 26(5):34–61, 2006.
- [LS15] E. A. Lee and S. A. Seshia. *Introduction to Embedded Systems, A Cyber-Physical Systems Approach*. <http://LeeSeshia.org>, 2015. ISBN 978-1-312-42740-2.
- [Lun05] K. H. Lundberg. History of analog computing. *IEEE Control Systems Magazine*, pages 22–28, March 2005.
- [LV11] E. A. Lee and P. Varaiya. *Structure and Interpretation of Signals and Systems*. LeeVaraiya.org, 2011. Available online at <http://leevaraiya.org>.
- [LW13] E. Lavretsky and K. A. Wise. *Robust and Adaptive Control with Aerospace Applications*. Springer, London, 2013.
- [LWE00] D. J. Leith and Leithead W. E. Survey of gain-scheduling analysis and design. *International Journal on Control*, 73(11):1001–1025, 2000.
- [MÅB⁺03] R. M. Murray, K. J. Åström, S. P. Boyd, R. W. Brockett, and G. Stein. Future directions in control in an information-rich world. *Control Systems Magazine*, April 2003.
- [Mac37] D. A. MacLulich. *Fluctuations in the Numbers of the Varying Hare (Lepus americanus)*. University of Toronto Press, 1937.
- [Mac45] L. A. MacColl. *Fundamental Theory of Servomechanisms*. Van Nostrand, Princeton, NJ, 1945. Dover reprint 1968.
- [Mac89] J. M. Maciejowski. *Multivariable Feedback Design*. Addison Wesley, Reading, MA, 1989.
- [Mal59] J. G. Malkin. *Theorie der Stabilität einer Bewegung*. Oldenbourg, München, 1959.
- [Man02] R. Mancini. *Op Amps for Everyone*. Texas Instruments, Houston. TX, 2002.
- [May70] O. Mayr. *The Origins of Feedback Control*. MIT Press, Cambridge, MA, 1970.

- [MC68] D. Michie and R. A. Chambers. Boxes: An experiment in adaptive control. In E. Dale and D. Michie (Eds), editors, *Machine Intelligence 2*, pages 137–152. Oliver and Boyd, Edinburgh, 1968.
- [McA83] T. McAvoy. *Interaction Analysis*. ISA, Research Triangle Park, NC, 2083.
- [McF53] M. W. McFarland, editor. *The Papers of Wilbur and Orville Wright*. McGraw-Hill, New York, 1953.
- [MCM⁺10] C. A. Monje, Y. Q. Chen, Vinagre. B. M., D. Xue, and V Feliu. *Fractional-order Systems and Controls: Fundamentals and Applications*. Springer, 2010.
- [MG90] D. C. McFarlane and K. Glover. *Robust Controller Design Using Normalized Coprime Factor Plant Descriptions*. Springer, New York, 1990.
- [MH98] J. E. Marsden and M. J. Hoffmann. *Basic Complex Analysis*. W. H. Freeman, New York, 1998.
- [Mil66] H. T. Milhorn. *The Application of Control Theory to Physiological Systems*. Saunders, Philadelphia, 1966.
- [Min02] D. A. Mindel. *Between Human and Machine: Feedback, Control, and Computing Before Cybernetics*. Johns Hopkins University Press, Baltimore, MD, 2002.
- [Min08] D. A. Mindel. *Digital Apollo: Human and Machine in Spaceflight*. The MIT Press, Cambridge, MA, 2008.
- [MLK06] A. Makroglou, J. Li, and Y. Kuang. Mathematical models and software tools for the glucose-insulin regulatory system and diabetes: An overview. *Applied Numerical Mathematics*, 56:559–573, 2006.
- [MLS94] R. M. Murray, Z. Li, and S. S. Sastry. *A Mathematical Introduction to Robotic Manipulation*. CRC Press, 1994.
- [MP69] M. Minsky and S. Papert. *Perceptrons: An Introduction to Computational Geometry*. MIT Press, Cambridge, Massachusetts, 1969.
- [MR94] J. E. Marsden and T. S. Ratiu. *Introduction to Mechanics and Symmetry*. Springer-Verlag, New York, 1994.
- [MRC07] C. Dalla Man, R. A. Rizza, and C. Cobelli. Meal simulation model of the glucose-insulin system. *IEEE Transactions on Biomedical Engineering*, 54:10:1740–1749, 2007.
- [MRRS00] D. Q. Mayne, J. B. Rawlings, C. V. Rao, and P. O. M. Scokaert. Constrained model predictive control: Stability and optimality. *Automatica*, 36(6):789–814, 2000.
- [MS15] J. R. Marden and J. S. Shamma. Game Theory and Distributed Control. In *Handbook of Game Theory with Economic Applications*, chapter 16, pages 861–899. Elsevier, 2015.
- [Mur03] R. M. Murray, editor. *Control in an Information Rich World: Report of the Panel on Future Directions in Control, Dynamics and Systems*. SIAM, Philadelphia, 2003.
- [Mur04] J. D. Murray. *Mathematical Biology, Vols. I and II*. Springer-Verlag, New York, 3rd edition, 2004.
- [Mur07] R. M. Murray. Recent research in cooperative control of multi-vehicle systems. *ASME Journal of Dynamic Systems, Measurement and Control*, 129(5):571–583, 2007.

- [MW80] Z. Manna and R. Waldinger. A deductive approach to program synthesis. *ACM Transactions on Programming Languages and Systems*, 2(1):90–121, 1980.
- [Nah88] P. J. Nahin. *Oliver Heaviside: Sage in Solitude: The Life, Work and Times of an Electrical Genius of the Victorian Age*. IEEE Press, New York, 1988.
- [NS99] H. Nijmeijer and J. M. Schumacher. Four decades of mathematical system theory. In J. W. Polderman and H. L. Trentelman, editors, *The Mathematics of Systems and Control: From Intelligent Control to Behavioral Systems*, pages 73–83. University of Groningen, 1999.
- [Nyq32] H. Nyquist. Regeneration theory. *Bell System Technical Journal*, 11:126–147, 1932.
- [Nyq56] H. Nyquist. The regeneration theory. In R. Oldenburger, editor, *Frequency Response*, page 3. MacMillan, New York, 1956.
- [O'D06] A. O'Dwyer. *Handbook of PI and PID Controller Tuning Rules*. Imperial College Press, 3rd edition, 2006.
- [Oga01] K. Ogata. *Modern Control Engineering*. Prentice Hall, Upper Saddle River, NJ, 4th edition, 2001.
- [Old56] R. Oldenburger, editor. *Frequency Response*. MacMillan, New York, 1956.
- [OSFM07] R. Olfati-Saber, J. A. Fax, and R. M. Murray. Consensus and cooperation in networked multi-agent systems. *Proceedings of the IEEE*, 95(1):215–233, 2007.
- [OWN96] A. V. Oppenheim, A. S. Willsky, and S. H. Nawab. *Signals and Systems*. Prentice-Hall, 2nd edition, 1996.
- [Pac13] D. Packard. *The HP Way: How Bill Hewlett and I Built Our Company*. Harper Collins, 2013.
- [Par93] L. E. Parker. Designing control laws for cooperative agent teams. In *Proc. IEEE International Conference on Robotics and Automation*, pages 582–587, 1993.
- [PB86] G. Pacini and R. N. Bergman. A computer program to calculate insulin sensitivity and pancreatic responsivity from the frequently sampled intravenous glucose tolerance test. *Computer Methods and Programs in Biomedicine*, 23:113–122, 1986.
- [PDS18] T. Van Pottelbergh, G. Deion, and R. Sepulchre. Robust modulation of integrate-and-fire models. *Neural Computing*, 30:987–1011, 2018.
- [Phi48] G. A. Philbrick. Designing industrial controllers by analog. *Electronics*, 21(6):108–111, 1948.
- [PN00] W. F. Powers and P. R. Nicastrì. Automotive vehicle control challenges in the 21st century. *Control Engineering Practice*, 8:605–618, 2000.
- [PPP02] S. Prajna, A. Papachristodoulou, and P. A. Parrilo. SOSTOOLS: Sum of squares optimization toolbox for MATLAB, 2002. Available from <http://www.cds.caltech.edu/sostools>.
- [Pto14] C. Ptolemaeus, editor. *System Design, Modeling, and Simulation using Ptolemy II*. Ptolemy.org, 2014.
- [QB97] S. J. Qin and T. A. Badgwell. An overview of industrial model predictive control technology. In J.C. Kantor, C.E. Garcia, and B. Carnahan, editors,

- Fifth International Conference on Chemical Process Control*, pages 232–256, 1997.
- [RÅ15] A. Rantzer and K. J. Åström. Control theory. In N. J. Higham, editor, *The Princeton Companion to Applied Mathematics*. Princeton University Press, Princeton and Oxford, 2015.
- [RHD⁺04] M. B. Reiser, J. S. Humbert, M. J. Dunlop, D. Del Vecchio, R. M. Murray, and M. H. Dickinson. Vision as a compensatory mechanism for disturbance rejection in upwind flight. In *Proc. American Control Conference*, volume 1, pages 311–316, 2004.
- [RHW86] D. E. Rumelhart, G. E. Hinton, and R. J. Williams. Learning representations by back-propagating error. *Nature*, 323(6088):533–536, 1986.
- [Rig63] D. S. Riggs. *The Mathematical Approach to Physiological Problems*. MIT Press, Cambridge, MA, 1963.
- [Ris60] J. Rissanen. Control system synthesis by analogue computer based on the generalized feedback concept. In Robert Vichnevetsky, editor, *Proceedings of the Symposium on Analogue Computation Applied to the Study of Chemical Processes*, pages 1–13, New York, NY, 1960. Gordon & Breach.
- [RM71] H. H. Rosenbrock and P. D. Moran. Good, bad or optimal? *IEEE Transactions on Automatic Control*, AC-16(6):552–554, 1971.
- [Ros62] F. Rosenblatt. *Principles of Neurodynamics*. Spartan Books, New York, 1962.
- [Rug91] W. J. Rugh. Analytic framework for gain scheduling. *Control Systems Magazine*, 11(1):79–84, 1991.
- [Rug95] W. J. Rugh. *Linear System Theory*. Prentice Hall, Englewood Cliffs, NJ, 2nd edition, 1995.
- [SA92] J. S. Shamma and M. Athans. Gain scheduling: potential hazards and possible remedies. *Control Systems Magazine*, 12(3):101–107, 1992.
- [SA14] T. Samad and A. M. Annaswamy, editors. *The Impact of Control Technology*. IEEE Control Systems Society, 2nd edition, 2014. Available at www.ieeecss.org.
- [SÅD⁺07] G. Schitter, K. J. Åström, B. DeMartini, P. J. Thurner, K. L. Turner, and P. K. Hansma. Design and modeling of a high-speed AFM-scanner. *IEEE Transactions on Control System Technology*, 15(5):906–915, 2007.
- [SÅH84] J. Sternby, K. J. Åström, and P. Hagander. Zeros of sampled systems. *Automatica*, 20, 1984.
- [Sar91] D. Sarid. *Atomic Force Microscopy*. Oxford University Press, Oxford, UK, 1991.
- [Sas99] S. Sastry. *Nonlinear Systems*. Springer, New York, 1999.
- [SC92] R. Shishko and R. G. Chamberlain. NASA systems engineering handbook. Technical report, National Aeronautics and Space Administration, 1992.
- [Sch87] M. Schwartz. *Telecommunication Networks*. Addison Wesley, Reading, MA, 1987.
- [Sch01] G. Schitter. High performance feedback for fast scanning atomic force microscopes. *Review of Scientific Instruments*, 72(8):3320–3327, 2001.
- [SEM04] D. E. Seborg, T. F. Edgar, and D. A. Mellichamp. *Process Dynamics and Control*. Wiley, Hoboken, NJ, 2nd edition, 2004.

- [Sen01] S. D. Senturia. *Microsystem Design*. Kluwer, Boston, MA, 2001.
- [SGA18] R. Sepulchre, Drion G., and Franci A. Excitable behaviors. In Tempo R. and Yurkovich S. and Misra P., editors, *Emerging Applications of Control and Systems Theory. Lecture Notes in Control and Information Sciences—Proceedings*, pages 269–280. Springer, 2018.
- [Sha01] L. Sha. Using simplicity to control complexity. *IEEE Software*, 18:20–28, 2001.
- [Shi96] F. G. Shinskey. *Process-Control Systems. Application, Design, and Tuning*. McGraw-Hill, New York, 4th edition, 1996.
- [SHM⁺16a] D. Silver, A. Huang, C. J. Maddison, A. Guez, L. Sifre, G. Van Den Driessche, J. Schrittwieser, I. Antonoglou, V. Panneershelvam, M. Lanctot, et al. Mastering the game of go with deep neural networks and tree search. *Nature*, 529(7587):484–489, 2016.
- [SHM⁺16b] D. Silver, A. Huang, C. J. Maddison, A. Guez, L. Sifre, G. Van Den Driessche, J. Schrittwieser, I. Antonoglou, V. Panneershelvam, M. Lanctot, and others. Mastering the game of go with deep neural networks and tree search. *Nature*, 529(7587):484–489, 2016.
- [Sim56] H. A. Simon. Dynamic programming under uncertainty with a quadratic criterion function. *Econometrica*, 24:74–81, 1956.
- [SLL16] L. Sun, D. Li, and K. Y. Lee. Optimal disturbance rejection for pi controller with constraints on relative delay margin. *ISA Transactions*, 63:103–111, 2016.
- [Smi52] J. M. Smith. The importance of the nervous system in the evolution of animal flight. *Evolution*, 6:127–129, 1952.
- [Smi57a] O. J. M. Smith. Closed control of loops with dead time. *Chemical Engineering Progress*, 53:217–219, 1957.
- [Smi57b] O. J. M. Smith. Posicast control of damped oscillatory systems. *Proc. IRE*, 45:1249–1255, 1957.
- [Son98] E. D. Sontag. *Mathematical Control Theory: Deterministic Finite Dimensional Systems*. Springer, New York, 2nd edition, 1998.
- [SP05] S. Skogestad and I. Postlethwaite. *Multivariable Feedback Control*. Wiley, Hoboken, NJ, 2nd edition, 2005.
- [SS02] E. B. Saf and A. D. Snider. *Fundamentals of Complex Analysis with Applications to Engineering, Science and Mathematics*. Prentice Hall, Englewood Cliffs, NJ, 2002.
- [SSS⁺04] J. Stelling, U. Sauer, Z. Szallasi, F. J. Doyle III, and J. Doyle. Robustness of cellular functions. *Cell*, 118(6):675–685, 2004.
- [Sta68] L. Stark. *Neurological Control Systems—Studies in Bioengineering*. Plenum Press, New York, 1968.
- [Ste80] G. Stein. Adaptive flight control: A pragmatic view. In K. S. Narendra and R. V. Monopoli, editors, *Applications of Adaptive Control*. Academic Press, 1980.
- [Ste02] J. Stewart. *Calculus: Early Transcendentals*. Brooks Cole, Pacific Grove, CA, 2002.

- [Ste03] G. Stein. Respect the unstable. *Control Systems Magazine*, 23(4):12–25, 2003.
- [Ste13] G. M. Steil. Algorithms for a closed-loop artificial pancreas: The case for proportional-integral-derivative control. *Journal Diabetes Science and Technology*, 7:6:1621–1631, 2013.
- [Str88] G. Strang. *Linear Algebra and Its Applications*. Harcourt Brace Jovanovich, San Diego, 3rd edition, 1988.
- [Str94] S. H. Strogatz. *Nonlinear Dynamics and Chaos, with Applications to Physics, Biology, Chemistry, and Engineering*. Addison-Wesley, Reading, MA, 1994.
- [SV89] M. W. Spong and M. Vidyasagar. *Robot Dynamics and Control*. John Wiley, 1989.
- [SZ14] K. Simonyan and A. Zisserman. Very deep convolutional networks for large-scale image recognition. *arXiv preprint arXiv:1409.1556*, 2014.
- [Tan96] A. S. Tannenbaum. *Computer Networks*. Prentice Hall, Upper Saddle River, NJ, 3rd edition, 1996.
- [Teo37] T. Teorell. Kinetics of distribution of substances administered to the body, I and II. *Archives Internationales de Pharmacodynamie et de Therapie*, 57:205–240, 1937.
- [TFKH16] H. Tullberg, M. Fallgren, K. Kusume, and Andreas Höglund. 5g use cases and system concept. In A. Osseiran, J. F. Monserrat, and P. Marsch, editors, *5G Mobile and Wireless Communications Technology*, chapter 2. Cambridge University Press, 2016.
- [Tha89] G. T. Thaler. *Automatic Control Systems*. West Publishing, St. Paul, MN, 1989.
- [THÅ00] Tore T. Hägglund and K. J. Åström. Supervision of adaptive control algorithms. *Automatica*, 36(8):1171—1180, 2000.
- [Til01] M. Tiller. *Introduction to Physical Modeling with Modelica*. Springer, Berlin, 2001.
- [Tru55] J. G. Truxal. *Automatic Feedback Control System Synthesis*. McGraw-Hill, New York, 1955.
- [TS90] D. Tipper and M. K. Sundareshan. Numerical methods for modeling computer networks under nonstationary conditions. *IEEE Journal of Selected Areas in Communications*, 8(9):1682–1695, 1990.
- [Tsi54] H. S. Tsien. *Engineering Cybernetics*. McGraw-Hill, New York, 1954.
- [Tus52] A. Tustin. Feedback. *Scientific American*, 48–54, 1952.
- [Vid84] M. Vidyasagar. The graph metric for unstable plants and robustness estimates for feedback stability. *ieeETAC*, 29:5:403–418, 1984.
- [Vid85] M. Vidyasagar. *Control Systems Synthesis*. MIT Press, Cambridge, MA, 1985.
- [Vin93] G. Vinnicombe. Frequency domain uncertainty and the graph topology. *IEEE Transactions on Automatic Control*, 38:1371–1383, 1993.
- [Vin01] G. Vinnicombe. *Uncertainty and Feedback: $\mathcal{H}_\infty$ Loop-Shaping and the ν -Gap Metric*. Imperial College Press, London, 2001.

- [Wad97] H.L. Wade. Inverted decoupling: a neglected technique. *ISA Transactions*, 36(1):3–10, 1997.
- [Whi99] F. J. W. Whipple. The stability of the motion of a bicycle. *Quarterly Journal of Pure and Applied Mathematics*, 30:312–348, 1899.
- [Wid41] D. V. Widder. *Laplace Transforms*. Princeton University Press, Princeton, NJ, 1941.
- [Wie48] N. Wiener. *Cybernetics: Or Control and Communication in the Animal and the Machine*. Wiley, 1948.
- [Wig90] S. Wiggins. *Introduction to Applied Nonlinear Dynamical Systems and Chaos*. Springer-Verlag, Berlin, 1990.
- [Wil99] H. R. Wilson. *Spikes, Decisions, and Actions: The Dynamical Foundations of Neuroscience*. Oxford University Press, Oxford, UK, 1999.
- [Wil04] D. G. Wilson. *Bicycling Science*. MIT Press, Cambridge, MA, 3rd edition, 2004. With contributions by Jim Papadopoulos.
- [Wis07] K. A. Wise. Guidance and control for military systems: Future challenges. In *AIAA Conference on Guidance, Navigation, and Control*, 2007. AIAA Paper 2007-6867.
- [WS85] B. Widrow and S. D. Stearns. *Adaptive Signal Processing*. Prentice-Hall, Englewood Cliffs, NJ, 1985.
- [WT24] E. P. M. Widmark and J. Tandberg. Über die Bedingungen für die Akkumulation indifferenten Narkotika. *Biochemische Zeitung*, 148:358–389, 1924.
- [WW97] F. R. Whitt and D. G. Wilson. *Bicycling Science*. MIT Press, 1997.
- [YH91] S. Yamamoto and I. Hashimoto. Present status and future needs: The view from Japanese industry. In Y. Arkun and W. H. Ray, editors, *Chemical Process Control—CPC IV*, 1991.
- [YHSD00a] T. M. Yi, Y. Huang, M. I. Simon, and J. Doyle. Robust perfect adaptation in bacterial chemotaxis through integral feedback control. *Proceedings of the National Academy of Sciences*, 97(9):4649–4653, 2000.
- [YHSD00b] T. M. Yi, Y. Huang, M. I. Simon, and J. C. Doyle. Robust perfect adaptation in bacterial chemotaxis through integral feedback control. *Proceedings of the National Academy of Sciences*, 97(9):4649–4653, 2000.
- [YJJBL74] D. C. Youla, Jr. J. J. Bongiorno, and C. N. Lu. Single-loop feedback stabilization of linear multivariable plants. *Automatica*, 10(2):159–173, 1974.
- [Zam81] G. Zames. Feedback and optimal sensitivity: Model reference transformations, multiplicative seminorms, and approximative inverse. *IEEE Transactions on Automatic Control*, AC-26(2):301–320, 1981.
- [ZD63] L. A. Zadeh and C. A. Desoer. *Linear System Theory: the State Space Approach*. McGraw-Hill, New York, 1963.
- [ZDG96] J. C. Zhou, J. C. Doyle, and K. Glover. *Robust and Optimal Control*. Prentice Hall, Englewood Cliffs, NJ, 1996.
- [ZES80] G. Zames and A. K. El-Sakkary. Unstable systems and feedback: The gap metric. In *Proc. Allerton Conference*, pages 380–385, 1980.
- [ZN42] J. G. Ziegler and N. B. Nichols. Optimum settings for automatic controllers. *Transactions of the ASME*, 64:759–768, 1942.

- [ZT11] L. Zaccariand and A. R. Teel. *Modern Anti-windup Synthesis: Control Augmentation for Actuator Saturation*. Princeton University Press, 2011.

Index

- acausal modeling, 3-7
- access control, *see* admission control
- acknowledgment (ack) packet, 4-13–4-15
- activator, 1-12, 3-40, *see also* biological circuits
- active filter, 6-24, *see also* operational amplifier
- actuators, 1-5, 1-6, 3-5, 3-30, 4-1, 4-17, 8-30, 10-20, 11-21, 12-10, 14-4, 14-7, 14-13, 14-15
 - effect on zeros, 10-20, 14-4
 - in computing systems, 4-11
 - saturation, 3-8, 8-32, 11-9, 11-15–11-17, 11-22, 12-10, 14-26
- A/D converters, *see* analog-to-digital converters
- adaptation, 11-6, 15-28
- adaptive control, 13-28
- additive uncertainty, 13-3, 13-10, 13-12, 13-13
- adjacency matrix, 3-38
- admission control, 3-35, 3-46, 4-13, 4-15, 10-8
- aerospace systems, 1-7–1-8, 1-15, 14-7, *see also* vectored thrust aircraft; X-29 aircraft
- AFM, *see* atomic force microscopes
- agile development, 15-3
- air-fuel ratio control, 1-22
- aircraft, *see* flight control
- alcohol, metabolism of, 4-29
- algebraic loops, 3-25–3-26, 8-12, 9-22–9-23
- aliasing, 8-31
- all-pass transfer function, 14-10
- alternating current [AC], 6-25
- amplifier, *see* operational amplifier
- amplitude ratio, *see* gain
- analog computing, 3-9, 3-26, 4-7, 9-22, 11-21
- analog implementation, controllers, 4-10, 9-41, 11-21
- analog-to-digital converters, 1-5, 1-6, 4-18, 8-30, 8-31, 11-21
- angle, of frequency response, *see* phase
- anticipation, in controllers, 1-19, 11-5, *see also* derivative action
- antiresonance, 6-26
- anti-windup compensation, 1-19, 11-15–11-18, 11-22, 11-23, 11-25
 - stability analysis, 11-25
- Apache web server, 4-11, *see also* web server control
- Arbib, M. A., 7-1
- architecture, 15-37
- argument, of a complex number, 9-29
- arrival rate (queuing systems), 3-35
- artificial neural network (ANN), 15-32
- artificial pancreas, 4-25
- assume-guarantee, 15-13
- asymptotes, in Bode plot, 9-31, 9-32
- asymptotic stability, 3-21, 5-8, 5-10, 5-12, 5-13, 5-18, 5-19, 5-22, 5-26, 5-27, 5-29, 6-10
 - discrete-time systems, 6-37
- atmospheric dynamics, *see* environmental science
- atomic force microscopes, 1-3, 3-29, 4-17–4-20
 - contact mode, 4-17, 6-25, 7-35
 - horizontal positioning, 10-17, 13-19
 - system identification, 9-37
 - tapping mode, 4-17, 10-28, 11-8, 11-13, 12-15
 - with preloading, 4-29
- attractor (equilibrium point), 5-10
- automatic reset, in PID control, 11-4
- automatic tuning, 11-15, 13-28
- automation, 3-5
- automotive control systems, 1-17, 3-29, 4-4, *see also* cruise control; vehicle steering
- autonomous differential equation, 3-3, *see also* time-invariant systems
- autonomous vehicles, 15-8
- autopilot, 1-15, 1-16
- AUTOSAR, 15-37
- average residence time, 11-7, 11-24

- balance systems, 3-11–3-13, 3-28, 7-4, 7-23, 9-24, 14-14, *see also* cart-pendulum system; inverted pendulum
- band-pass filter, 6-24, 6-25, 9-35
- bandwidth, 2-18, 6-25, 7-21, 12-6, 12-7, 12-31, 14-13
- behavioral modeling, 3-7
- Bell Labs, 1-14, 10-27, 12-30
- Bennett, S., 1-27, 10-27, 11-23
- bicycle dynamics, 4-5–4-7, 4-27, 5-31, 8-33, 14-18
 - Whipple model, 4-7, 7-35
- bicycle model, for vehicle steering, 3-29–3-31
- bifurcations, 5-30–5-32, 5-39, *see also* root locus plots
- biological circuits, 1-12, 3-23, 3-39–3-40, 5-38, 6-37, 9-36
 - genetic switch, 3-46, 5-23
 - repressilator, 3-40
- biological systems, 1-1–1-3, 1-8, 1-12, 1-27, 3-39–3-43, 5-34, 11-2, 11-6, *see also* biological circuits; drug administration; neural systems; population dynamics
- bistability, 5-26
- Black, H. S., 1-7, 1-14, 4-7, 4-9, 6-1, 10-1, 10-27, 13-1
- block diagonal systems, 5-12, 5-38, 6-9, 6-15, 6-19, 8-13
- block diagram algebra, 2-11, 9-17, 9-19, 13-12
- block diagrams, 1-1, 2-10, 3-23–3-25, 9-8, 9-17–9-23
 - control system, 1-5, 9-1, 9-18
 - Kalman decomposition, 8-16
 - observable canonical form, 8-5
 - observer, 8-2, 8-10
 - observer-based control system, 8-14
 - PID controllers, 11-2, 11-4, 11-22
 - reachable canonical form, 7-7
 - two degree-of-freedom control, 8-23
 - two degree-of-freedom controller, 12-2, 13-16
 - Youla parameterization, 13-15
- Bode, H., 9-1, 10-27, 13-28
- Bode plots, 9-28–9-37, 10-18
 - asymptotic approximation, 9-31, 9-32, 9-44
 - low-, band-, high-pass filters, 9-35
 - of rational function, 9-29
 - sketching, 9-32
- Bode's ideal loop transfer function, 13-13, 13-30
- Bode's integral formula, 14-5–14-10, 14-30, 14-31
- Bode's phase area formula, 12-15
- Bode's relations, 10-18, 10-19, 12-13
- Bode, H., 1-7
- BOXES, 15-31
- Brahe, T., 3-2
- breakpoint, 9-31, 10-7
- Bristol's RGA, 15-24
- Brockett, R. W., ix, 6-35
- Bryson, A. E., 7-36
- bump test, 11-11, 11-12
- bumpless transfer, 13-28
- Bush, V., 11-23
- calibration, versus feedback, 1-8, 7-14, 7-25, 7-26
- cancellation, *see* pole/zero cancellations
- Cannon, R. H., 3-43, 6-1
- capacitor, transfer function for, 9-9
- car, *see* automotive control systems; cruise control; vehicle steering
- carrying capacity, in population models, 4-26
- cart-pendulum system, 3-12, 7-5, 7-6, 14-28, 15-31, *see also* balance systems
- cascade control, 15-16–15-17
- causal reasoning, 1-1, 4-7
- Cayley-Hamilton theorem, 7-4, 7-27, 7-35, 8-3
- center (equilibrium point), 5-10
- centrifugal governor, 1-2, 1-13
- certainty equivalence principle, 15-29
- chain of integrators (normal form), 3-43, 7-7
- characteristic polynomial, 2-6, 2-9, 5-11, 7-35, 9-8, 9-24
 - for closed loop transfer function, 10-2
 - observable canonical form, 8-5
 - output feedback controller, 8-13
 - reachable canonical form, 7-7, 7-9, 7-13, 7-34
- chemical systems, 1-8, 11-1, *see also* process control; compartment models
- circle criterion, 10-24, 11-17, 11-18, 13-13
- circuits, *see* biological circuits; electrical circuits
- class of signals $\mathcal{E}$, *see* exponential signals
- classical control, viii, 13-28
- closed loop, 1-1, 1-2, 1-5, 6-33, 7-10, 7-17, 10-1, 10-2, 10-23, 12-1
 - versus open loop, 1-2, 10-4, 12-1

- co-design, 15-1
- command signals, 1-3, 1-6, 8-24, 11-2, *see also* reference signal; setpoint
- compartment models, 4-20–4-25, 5-13, 6-21, 7-20, 8-3, 8-8, 8-34
- compensator, *see* control law
- complementary filtering, 15-22
- complementary sensitivity function, 12-3, 13-11, 13-14, 13-17, 13-22, 13-29, 14-6, 14-25
- complexity, of control systems, 1-8, 1-17, 11-7
- computed torque, 6-34
- computer implementation, controllers, 8-30–8-32, 11-21–11-23
- computer science, relationship to control, 1-6
- computer systems, control of, 1-10, 1-27, 3-15, 3-36, 3-37, 4-11–4-17, 6-28, *see also* queuing systems
- conditional stability, 10-13
- configuration variables, 3-12
- congestion control, 1-10, 4-13–4-17, 5-10, 10-8, 10-29, *see also* queuing systems router dynamics, 4-28
- consensus, 3-37
- control
 - definition of, 1-5–1-6
 - early examples, 1-2, 1-6–1-8, 1-14, 1-17, 1-27, 11-4
 - fundamental limits, 13-27–13-28, 14-1–14-30
 - history of, 1-27, 11-23
 - modeling for, 1-6, 3-5–3-6, 3-43, 13-1
 - successes of, 1-8, 1-27
 - system, 1-5, 7-9, 8-14, 8-23, 8-30, 9-1, 12-2, 12-5, 13-16
 - using estimated state, 8-11–8-14, 13-23
- control error, 1-18, 9-18, 11-2
- control law, 1-6, 1-18, 1-19, 6-33, 7-10, 7-13, 9-18
- control Lyapunov function, 5-33
- control matrix, 3-10, 3-14
- control protocol, 15-11
- control signal, 3-5, 6-27, 11-2
- controllability, 7-33, *see also* reachability
- controlled differential equation, 3-3, 3-10, 9-8
- controller architecture, 8-23–8-24
- convolution, 15-33
- convolution equation, 6-15–6-17, 6-19, 6-20, 7-4, 9-16
 - discrete-time, 6-37
- convolutional neural network (CNN), 15-33
- coordinate transformations, 5-12, 6-17–6-19, 7-7, 8-32, 9-12
 - to Jordan form, 6-9
 - to observable canonical form, 8-6
 - to reachable canonical form, 7-8, 7-9
- Coriolis forces, 3-12, 6-34
- corner frequency, 9-31
- correct-by-construction, 15-15
- cost function, 7-28
- coupled spring-mass system, 6-12, 6-14, 6-18
- covariance matrix, 8-17, 8-18
- critical gain, 11-11, 11-12, 11-14
- critical period, 11-12, 11-14
- critical point, 10-2, 10-6, 10-7, 10-15, 10-16, 10-26, 10-27, 11-12, 13-9, 13-10
- critically damped oscillator, 7-18
- crossover frequency, *see* gain crossover frequency; phase crossover frequency
- crossover frequency inequality, *see* gain crossover frequency inequality
- cruise control, 1-14, 1-21, 4-1–4-5
 - control design, 7-25, 11-9, 11-20
 - electric car, 15-25
 - feedback linearization, 6-33
 - integrator windup, 11-15, 11-17
 - linearization, 6-29, 6-31
 - pole/zero cancellation, 9-27
 - robustness, 1-14, 13-1, 13-2, 13-11
- Curtiss seaplane, 1-15, 1-16
- cybernetics, 1-9, *see also* robotics
- cyberphysical system, 3-7, *see also* hybrid system
- D contour, *see* Nyquist contour
- D/A converters, *see* digital-to-analog converters
- damped frequency, 2-15, 7-18
- damper
 - tuned mass, 9-9
 - vibration, 9-9
- damping, 3-2, 3-12, 3-19, 5-2
- damping ratio, 2-15, 7-18, 7-19, 7-22, 11-9
- DARPA Grand Challenge, 1-26, 15-9
- DC gain, 6-25, *see also* zero frequency gain
- dead zone, 1-18
- deep learning, 15-33
- delay, *see* time delay

- delay compensation, 13-30
- delay dominated:derivative action, 11-14
- delay margin, 10-17
- delta function, *see* impulse function
- derivative action, 1-19, 1-20, 11-2, 11-4–11-6, 11-21
 - filtering, 11-5, 11-19, 11-22, 11-23, 12-10
 - setpoint weighting, 11-20, 11-23
 - time constant, 11-2
- derivative gain, 11-2
- derivative time constant, 11-5
- describing functions, 10-25–10-27, 10-30, 14-27, 14-29
- design of dynamics, 1-15, 5-16, 5-32–5-34, 6-1, 7-1, 7-11, 7-17
- diabetes, *see* insulin-glucose dynamics
- diagonal systems, 5-12, 6-9
 - Kalman decomposition for, 8-15
 - transforming to, 5-12, 5-38, 6-8
- dialonal systems, *see also* block diagonal systems
- difference equations, 3-9, 3-14–3-16, 3-20, 3-44, 6-27, 8-31, 11-22
- differential algebraic equations, 3-7, *see also* algebraic loops
- differential equations, 2-5, 3-2, 3-9–3-14, 5-1–5-4
 - controlled, 3-3, 6-3, 9-8
 - equilibrium points, 5-6–5-7
 - existence and uniqueness of solutions, 5-2–5-4
 - first-order, 3-5, 11-7
 - periodic solutions, 5-7, 5-17
 - qualitative analysis, 5-4–5-7
 - second-order, 5-5, 7-17, 11-7
 - solution, 2-8, 6-15
 - solutions, 5-1, 5-2, 6-3, 6-7, 6-15, 9-44
 - stability, *see* stability
 - transfer functions for, 9-11
- differential flatness, 8-26, 15-10
- digital control systems, *see* computer implementation, controllers
- digital-to-analog converters, 1-5, 1-6, 4-18, 8-30, 8-31, 11-21
- dimension-free variables, 3-28, 3-43
- direct connection, 3-25
- direct term, 3-10, 3-14, 3-26, 6-17, 8-12, 9-22
- discrete control, 3-36
- discrete transition system, 15-11
- discrete-time systems, 3-14, 3-44, 5-37, 6-27, 6-36, 11-22
 - Kalman filter for, 8-17
 - linear quadratic control for, 7-30
- disturbance attenuation, 1-5, 2-4–2-5, 2-12–2-16, 7-10, 12-9–12-10, 13-16–13-17
 - design of controllers for, 12-13, 12-19, 12-32, 13-23, 14-6
 - in biological systems, 9-37, 11-6
 - integral gain as a measure of, 11-5, 13-16
 - relationship to sensitivity function, 12-9, 12-31, 13-16, 14-6
- disturbance modeling, 8-19, 8-27
- disturbance weighting, 13-26
- disturbances, 1-6, 3-3, 3-6, 9-18, 9-27, 12-1, 12-5
 - generalized, 13-24
 - random, 8-17
- Dodson, B., 1-1
- dominant eigenvalues (poles), 7-21, 11-9, 11-10
- double integrator, 6-7, 7-2, 9-11, 9-36
- Doyle, J. C., ix, 12-30, 13-28
- drag, 4-3
- drug administration, 4-20–4-25, 4-29, 6-21, 7-20, *see also* compartment models
- drum boiler, 3-33
- dual control, 15-31
- duality, 8-7, 8-11
- Dubins car model, 3-31, 3-45
- dynamic compensator, 7-25, 8-13
- dynamic inversion, 6-34
- dynamic voltage frequency scaling, 11-24
- dynamical systems, 1-1, 3-1, 5-1, 5-4, 5-34
 - linear, 5-11, 6-1
 - observer as a, 8-1
 - state of, 7-9
 - stochastic, 8-17
 - uncertainty in, 13-1–13-3
 - see also* differential equations
- dynamics matrix, 3-10, 3-14, 5-11, 6-12
- Dyson, F., 3-1
- $\mathcal{E}$, *see* exponential signals
- e-commerce, 1-10
- e-mail server, control of, 3-15, 6-28
- economic systems, 1-4, 1-10–1-11, 3-44
- ecosystems, 1-12–1-13, 4-25, 7-15, *see also* predator-prey system
- eigenvalue assignment, 7-11, 7-13–7-17, 7-23, 8-33, 11-9, 11-24
 - by output feedback, 8-13

- for observer design, 8-7
- eigenvalues, 5-11, 5-22, 5-31, 6-12, 9-5
 - and Jordan form, 6-9-6-11, 6-36
 - distinct, 6-8, 6-14, 8-15
 - dominant, 7-21
 - effect on dynamic behavior, 7-17-7-21, 9-4, 9-5
 - for discrete-time systems, 6-37
 - invariance under coordinate transformation, 5-12
 - relationship to modes, 6-12-6-15
 - relationship to poles, 9-24
 - relationship to stability, 5-26, 6-10, 6-11
- eigenvectors, 5-13, 6-12, 6-13
 - relationship to mode shape, 6-13
- electric car, 15-25
- electric power, *see* power systems (electric)
- electrical circuits, 3-7, 3-23, 4-10, 6-1, 9-9, *see also* operational amplifier
- electrical engineering, 1-6-1-7, 3-3-3-5, 6-25, 10-13
- elephant, modeling of an, 3-1
- Elowitz, M. B., 3-40
- encirclement, 10-6, *see also* Nyquist criterion
- environmental science, 1-3, 1-8
- equation-based modeling, 3-7
- equilibrium points, 3-39, 4-26, 5-6, 5-12, 6-2, 6-30, 7-2
 - bifurcations of, 5-30
 - discrete time, 3-39, 3-44
 - for closed loop system, 7-11, 7-25
 - for planar systems, 5-10
 - region of attraction, 5-28-5-30
 - stability, 5-8
- equipment protection, 15-18
- error coefficients, 12-7
- error feedback, 2-18, 11-2, 11-19, 11-20, 12-4
- estimators, *see* observers
- Euler integration, 3-20
- exponential functions
 - simplified notation, 9-5
- exponential growth, in population models, 2-23, 4-25
- exponential input, 2-7
- exponential signals, 9-2-9-12, 9-23, 9-28
- extended Kalman filter, 8-30
- extremum seeking, 15-22
- Falb, P. L., 7-1
- feedback, 1-1-1-3, 2-1
 - as technology enabler, 1-3
 - drawbacks of, 1-3, 1-17, 11-19, 13-9, 13-17
 - generation of discrete behavior, 2-27
 - in biological systems, 1-1-1-3, 1-12, 1-27, 11-6, *see also* biological circuits
 - in engineered systems, *see* control
 - in financial systems, 1-3
 - in nature, 1-3, 1-11-1-13, 4-25
 - positive, *see* positive feedback
 - properties, 1-3, 1-6, 1-13-1-17, 13-1
 - robustness through, 1-13
 - versus feedforward, 1-4, 11-4, 12-19
- feedback amplifier, 1-7
- feedback connection, 2-10, 2-11, 9-17, 10-23, 10-25
- feedback controller, 9-18, 12-1
- feedback linearization, 6-33-6-34
- feedback loop, 1-5, 10-1
- feedback uncertainty, 13-3, 13-13
- feedforward, 1-3-1-4, 3-6, 8-24, 8-28, 9-18, 11-17, 12-1, 12-18
 - design, 12-18
 - sensitivity to process variations, 13-29
- Fermi, E., 3-1
- filters
 - active, 6-24
 - complementary filtering, 15-22
 - for measurement signals, 1-17, 8-31, 13-17
 - see also* band-pass filters; high-pass filters; low-pass filters
- final value theorem, 9-16
- financial systems, *see* economic systems
- finite escape time, 5-3
- finite state machine, 1-21, 3-7, 3-17-3-19, 4-5, 4-12
- first-order and time-delay (FOTD) model, 11-12
- first-order systems, 6-3, 6-36, 8-35, 9-11, 9-30, 9-31
- fisheries management, 4-30
- FitzHugh-Nagumo equations, 3-42, 3-43, 3-47, *see also* Hodgkin-Huxley equations
- flatness, *see* differential flatness
- flight control, 1-8, 1-15, 3-31, 6-34
 - X-29 aircraft, 14-7
 - see also* vectored thrust aircraft
- flow, of a vector field, 3-3, 5-5
- flow in a tank, 5-35
- flow model (queuing systems), 3-35,

- 10-29
- flyball governor, *see* centrifugal governor
- flying home mode, 15-16
- force feedback, 1-8
- forced response, 6-3, 9-3
- Forrester, J. W., 1-11
- FOTD model, 11-12
- Fourier, J. B. J., 3-43, 9-40
- fractional transfer functions, 13-28
- frequency domain, 9-1-9-3, 10-1, 10-21, 12-1
- frequency response, 2-8, 2-9, 3-4, 3-21, 3-22, 6-21-6-27, 9-2, 10-27
 - relationship to Bode plot, 9-29
 - relationship to Nyquist plot, 10-4, 10-6
 - second-order systems, 7-20, 9-35
 - system identification using, 9-37
- frequency response analyzer, 9-40
- friction, 3-11, 3-13, 3-19, 4-3, 6-29, 14-28-14-30
- fully actuated systems, 9-24
- fundamental limits, *see* control: fundamental limits
- Furuta pendulum, 5-39
- gain, 1-19, 2-2, 2-8, 3-22, 4-9, 6-23, 7-20, 9-3, 9-6, 9-23, 9-29, 10-14, 10-21-10-23, 10-25, 13-1
 - feedback, 7-25
 - generalized, 10-21
 - H_∞ , 10-23
 - observer, *see* observer gain
 - state feedback, 7-10, 7-11, 7-15, 7-25, 7-33
 - zero frequency, *see* zero frequency gain
 - see also* integral gain
- gain crossover frequency, 10-15, 10-16, 12-6, 12-13, 12-33, 14-11, 14-25
- gain crossover frequency inequality, 14-11, 14-13
- gain curve (Bode plot), 9-29-9-32, 10-18, 12-13
- gain margin, 10-14-10-17
 - from Bode plot, 10-15
 - reasonable values, 10-17
- gain scheduling, 8-27, 8-28, 13-27
- gain-bandwidth product, 4-10, 9-7, 13-18
- Gang of Four, 12-3, 12-30, 13-15
- Gang of Six, 12-3
- gene regulation, 1-12, 3-39, 3-40, 6-37, 9-36
- generalized impedance, 9-9
- generalized stability margin, 13-25
- genetic switch, 5-23, 5-24
- global behavior, 5-10, 5-29-5-32
- Glover, K., 12-30, 13-28
- glucose regulation, *see* insulin-glucose dynamics
- Golomb, S., 4-1
- governor, *see* centrifugal governor
- H_∞ control, 13-24-13-28, 13-31
 - disturbance weighting, 13-31
- Harrier AV-8B aircraft, 3-31
- heat propagation, 9-11, 10-28
- Heaviside, O., 6-35
- Heaviside step function, 6-20, 6-35
- Hellerstein, J. L., 1-27, 4-17
- Hewlett's oscillator, 2-24
- Hewlett-Packard, 2-24
- hidden technology, 15-36
- high-frequency roll-off, 11-19, 12-10, 12-13, 13-17, 13-20, 14-28
- high-pass filter, 9-35
- Hill chart, 13-22
- Hill function, 3-39
- Hoagland, M. B., 1-1
- Hodgkin-Huxley equations, 3-40-3-43, 3-47, *see also* FitzHugh-Nagumo equations
- homeostasis, 1-3, 3-39
- homogeneous equation, 2-6, 9-23
- homogeneous system, 6-3, 6-6, 6-7
- Horowitz, I. M., 8-32, 12-30, 13-22, 13-28, 14-30
- human-machine interface, 1-20, 4-1, 4-4
- hybrid system, 1-27, 3-7, 3-8, 3-19, 3-43, 15-11
- hydroelectric power generation, 14-12
- hyper state, 15-31
- hysteresis, 1-18, 2-26, 2-27, 10-26
- I-PD controller, 11-20
- identification, *see* system identification
- impedance, 9-8, 9-9, 11-21
- implementation, controllers, *see* analog implementation; computer implementation
- impulse function, 6-16, 6-35, 7-4
- impulse response, 6-5, 6-16, 6-17, 9-15, 9-16
- inductor, transfer function for, 9-9
- inertia matrix, 3-12, 6-34
- inferential control, *see* internal model control
- infinity norm, 10-23, 13-25

- information systems, 1-10, 3-34–3-39, *see also* congestion control; web server control
- initial condition, 5-2, 5-5, 5-8, 6-2, 6-7, 6-14, 8-17
- initial condition response, 6-3, 6-4, 6-6–6-9, 6-12, 6-14, 6-17, 9-3
- initial value problem, 5-2
- initial value theorem, 9-16
- inner loop control, 12-27, 12-29
- input sensitivity function, *see* load sensitivity function
- input/output models, 1-6, 2-5, 3-3, 3-5, 6-2, 6-15–6-28, 9-2, 10-22, *see also* frequency response; steady-state response; step response
 - and transfer functions, 9-16
 - and uncertainty, 3-9
 - from experiments, 9-37
 - relationship to state space models, 3-6, 5-1, 6-16
 - steady-state response, 6-19
 - transfer function for, 9-8
- input/output stability, 10-23
- inputs, 3-3, 3-6
- insect flight control, 3-24–3-25
- instrumentation, 1-8–1-9, 4-7
- insulin-glucose dynamics, 1-2, 4-23–4-25, 4-30
 - minimal model, 4-24
- integral action, 1-19, 1-20, 1-28, 2-17, 2-25, 7-25–7-28, 7-33, 8-27, 11-2, 11-4–11-5, 11-7
 - by positive feedback, 2-25
 - for bias compensation, 8-33
 - setpoint weighting, 11-20, 11-23
 - time constant, 11-2
- integral gain, 1-19, 11-2, 11-5, 11-7
- integrated error, 11-5
- integrator, 3-24, 7-25, 7-26, 8-5, 9-11, 9-30, 10-18, *see also* double integrator
- integrator windup, 1-19, 8-32, 11-15, 11-17, 11-25
 - conditional integration, 11-25
- intelligent machines, *see* robotics
- interaction, 15-23
- internal model control, 15-19
- internal model principle, 8-13, 8-30, 15-40
- internal stability, 12-5
- Internet, 1-10, 4-11, 4-13, 4-17, *see also* congestion control
- Internet of Things (IoT), 15-39
- Internet Protocol (IP), 4-13
- invariant set, 5-27, 5-30
- inverse model, 6-33, 6-34, 12-19, 12-20
 - approximate, 12-22
- inverse response, 3-34, 10-20, 10-30, 12-21
- inverted pendulum, 3-13–3-14, 4-5, 5-6, 5-14, 5-27, 5-29, 5-37, 5-39, 10-12, 14-7, *see also* balance systems
- Jacobian linearization, 6-29–6-33
- Janert, P. K., 1-27
- Jordan block, 6-9
- Jordan form, 6-9–6-12, 6-36, 7-22
- Kalman, R. E., 7-1, 7-33, 8-1, 8-16, 8-32
- Kalman decomposition, 8-15–8-17, 9-40, 9-41
- Kalman filter, 8-11, 8-17–8-22, 8-32, 13-23
 - extended, 8-30
- Kalman's inequality, 10-29
- Kalman-Bucy filter, 8-20
- Kelly, F. P., 4-17
- Kepler, J., 3-2
- Keynesian economic model, 3-44, 6-37
- Krasovski-Lasalle principle, 5-27
- LabVIEW, 5-31, 6-35
- ladder diagrams, LD, 15-37
- lag, *see* phase lag
- lag compensation, 12-14, 12-15
- lag-dominated dynamics, 11-12, 11-14
- Laplace transforms, ix, 9-14–9-16
- Laplacian matrix, 3-39
- Lasalle's invariance principle, *see* Krasovski-Lasalle principle
- lead, *see* phase lead
- lead compensation, 12-14, 12-15, 12-18, 12-27, 12-33
- lead-lag compensation, 12-32
- learning, 15-28
- limit cycle, 4-27, 5-7, 5-17–5-18, 5-31, 10-25
- linear quadratic control, 7-28–7-32, 8-19, 8-32, 13-23–13-24
 - proof of optimality, 7-37
- linear range, 1-19, 2-2–2-4
- linear systems, 2-6, 3-4, 3-10, 4-10, 5-11, 6-1–6-35, 8-15, 9-3, 9-8, 9-40, 10-22
- linear temporal logic, 15-12
- linear time-invariant systems, 2-6, 3-4, 3-10, 6-4
- linearity, 6-2, 9-29
- linearization, 5-15, 5-26, 6-2, 6-28–6-34,

- 8-28, 13-1
- Lipschitz continuity, 5-4
- load disturbances, 2-1, 2-4, 12-1, 13-16,
 - see also* disturbances, disturbance attenuation
- load sensitivity function, 12-3
- local behavior, 5-10, 5-16, 5-26, 5-29, 6-30
- locally asymptotically stable, 5-10
- logic and sequencing, 15-37
- logistic growth model, 4-25, 4-26, 4-30
- loop analysis, 10-1, 12-1
- loop shaping, 10-4, 12-12–12-18, 12-30, 13-22
 - design rules, 12-14
 - see also* Bode's loop transfer function
- loop transfer function, 10-1–10-4, 10-15, 10-23, 12-1, 12-5, 12-12, 12-13, 12-30, 14-6, *see also* Bode's loop transfer function
- Lotka-Volterra equations, 4-30
- Lotus Notes server, *see* e-mail server
- low pass filter, 12-10
- low-order models, 11-7
- low-pass filter, 9-35, 11-19
- LQ control, *see* linear quadratic control
- LTI systems, *see* linear time-invariant systems
- Lyapunov equation, 5-22, 5-36
- Lyapunov functions, 5-19, 5-21–5-23, 5-29, 6-36
 - design of controllers using, 5-27, 5-32
 - existence of, 5-21
- Lyapunov stability analysis, 3-21, 5-18–5-29, 5-34
 - discrete time, 5-37
- magnitude, of frequency response, *see* gain
- manifold, 5-28
- manual control, 11-17
- margins, *see* stability margins
- materials science, 1-8
- Mathematica, 3-20, 5-31, 6-35
- MATLAB, 2-11, 3-20, 5-31, 6-35, 6-37, 13-23, 13-25, 15-24
 - acker, 7-15, 8-11
 - dlqe, 8-19
 - dlqr, 7-32
 - feedback, 2-11
 - gapmetric, 13-7
 - jordan, 6-9
 - kalman, 8-20
 - linmod, 6-31
 - lqr, 7-29
 - parallel, 2-11
 - place, 7-15, 7-23, 8-11
 - series, 2-11
 - step, 2-12
 - trim, 6-31
- matrix exponential, 6-6–6-15, 6-34, 6-35
 - coordinate transformations, 6-18
 - Jordan form, 6-10
 - second-order systems, 6-35
- maximum complementary sensitivity, 13-11, 14-25
- maximum complementary sensitivity M_t , 12-7
- maximum modulus principle, 14-15
- maximum selector, 1-22, 15-18
- maximum sensitivity, 12-6, 12-10, 13-9, 14-25
- measured signals, 3-5, 3-6, 3-10, 5-1, 8-1, 8-14, 8-31, 12-2, 12-5, 13-24
- measurement noise, 1-6, 1-17, 8-1, 8-3, 8-17, 8-19, 9-18, 11-19, 12-1, 12-2, 12-13, 13-17, 14-27–14-28
 - response to, 12-10–12-11, 13-17
- mechanical systems, 3-5, 3-12, 3-21, 3-29, 3-43, 6-34
- mechanics, 3-2–3-3, 3-5, 5-34, 6-1
- median selectors, 15-19
- mid-range control, 15-17
- minimal model (insulin-glucose), 4-24, *see also* insulin-glucose dynamics
- minimum phase, 10-19, 10-27, 14-10
- minimum selector, 1-22, 15-18
- mixed integer solvers, 15-13
- mixed logical dynamical, 15-12
- modal form, *see* diagonal systems
- model checking, 15-14
- model predictive control, 4-25
- model reference, 12-2
- Modelica, 3-7, 3-26, 6-34, 9-23
- modeling, 1-6, 3-1–3-9, 3-43, 4-1
 - control perspective, 3-5
 - discrete control, 3-36
 - discrete-time, 3-14, 6-27–6-28
 - frequency domain, 9-1–9-3
 - from experiments, 3-26–3-28
 - model reduction, 1-6
 - normalization and scaling, 3-28
 - of uncertainty, 3-8–3-9
 - simplified models, use of, 3-6, 11-7, 13-2, 13-11, 13-12
 - software for, 3-7, 6-31, 6-34

- state space, 3-9–3-22
- uncertainty, *see* uncertainty
- modes, 6-12–6-14, 9-23
 - relationship to poles, 9-24
- motion control systems, 3-29–3-32, 8-32
- motors, electric, 3-46, 7-35, 8-34, 10-2, 14-26
- multi-input, multi-output systems, 5-1, 10-23, 12-6, 12-14, *see also* input/output models
- multiplicative uncertainty, 13-3, 13-12, 13-13
- nanopositioner (AFM), 10-17, 13-19
- natural frequency, 2-15, 7-18, 11-9
 - damped, 2-15, 7-18
- negative definite function, 5-19
- negative feedback, 1-3, 1-14, 2-2, 4-9, 7-10, 10-1, 11-6
- Nernst's law, 3-42
- networking, 1-10, 3-23, 4-17, *see also* congestion control
- neural systems, 1-8, 3-25, 3-40–3-42, 11-6
- neutral stability, 5-8–5-10
- Newton, I., 3-2
- Nichols, N. B., 6-34, 11-11, 12-30
- Nichols chart, 13-22, 13-23
- Nobel Prize, 1-8, 1-9, 3-42, 4-17
- noise, *see* disturbances; measurement noise
- noise attenuation, 9-37, 12-10–12-11
- noise cancellation, 5-33
- noise sensitivity function, 12-3
- non-minimum phase, 10-19, 10-20, 10-30, 14-10, 14-11, *see also* inverse response
- nonlinear systems, 2-1–2-2, 2-22, 3-5, 5-1, 5-4, 5-7, 5-15, 5-18, 5-23, 5-29–5-34, 8-2, 8-24, 8-30, 10-22, 10-23, 10-25, 13-13, 14-25–14-30
 - linear approximation, 5-26, 6-30, 13-1
- nonunique solutions (ODEs), 5-3
- normalized coordinates, 3-28–3-29, 3-45, 6-32
- norms, 10-21–10-23
- Nyquist, H., 10-1, 10-27
- Nyquist contour, 10-5
- Nyquist criterion, 10-5, 10-8, 10-11, 10-12, 10-25, 11-12
 - for robust stability, 13-9
 - general, 10-9
- Nyquist plot, 10-4–10-5, 10-14, 11-12, 12-9, 13-23
- Nyquist, H., 1-7
- observability, 3-6, 8-1–8-2, 8-15, 8-32
 - rank condition, 8-3
 - tests for, 8-2–8-3
 - unobservable systems, 8-4, 8-15–8-17, 9-44
- observability matrix, 8-3, 8-5
- observable canonical form, 8-5, 8-33
- observer gain, 8-7, 8-9–8-11, 8-13, 8-18, 8-20
- observers, 8-1, 8-6–8-9, 8-13, 8-20, 8-30
 - block diagram, 8-2, 8-10
 - see also* Kalman filter
- ODEs, *see* differential equations
- Ohm's law, 3-42, 4-9, 9-9
- on-off control, 1-18
- open loop, 1-1, 2-2, 4-9, 7-2, 9-20, 10-1, 11-15, 12-1, 12-9, 13-4
- operational amplifier, 4-7–4-11, 9-6, 10-27, 11-21, 13-14
 - circuits, 4-27, 6-24, 13-18
 - dynamical model, 4-10, 9-6
 - input/output characteristics, 4-8
 - oscillator using, 4-28, 5-37
 - static model, 4-8, 9-6
- optimal control, 7-28, 8-18, 8-20, 13-23
- order, of a model, 3-10
- ordinary differential equations, *see* differential equations
- oscillator dynamics, 4-28, 5-2, 5-3, 5-17, 5-37, 6-8, 7-18, 9-5, 9-11
 - normal form, 3-45
 - see also* nanopositioner (AFM); spring-mass system
- outer loop control, 12-27–12-29
- output feedback, 8-12, 8-13, 8-32, *see also* control: using estimated state; loop shaping; PID control
- output sensitivity function, *see* noise sensitivity function
- outputs, *see* measured signals
- overdamped oscillator, 7-18
- overshoot, 2-12, 6-21, 7-10, 7-19, 7-20, 12-6
- Padé approximation, 10-30, 14-5
- paging control (computing), 3-36
- pairing problem (relative gain array), 15-23, 15-24
- parallel connection, 2-10, 2-11, 9-17
- parallel systems, 15-25–15-27
- parametric stability diagram, 5-30–5-32

- parametric uncertainty, 3-8, 13-1
- particular solution, 2-6, 6-3, 6-21, 9-5,
 - see also* forced response
 - transfer function, 2-7
- passive systems, 10-23
- passivity theorem, 10-24
- patch clamp, 1-8
- PD control, 11-4, 12-15
- peak frequency, 6-25, 12-6, 12-7
- peak frequency-peak time product, 12-31
- peak value, 12-6, 12-7
- pendulum dynamics, 5-21, *see also* inverted pendulum
- perfect adaptation, 11-6
- performance limits, 13-27, 14-6, 14-10, 14-25
 - due to right half-plane poles and zeros, 10-20
 - see also* control: fundamental limits
- performance specifications, 2-12, 4-12, 6-21, 7-9, 7-36, 12-1, 12-6–12-12, 12-14, 13-16, *see also* overshoot; maximum sensitivity; resonant peak; rise time; settling time
 - test points, 12-12, 15-4
- periodic solutions, *see* differential equations; limit cycles
- persistence, of a web connection, 4-11, 4-13
- persistent excitation, 15-31
- Petri net, 3-23
- pharmacokinetics, 4-20, 4-21, 4-23, *see also* drug administration
- phase, 2-8, 3-22, 6-23, 7-20, 9-3, 9-6, 9-29, 10-21–10-23, 10-25, *see also* minimum phase; non-minimum phase
- phase area formula, *see* Bode's phase area formula
- phase crossover frequency, 10-14, 10-15
- phase curve (Bode plot), 9-29–9-32
 - relationship to gain curve, 10-18, 12-13
- phase lag, 6-23, 9-35, 10-19, 14-11, 14-13
- phase lead, 6-23, 9-35, 12-14, 12-33
- phase margin, 10-15, 10-16, 12-13, 12-33, 13-30, 14-11
 - from Bode plot, 10-15
 - reasonable values, 10-17
 - relation to stability margin, 13-26
- phase portrait, 3-2, 3-3, 5-4–5-5, 5-29
- Philbrick, G. A., 4-11
- photoreceptors, 11-6
- physics, relationship to control, 1-6
- PI control, 1-14, 1-20, 2-14–2-16, 4-1, 4-4, 11-4, 11-10, 12-14, 12-15
 - first-order system, 11-9, 14-21
- PID control, 1-18–1-20, 11-1–11-24
 - block diagram, 11-2, 11-4, 11-16
 - computer implementation, 11-21
 - ideal form, 11-2, 11-23
 - implementation, 11-4, 11-19–11-23
 - in biological systems, 11-6
 - op amp implementation, 11-21
 - proportional action, 11-3
 - tuning, 11-11–11-15
 - see also* derivative action; integral action
- pitchfork bifurcation, 5-39
- planar dynamical systems, 5-5, 5-10, *see also* second-order systems
- pole excess, 9-23, 12-20, 12-24
- pole placement, 7-11, 14-25, *see also* eigenvalue assignment
- pole zero diagram, 9-24
- pole/zero cancellations, 9-13, 9-26–9-28, 9-40, 9-44, 14-25, 15-26
 - unstable, 9-27, 12-4–12-5
- pole/zero pair, right half-plane, 14-13–14-14, 14-18, 14-20, 14-31
- poles, 2-8, 9-9, 9-23, 9-24
 - dominant, *see* dominant eigenvalues (poles)
 - fast stable, 14-21, 14-25
 - pure imaginary, 10-5, 10-12
 - relationship to eigenvalues, 9-24
 - right half-plane (unstable), 9-24, 9-33, 10-20, 14-6, 14-10, 14-12–14-14, 14-17, 14-20, 14-21, 14-25, 14-31
- population dynamics, 4-25–4-27, 4-30, *see also* predator-prey system
- positive definite function, 5-19, 5-22, 5-27
- positive definite matrix, 5-22, 7-28
- positive feedback, 1-2–1-3, 1-17, 2-4, 2-23–2-27, 11-4
- power of a matrix, 6-6
- power systems (electric), 1-6–1-7, 3-45, 5-7, 5-36
- predator-prey system, 3-14–3-15, 4-26–4-27, 4-30, 5-30, 7-15
- prediction, in controllers, 1-19, 8-30, 11-5, 13-30, *see also* derivative action
- prediction time, 11-5
- principle of the argument, *see* variation of the argument, principle of
- process control, 1-8, 3-23
- program synthesis, 15-15
- programmable logic controller (PLC),

- 15-37, 15-38
- proper transfer function, 9-23
- proportional band, 11-2
- proportional control, 1-18, 1-19, 2-13, 2-14, 11-2-11-4, *see also* PID control
- proportional-derivative control, *see* PD control
- proportional-integral control, *see* PI control
- proportional-integral-derivative control, *see* PID control
- protocol, *see* congestion control; consensus
- pulse signal, 6-16, 6-17, 7-22, *see also* impulse function
- pupil response, 2-29, 9-38, 11-6
- pure exponential solution, 9-5
- Q -value, 7-20, 9-32
- quantitative feedback theory (QFT), 13-22
- quarter car model, 9-43
- queuing systems, 3-35-3-36, 3-46
- ramp input, 12-7
- random process, 3-35, 8-17, 8-18, 8-34
- reachability, 3-6, 7-1-7-9, 7-33, 8-15
 - rank condition, 7-4, 14-2
 - tests for, 7-3
 - unreachable systems, 7-5, 7-34, 8-15-8-17, 9-44
- reachability matrix, 7-3, 7-8
- reachable canonical form, 3-11, 7-6-7-9, 7-13, 7-14, 7-34
- reachable set, 7-1
- real-time systems, 1-6
- realization, 9-12
 - minimal, 9-13
- reasoning, 15-28
- receding horizon control, 15-9
- rectified linear unit (ReLU), 15-34
- reference signal, 1-18, 7-9, 7-10, 9-1, 9-18, 11-2, 11-19, *see also* command signals; setpoint
 - effect on observer error, 8-12, 8-17, 8-24
 - response to, 12-7, 13-29
 - tracking, 2-2, 2-17, 7-9, 8-23, 8-28, 12-13, 13-17-13-18
- reference weighting, *see* setpoint weighting
- region of attraction, *see* equilibrium points: regions of attraction
- regulation problem, 2-12
- regulator, *see* control law
- reinforcement learning, 15-31
- relative degree, 9-23
- relative gain array (RGA), 15-23-15-25
- relay feedback, 10-26, 11-14
- Reno (protocol), *see* Internet; congestion control
- repressilator, 3-40
- repressor, 1-12, 3-40, 3-46, 5-23, 9-37, *see also* biological circuits
- requirements, 15-2, *see also* performance specifications
- reset logic, 3-8
- reset, in PID control, 11-4
- resonant frequency, 7-21, 10-23
- resonant peak, 6-25, 7-21, 13-12
- resource usage, in computing systems, 3-35, 3-37, 4-11, 4-12
- response, *see* input/output models
- retina, 11-6, *see also* pupil response
- Riccati differential equation, 7-28
- Riccati equation, 7-29, 7-37, 8-20, 13-25, 13-28
- Riemann sphere, 13-6, 13-29
- right half-plane poles and zeros, *see* poles: right half-plane; zeros: right half-plane
- rise time, 2-12, 6-21, 7-10, 7-19, 7-20, 12-6, 12-31
- rise time-bandwidth product, 12-9, 12-31
- robotics, 1-9-1-10, 6-34
- robust stability, 13-3
- robustness, 1-13-1-14, 2-3, 2-20-2-23, 11-19, 12-6, 13-4, 13-28
 - nonlinear gain variations, 2-20, 13-13
 - performance, 13-16-13-28
 - stability, 13-9-13-16
 - using gain and phase margin, 10-17, 12-13
 - using maximum sensitivity, 12-10, 12-13, 13-9, 13-30
 - via gain and phase margin, 10-15
 - see also* uncertainty
- roll-off, *see* high-frequency roll-off
- root locus diagram, 5-31, 5-32, 12-23-12-26
 - asymptotes, 12-33
 - initial direction, 12-33
 - real line segments, 12-33
- Routh-Hurwitz criterion, 2-9
- routing matrix, 4-15
- rush-hour effect, 3-36

- saddle (equilibrium point), 5-10
- safety, 15-18
- sampling, 6-27–6-28, 8-30, 8-31, 11-22
- saturation function, 2-26
- saturation function, 2-2, 2-25, 3-24, 4-8, 11-22, *see also* actuators: saturation
- scaling, *see* normalized coordinates
- scanning tunneling microscope, 4-17
- schematic diagrams, 3-23, 4-7
- Schitter, G., 4-19, 4-20
- Schmitt trigger, 2-27
- second-order systems, 3-2, 6-35, 7-17–7-21, 7-36, 9-31, 9-32, 11-10, 12-31
- sector-bounded nonlinearity, 10-24
- Segway Personal Transporter, 3-12, 7-4, 7-5
- selector control, 1-22, 15-18–15-19
- self-activation, 5-38
- self-optimizing controllers, 15-22
- self-repression, 6-37, 9-36
- semidefinite function, 5-19
- sensitivity crossover frequency, 12-7, 12-9
- sensitivity function, 2-3, 12-3, 12-13, 12-33, 13-9, 13-18, 14-25
 - and disturbance attenuation, 12-9, 12-31, 14-6
- sensor fusion, 15-22
- sensor matrix, 3-10, 3-14
- sensor networks, 3-37
- sensors, 1-5, 1-6, 8-2, 8-30, 10-20, 11-21, 12-1, 12-5, 14-4, 14-13
 - effect on zeros, 10-20, 14-4
 - in computing systems, 4-11
 - see also* measured signals
- separation principle, 8-13, 8-23, 8-32
- series connection, 2-10, 2-11, 9-17
- service rate (queuing systems), 3-35
- servo problem, 2-17
- setpoint, 1-16, 11-2
- setpoint weighting, 11-19–11-20, 11-23
- settling time, 2-12, 6-21, 6-36, 7-10, 7-20, 12-6
- sgn (function), 4-3
- ship dynamics, 5-16, 15-29
- signal blocking, *see* zeros: signal blocking property
- similarity of two systems, 13-3–13-9
- simulation, 3-9, 3-19–3-20
- SIMULINK, 6-31
- single-input, single-output (SISO) systems, 5-1, 6-2, 6-3, 6-29, 8-4, 10-22
- singular values, 10-22, 10-23
- sink (equilibrium point), 5-10
- small gain theorem, 10-23–10-24, 13-12–13-13
- Smith predictor, 13-30, 15-20
- software tools for control, viii
- solution (ODE), *see* differential equations: solutions
- source (equilibrium point), 5-10
- specifications, *see* performance specifications
- spectrum analyzer, 9-37
- Sperry autopilot, 1-15
- spring-mass system, 3-2, 3-11, 3-19, 3-21, 4-18, 5-22, 5-36, 9-35
 - coupled, 6-14, 6-18
 - generalized, 3-12, 4-7
 - identification, 3-26
 - normalization, 3-28, 3-45
 - see also* oscillator dynamics
- stability, 1-5, 1-6, 1-15, 2-9, 3-21, 5-4, 5-8–5-29
 - asymptotic stability, 5-8, 5-13, 5-18
 - conditional, 10-13
 - in the sense of Lyapunov, 5-8
 - internal, 12-5
 - local versus global, 5-10, 5-29
 - Lyapunov analysis, *see* Lyapunov
- stability analysis
 - neutral, 5-8, 5-10
 - of a system, 5-12
 - of equilibrium points, 3-21, 5-8, 5-10, 5-19, 5-26, 5-27
 - of feedback loop, *see* Nyquist criterion
 - of limit cycles, 5-17–5-18
 - of linear systems, 5-11–5-14, 5-21, 6-10
 - of solutions, 5-8, 5-9, 5-18
 - of transfer functions, 9-24
 - robust, *see* robust stability
 - Routh-Hurwitz criterion, 2-9
 - unstable solutions, 5-10
 - using eigenvalues, 5-26, 6-10, 6-11
 - using linear approximation, 5-14, 5-26, 6-31
 - using state feedback, 7-9–7-32
 - see also* bifurcations; equilibrium points
- stability diagram, *see* parametric stability diagram
- stability margin (quantity), 10-14, 10-15, 10-17, 12-10, 13-9, 13-30, 14-31
 - generalized, 13-25
 - reasonable values, 10-17
- stability margins (concept), 10-14–10-18,

- 10-29, 12-13
- stabilizability, 14-3
- Stark, L., 9-38
- state, of a dynamical system, 3-2, 3-5, 3-9
- state estimators, *see* observers
- state feedback, 7-1–7-32, 8-7, 8-13, 13-24, 15-17, *see also* eigenvalue assignment; linear quadratic control
- state space, 3-2, 3-9–3-22, 7-9
- state vector, 3-2, 3-9
- static gain, *see* gain, zero frequency
- steady-state gain, *see* zero frequency gain
- steady-state response, 1-28, 2-12, 3-20, 6-19–6-21, 6-23, 6-27, 7-11, 7-20, 9-2, 9-37, 9-40
- steady-state solution, 9-5
- steam engines, 1-2, 1-13
- steering, *see* vehicle steering
- Stein, G., x, 12-1, 14-6, 14-7
- step input, 3-4, 6-5, 6-20, 9-23
- step response, 2-11, 2-12, 3-4, 3-5, 3-26, 3-27, 6-5, 6-17, 6-20, 6-21, 7-10, 7-19, 7-20, 11-11, 12-31
- stereographic projection, 13-6
- stochastic systems, 8-17, 8-19
- strictly proper, 9-23
- strong stabilizability, 14-2, 14-3
- summing junction, 3-24
- superposition, 3-4, 6-3, 6-4, 6-17, 6-27, 6-35, 9-2, 9-17
- superregenerative amplifier, 2-4
- supervised learning, 15-31
- supervisory control, *see* decision making: higher levels of
- supply chains, 1-11
- supremum (sup), 10-22
- switching behavior, 5-26, 13-28
- system identification, 3-26, 3-28, 3-45, 9-37
- system inversion, *see* inverse model
- tapping mode, *see* atomic force microscopes
- task description, 8-24
- TCP/IP, *see* Internet; congestion control
- temporal logic, 15-11
- Teorell, T., 4-21, 4-23
- test points, 12-12, 15-4
- thermofluid systems, 3-32–3-34, 5-35, 9-11, 10-28
 - drum boiler, 3-33
 - water heater, 3-32
- three-term controllers, 11-2, *see also* PID control
- thrust vectored aircraft, *see* vectored thrust aircraft
- time constant, 2-6, 6-36
- time delay, 1-10, 9-10, 9-11, 10-2, 10-17, 10-19, 11-11, 11-12, 11-22, 12-20, 14-13, 14-14, 14-31
 - compensation for, 13-30
 - Padé approximation, 10-29
- time plot, 3-2
- time-invariant systems, 2-6, 3-4, 3-10, 5-35, 6-4–6-5
- tracking, *see* reference signal: tracking
- tracking mode, 11-17–11-18
- traffic light controller, 3-17
- trail (bicycle dynamics), 4-6, 4-7
- transcription factors, 3-39
- transcriptional regulation, *see* gene regulation
- transfer functions, 2-7, 9-1–9-40
 - and impulse response, 9-15
 - by inspection, 9-8
 - common systems, 9-11
 - derivation using exponential signals, 9-3
 - for control systems, 9-18, 9-42
 - for electrical circuits, 9-9
 - for linear systems, 9-15
 - for time delay, 9-10
 - for tuned damper, 9-9
 - frequency response, 9-2, 9-28
 - from experiments, 9-37
 - irrational, 9-11, 9-12
 - linear input/output systems, 2-8, 9-3, 9-8, 9-10, 9-11, 9-41
 - loop tracing, 9-20
 - qualitative insight, 9-35
 - simplified notation, 9-5
- transient response, 3-20, 6-19, 6-20, 6-23, 7-2, 7-22
- Transmission Control Protocol (TCP), 4-13
- transmission zero, *see* zeros, blocking property
- Tsien, H. S., 1-9
- tuning rules, *see* Ziegler-Nichols tuning
- Tustin, A., 2-1
- two degree-of-freedom control, 2-18–2-20, 8-23, 8-24, 11-2, 11-20, 12-1, 12-18, 12-30, 12-31, 13-29
- two-out-of-three selectors, 15-19
- uncertainty, 1-6, 1-13–1-14, 3-6, 3-8–3-9,

- 7-25, 13-1–13-9
 - component or parameter variation, 1-6, 2-3, 3-8, 13-1
 - disturbances and noise, 1-6, 3-6, 7-9, 9-18, 12-1
 - unmodeled dynamics, 1-6, 2-16–2-17, 3-8, 13-2, 13-10
 - see also* additive uncertainty; feedback uncertainty; multiplicative uncertainty
- uncertainty lemon, 3-9, 4-4, 4-10, 4-20
- underdamped oscillator, 5-2, 7-18, 7-19
- unit step, 6-20
- unmodeled dynamics, *see* uncertainty: unmodeled dynamics
- unstable pole, *see* poles: right half-plane
- unstable solution, for a dynamical system, 5-10, 5-13, 6-11, 9-24
- unstable zero, *see* zeros: right half-plane

- V-model, 15-2
- variation of the argument, principle of, 10-9, 10-27
- vector field, 3-3, 5-4, 5-5
- vectored thrust aircraft, 3-31–3-32, 6-11, 7-29, 8-21, 9-43, 12-16, 12-26
- vehicle steering, 3-29–3-31, 3-45, 6-31, 7-11, 8-9, 8-13, 8-25, 8-28, 9-20, 10-20, 10-28, 12-19, 14-4, 14-22, *see also* ship dynamics
- vehicle suspension, 9-43, *see also* coupled spring-mass system
- vertical contract, 15-13
- vertical takeoff and landing, *see* vectored thrust aircraft
- vibration damper, 9-9
- Vinnicombe, G., 12-30, 13-6, 13-28
- Vinnicombe metric, 13-6–13-9, 13-29
 - numerical computation, 13-7
- voltage clamp, 1-8, 1-9, 3-42
- Voterra equations, *see* Lotka-Volterra equations

- water heater, 3-32
- waterbed effect, 14-6
- Watt governor, *see* centrifugal governor
- Watt steam engine, 1-2, 1-13
- web server control, 4-11–4-13, 7-30, 11-24, 12-31
- web site, companion, viii
- Whipple, F. J. W., 4-7
- Wiener, N., 1-9
- winding number, 10-6, 10-10, 10-12, 13-7
- window size (TCP), 4-14, 4-15, 4-17, 5-11
- windup, *see* integrator windup
 - selector control, 15-19
- Wright, F. L., 15-1
- Wright, W., 1-15
- Wright Flyer, 1-8, 1-15

- X-29 aircraft, 14-7

- Youla parameterization, 13-14–13-16

- zero frequency gain, 2-8, 6-25, 7-11, 7-14, 7-21, 9-23, 11-12
- zeros, 2-9, 9-9, 9-23
 - blocking property, 2-9
 - Bode plot for, 9-44
 - effect of sensors and actuators on, 10-20, 10-21, 14-4
 - for a state space system, 9-24
 - right half-plane, 9-24, 9-33, 10-19, 10-20, 12-20, 14-7, 14-10, 14-12–14-14, 14-16, 14-17, 14-20, 14-25, 14-31
 - signal-blocking property, 9-23, 9-24
 - slow, 14-22, 14-24, 14-25
 - stable/unstable, 14-22
- Ziegler, J. G., 11-11, 11-23
- Ziegler-Nichols tuning, 11-11–11-14, 11-23
 - drawbacks, 11-12
 - frequency response, 11-11
 - improved method, 11-12
 - step response, 11-11