

Feedback Systems

An Introduction for Scientists and Engineers
SECOND EDITION

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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, 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 Appl.*, 12A(6):653–662, 1986.
- [ÅH06] K. J. Åström and T. Hägglund. *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.

- [Ång61] A. I. Ångström. Neue Methode, das Wärmeleitungsvermögen der Körper zu bestimmen. *Annalen der Physik und Chemie*, 114:513–530, 1861.
- [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.
- [Bec20] J. Bechhoefer. *Control Theory for Physicists*. Cambridge Universtiy Press, Cambridge, UK, 2020. 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, UK, 1979.
- [Ben93] S. Bennett. *A History of Control Engineering: 1930–1955*. Peter Peregrinus, Stevenage, UK, 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, NJ, 1987.
- [BH75] A. E. Bryson, Jr. and Y.-C. Ho. *Applied Optimal Control: Optimization, Estimation, and Control*. Wiley, New York, 1975.
- [BHÅ16] J. Berner, T. Hägglund, and K. J. Åström. Asymmetric relay autotuning—Practical features for industrial use. *Control Engineering Practice*, 54:231–245, 2016.
- [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*, 14(12):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.
- [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, 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 open source tool for symbolic model checking. In *Proceedings of the 14th International Conference on Computer Aided Verification*, pages 359–364. Springer, 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, London, 1991.
- [CFG⁺06] L. B. Cremean, T. B. Foote, J. H. Gillula, G. H. Hines, D. Kogan, K. L. Kriegbaum, 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. *Systèmes 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, Princeton, NJ, 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. *Journal Royal Aeronautical Society*, 59(July):451–477, 1955. 45th Wilber Wright Memorial Lecture.
- [DRC07] 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.

- [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*, 427(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. Mezić. 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-Verlag, Berlin and Heidelberg, 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. Canonica, 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 nonlinear 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 H_∞ Control*. Springer, 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, New York, 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, 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, Princeton, NJ, 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. Hajiye 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.
- [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.
- [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*, 53:255–291, 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, 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, Sebastopol, CA, 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. *Boletin 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.
- [KÄT⁺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-Interscience, New York, 1995.
- [Kle75] L. Kleinrock. *Queueing 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, editors, *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, New York, 2nd edition, 2008.
- [KS09] J. Keener and J. Sneyd. *Mathematical Physiology II: Systems Physiology*. Springer, New York, 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-Lagarrigue, 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. H. Low. *Analytical Methods for Network Congestion Control*. Morgan and Claypool, San Rafael, CA, 2017.
- [LP15] A. Lindquist and G. Picci. *Linear Stochastic Systems: A Geometric Approach to Modeling, Estimation and Identification*. Springer, 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 R. S. Sharp. 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, 20083.
- [McF53] M. W. McFarland, editor. *The Papers of Wilbur and Orville Wright*. McGraw-Hill, New York, 1953.
- [MCV⁺10] C. A. Monje, Y. Q. Chen, B. M. Vinagre, 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, Boca Raton, FL, 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, New York, 1994.
- [MR96] E. S. Meadows and J. B. Rawlings. Model predictive control. In *Nonlinear Process Control*, chapter 5. Prentice Hall, 1996.
- [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, 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.
- [Nyg32] H. Nyquist. Regeneration theory. *Bell System Technical Journal*, 11:126–147, 1932.
- [Nyg56] 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.
- [Ope14] The Open Group. The Open Group technical standard for the future airborne capability environment. Technical Report C145, The Open Group, 2014.
- [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, New York, 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. 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] 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. Gordon & Breach, New York, 1960.
- [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*, 20:31–38, 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.

- [SDF18] R. Sepulchre, G. Drion, and A. Franci. Excitable behaviors. In R. Tempo, S. Yurkovich, and P. Misra, editors, *Emerging Applications of Control and Systems Theory. Lecture Notes in Control and Information Sciences—Proceedings*, pages 269–280. Springer, 2018.
- [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.
- [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, S. Dieleman, D. Grewe, J. Nham, N. Kalchbrenner, I. Sutskever, T. Lillicrap, M. Leach, K. Kavukcuoglu, T. Graepel, and D. Hassabis. 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 of Diabetes Science and Technology*, 7(6):1621–1631, 2013.
- [Str88] G. Strang. *Linear Algebra and Its Applications*. Harcourt Brace Jovanovich, San Diego, CA, 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, New York, 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*, 187:48–54, 1952.
- [Vid84] M. Vidyasagar. The graph metric for unstable plants and robustness estimates for feedback stability. *IEEE Transactions on Automatic Control*, 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(9):1371–1383, 1993.
- [Vin01] G. Vinnicombe. *Uncertainty and Feedback: \mathcal{H}_∞ 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, New York, 1948.
- [Wig90] S. Wiggins. *Introduction to Applied Nonlinear Dynamical Systems and Chaos*. Springer, 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 indifferenter Narkotika. *Biochemische Zeitung*, 148:358–389, 1924.
- [WW97] F. R. Whitt and D. G. Wilson. *Bicycling Science*. MIT Press, 1997.
- [YBL74] D. C. Youla, J. J. Bongiorno, Jr., and C. N. Lu. Single-loop feedback stabilization of linear multivariable plants. *Automatica*, 10(2):159–173, 1974.
- [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. C. Doyle. Robust perfect adaptation in bacterial chemotaxis through integral feedback control. *Proceedings of the National Academy of Sciences*, 97(9):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.
- [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. Zaccarian and A. R. Teel. *Modern Anti-windup Synthesis: Control Augmentation for Actuator Saturation*. Princeton University Press, Princeton, NJ, 2011.

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