# Feedback Systems

*An Introduction for Scientists and Engineers*
*SECOND EDITION*

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# Bibliography


[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.

[Agn76] C. E. Agnew. Dynamic modeling and control of congestion-prone systems. *Operations Research*, 24(3):400–419, 1976.

[ÅH05] K. J. Åström and T. Hägglund. *Advanced PID Control*. ISA—The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC, 2005.

[Ahl66] L. V. Ahlfors. *Complex Analysis*. McGraw-Hill, New York, 1966.

[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.

[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.

[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.

[ÅW08] 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. *$H^\infty$-Optimal Control and Related Minimax Design Problems: A Dynamic Game Approach*. Birkhauser, Boston, 1991.

[BC48] G. S. Brown and D. P. Campbell. *Principles of Servomechanims*. 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.

[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.

[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.

[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.

[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.

[Bod45] H. W. Bode. *Network Analaysis 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.

[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.

[Can03] R. H. Cannon. *Dynamics of Physical Systems*. Dover, New York, 2003. Originally published by McGraw-Hill, 1967.

[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.

[CEHM10] M. Campbell, M. Egerstedt, J. P. How, and R. M Murray. Autonomous driving in urban environments: Approaches, lessons and challenges. *Philosophical Transactions of the Royal Society – A*, 368(1928), 2010.

[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.

[Cro75] Crocus. *Systemes d'Exploitation des Ordinateurs*. Dunod, Paris, 1975.

[CT84] C. Cobelli and G. Toffolo. Model of glucose kinetics and their control by insulin, compartmental and non-compartmental approaches. *Mathematical Biosciences*, 72(2):291–316, 1984.

[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 $H_\infty$ control problems. *IEEE Transactions on Automatic Control*, 34(8):831–847, 1989.

[DH85] J. P. Den Hartog. *Mechanical Vibrations*. Dover, New York, 1985. Reprint of 4th ed. from 1956; 1st ed. published in 1934.

[Dic07] E. D. Dickmanns. *Dynamic Vision for Perception and Control of Motion*. Springer, Berlin, 2007.

[dJ02] H. de Jong. Modeling and simulation of genetic regulatory systems: A literature review. *Journal of Computational Biology*, 9:67–103, 2002.

[DM02] 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.

[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.

[DRRS00] D. Dvorak, R. D. Rasmussen, G. Reeves, and A. Sacks. Software architecture themes in jpl's mission data system. In *Proceedings of 2000 IEEE Aerospace Conference*, 2000.

[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.

[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 parturient 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.

[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 Instut 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 $\mathscr{H}_\infty$ 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.

[Gan60] F. R. Gantmacher. *The Theory of Matrices*. 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.

[GM61] D. Graham and D. McRuer. *Analysis of Nonlinear Control Systems*. Wiley, New York, 1961.

[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.

[Gui63] E. A. Guillemin. *Theory of Linear Physical Systems*. MIT Press, Cambridge, MA, 1963.

[Hah67] W. Hahn. *Stability of Motion*. Springer, Berlin, 1967.

[HB90] J. K. Hedrick and T. Batsuen. Invariant properties of automobile suspensions. In *Proceedigns of the Institution of Mechanical Engineers*, volume 204, pages 21–27, London, 1990.

[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.

[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.

[HMTG00] C. V. Hollot, V. Misra, D. Towsley, and W-B. Gong. A control theoretic analysis of RED. In *Proceedings of IEEE Infocom*, pages 1510–1519, 2000.

[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.

[Hug93] T. P. Hughes. *Elmer Sperry: Inventor and Engineer*. John Hopkins University Press, Baltimore, MD, 1993.

[HW00] D. Hanahan and R. A. Weinberg. The hallmarks of cancer. *Cell*, 100:57–70, 2000.

[IRBM05] M. Ingham, R. Rasmussen, M. Bennett, and A. Moncada. Engineering complex embedded systems with state analysis and the mission data system. *J. Aerospace Computing, Information and Communication*, 2, 2005.

[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*, 7:162178, 1970.

[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 Scientists*. O'Reilly Media, 2014.

[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. *Boletin de la Sociedad Matématica 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.

[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.

[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.

[KN00] U. Kiencke and L. Nielsen. *Automotive Control Systems: For Engine, Driveline, and Vehicle*. Springer, Berlin, 2000.

[Kra63] N. N. Krasovski. *Stability of Motion*. Stanford University Press, Stanford, CA, 1963.

[KS01] J. Keener and J. Sneyd. *Mathematical Physiology*. Springer, New York, 2001.

[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.

[LaS60] J. P. LaSalle. Some extensions of Lyapunov's second method. *IRE Transactions on Circuit Theory*, CT-7(4):520–527, 1960.

[Lew03] A. D. Lewis. A mathematical approach to classical control. Technical report, Queens University, Kingston, Ontario, 2003.

[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.

[Lun05] K. H. Lundberg. History of analog computing. *IEEE Control Systems Magazine*, pages 22–28, March 2005.

[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 Servomechanims*. 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.

[McF53] M. W. McFarland, editor. *The Papers of Wilbur and Orville Wright*. McGraw-Hill, New York, 1953.

[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.

[MR94] J. E. Marsden and T. S. Ratiu. *Introduction to Mechanics and Symmetry*. Springer-Verlag, New York, 1994.

[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.

[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.

[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.

[PB86] G. Pacini and R. N. Bergman. A computer program to calculate insulin sensitivity and pancreatic responsivity from the frequently sampled intraveneous glucose tolerance test. *Computer Methods and Programs in Biomedicine*, 23:113–122, 1986.

[Phi48] G. A. Philbrick. Designing industrial controllers by analog. *Electronics*, 21(6):108–111, 1948.

[PN00] W. F. Powers and P. R. Nicastri. 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] Claudius Ptolemaeus, editor. *System Design, Modeling, and Simulation using Ptolemy II*. Ptolemy.org, 2014.

[Pyt] Python control systems library. Available from http://python-control.org.

[Ras01] R. D. Rasmussen. Goal-based fault tolerance for space systems using the Mission Data System. In *IEEE Aerospace Conference*, 2001.

[Rig63] D. S. Riggs. *The Mathematical Approach to Physiological Problems*. MIT Press, Cambridge, MA, 1963.

[RM71] H. H. Rosenbrock and P. D. Moran. Good, bad or optimal? *IEEE Transactions on Automatic Control*, AC-16(6):552–554, 1971.

[RST12] G. Rafal, R. G. Sanfelice, and A. Teel. *Hybrid Dynamical Systems: Modeling, Stability, and Robustness*. Princeton University Press, 2012.

[Rug95] W. J. Rugh. *Linear System Theory*. Prentice Hall, Englewood Cliffs, NJ, 2nd edition, 1995.

[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.

[Sar91] D. Sarid. *Atomic Force Microscopy*. Oxford University Press, Oxford, UK, 1991.

[Sas99] S. Sastry. *Nonlinear Systems*. Springer, New York, 1999.

[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.

[Shi96] F. G. Shinskey. *Process-Control Systems. Application, Design, and Tuning*. McGraw-Hill, New York, 4th edition, 1996.

[Smi52] J. M. Smith. The importance of the nervous system in the evolution of animal flight. *Evolution*, 6(1):127–129, 1952.

[Son98] E. P. 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. Saff and A. D. Snider. *Fundamentals of Complex Analysis with Applications to Engineering, Science and Mathematics*. Prentice Hall, Englewood Cliffs, NJ, 2002.

[Sta68] L. Stark. *Neurological Control Systems—Studies in Bioengineering*. Plenum Press, New York, 1968.

[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.

[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. *Dynamics and Control of Robot Manipulators*. John Wiley, 1989.

[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.

[Tha89] G. T. Thaler. *Automatic Control Systems*. West Publishing, St. Paul, MN, 1989.

[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.

[Vin01] G. Vinnicombe. *Uncertainty and Feedback: $\mathscr{H}_\infty$ Loop-Shaping and the $\nu$-Gap Metric*. Imperial College Press, London, 2001.

[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.

[WT24] E. P. M. Widmark and J. Tandberg. Über die Bedingungen für die Akkumulation indifferenter Narkotika. *Biochemische Zeitung*, 148:358–389, 1924.

[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.

[YHSD00] T.-M. Yi, Y. Huang, M. I. Simon, and J. Doyle. Robust perfect adaptation in bacterial chemotaxis through integral feedback control. *PNAS*, 97:4649–4653, 2000.

[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.

[ZN42] J. G. Ziegler and N. B. Nichols. Optimum settings for automatic controllers. *Transactions of the ASME*, 64:759–768, 1942.

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