Index

access control, see admission control acknowledgment (ack) packet, 77-79 activator, 16, 59, 129 active filter, 154, see also operational amplifier actuators, 4, 31, 51, 65, 81, 178, 224, 266, 283, 311, 324, 333-335, 337 effect on zeros, 284, 334 in computing systems, 75 saturation, 50, 225, 300, 306-307, 311, 324 A/D converters, see analog-to-digital converters adaptation, 297 adaptive control, 21, 373, 374 additive uncertainty, 349, 353, 356, 376 admission control, 54, 63, 78, 79,274 advertising, 15 aerospace systems, 8-9, 18, 339, see also vectored thrust aircraft; X-29 aircraft AFM, see atomic force microscope aircraft, see flight control alcohol, metabolism of, 94 algebraic loops, 211, 249-250 aliasing, 225 all-pass transfer function, 331 alternating current (AC), 7, 155 amplifier, see operational amplifier amplitude ratio, see gain analog computing, 51, 71, 250, 309

analog implementation, controllers, 74, 263, 309-311 analog-to-digital converters, 4, 82, 224, 225, 311 analytic function, 236 anticipation, in controllers, 6, 24, 296, see also derivative action antiresonance, 156 anti-windup compensation, 307, 311, 312, 314 Apache web server, 76, see also web server control apparent volume of distribution, 86, 94 Arbib, M. A., 167 argument, of a complex number, 250 arrival rate (queuing systems), 55 artificial intelligence (AI), 12, 20 asymptotes, in Bode plot, 253, 254 asymptotic stability, 42, 102-106, 112, 114, 117, 118, 120, 140 discrete-time systems, 165 atmospheric dynamics, see environmental science atomic force microscopes, 3, 51.81-84 contact mode, 81, 156, 199 horizontal positioning, 281, 366 system identification, 257 tapping mode, 81, 290, 299, 304, 328 with preloading, 93 attractor (equilibrium point), 104

automatic reset, in PID control, 296 automatic tuning, 306, 373 automotive control systems, 6, 22, 51, 69, see also cruise control; vehicle steering autonomous differential equation, 29, see also time-invariant systems autonomous vehicles, 8, 20-21 autopilot, 6, 19, 20 balance systems, 35-37, 49, 170, 188, 240, 334, see also cart-pendulum system; inverted pendulum band-pass filter, 154, 155, 255, 256 bandwidth, 155, 186, 322, 333 Bell Labs, 18, 290 Bennett, S., 25, 290, 312 bicycle dynamics, 69-71, 91, 123, 226 Whipple model, 71 bicycle model, for vehicle steering, 51-53 bicycledynamics Whipple model, 199 bifurcations, 121-124, 130, see also root locus plots biological circuits, 16, 45, 58-60, 129, 166, 256 genetic switch, 64, 114 repressilator, 59-60 biological systems, 1-3, 10, 16, 22, 25, 58-61, 126, 293, 297, see also biological circuits; drug administration; neural systems; population dynamics bistability, 23, 117

Black, H. S., 18, 19, 71, 73. 131, 267, 290, 347 block diagonal systems, 106, 129, 139, 145, 149, 212 block diagram algebra, 242, 245, 356 block diagrams, 1, 44-47, 238, 242-247, 249 control system, 4, 229, 244, 315 Kalman decomposition, 223 observable canonical form, 205 observer, 202, 210 observer-based control system, 213 PID controllers, 293, 296, 311 reachable canonical form, 172 two degree-of-freedom controller, 219, 316, 358 Youla parameterization, 357 Bode, H., 229, 290, 344, 374 Bode plots, 250-257, 282 asymptotic approximation, 253, 254, 264 low-, band-, high-pass filters, 256 nonminimum phase systems, 284 of rational function, 251 sketching, 254 Bode's ideal loop transfer function, 356, 375 Bode's integral formula, 335-337, 339-340 Bode's relations, 282, 283, 327 Brahe, T., 28 breakpoint, 253, 272 Brockett, R. W., xii, 1, 163 Bryson, A. E., 200 bumpless transfer, 373 Bush, V., 312 calibration, versus feedback, 10, 180, 195, 197 Cannon, R. H., 61, 131 capacitor, transfer function for, 236 car, see automotive control

systems

carrying capacity, in population models, 90 cart-pendulum system, 36, 172, see also balance systems causal reasoning, 1, 70 Cayley-Hamilton theorem, 170, 199, 203 center (equilibrium point), 104 centrifugal governor, 2, 3, 6, 17 chain of integrators (normal form), 61, 173 characteristic polynomial, 105, 199, 235, 240 for closed loop transfer function, 268 observable canonical form, 205 output feedback controller, 212, 213 reachable canonical form, 173, 175, 179, 198 chemical systems, 9, 293, see also process control; compartment models chordal distance, 351 Chrysler autopilot, 6 circuits, see biological circuits; electrical circuits classical control, xi, 374 closed loop, 1, 2, 4, 6, 162, 176, 183, 267, 268, 287, 315 versus open loop, 2, 269, 288, 315 command signals, 4, 22, 220, 293, see also reference signal; setpoint compartment models, 85-89, 106, 151, 186, 203, 208, 227 exercises, 164 compensator, see control law complementary sensitivity function, 317, 325, 337, 350, 354, 356, 360, 365, 369, 375 complexity, of control systems, 9, 21, 298 computed torque, 163 computer implementation,

controllers, 224-226, 311-312 computer science, relationship to control, 5 computer systems, control of, 12-14, 25, 39, 56, 57, 75-81, 157, see also queuing systems conditional integration, 314 conditional stability, 275 congestion control, 12, 77-80, 104, 273, 292, 313, see also queuing systems router dynamics, 93 consensus, 57 control definition of, 3-5 early examples, 2, 5, 6, 8, 10, 18, 22, 25, 296 fundamental limitations, 283, 331-340, 344, 363, 366, 373-374 history of, 25, 312 modeling for, 5, 31-32, 61, 347 successes of, 8, 25 system, 3, 175, 213, 219, 224, 229, 316, 318, 358 using estimated state, 211-214, 370 control error, 23, 244, 294 control law, 4, 23, 24, 162, 176, 179, 244 control Lyapunov function, 124 control matrix, 34, 38 control signal, 31, 157, 293 controllability, 197, see also reachability controlled differential equation, 29, 34, 235 convolution equation, 145-147, 149, 150, 170, 261 discrete-time, 165 coordinate transformations, 106, 147–149, 173, 226, 234-235 to Jordan form, 139 to observable canonical form, 206 to reachable canonical form,

INDEX

174.175 Coriolis forces, 36, 163 corner frequency, 253 correlation matrix, 215, 216 cost function, 190 coupled spring-mass system, 142, 144, 148 covariance matrix, 215 critical gain, 303, 305, 306 critical period, 303, 305 critical point, 271, 273, 279, 289, 290, 303, 352, 353, 372 critically damped oscillator, 184 crossover frequency, see gain crossover frequency; phase crossover frequency crossover frequency inequality, see gain crossover frequency inequality cruise control, 6, 17-18, 65-69 Chrysler autopilot, 6 control design, 196, 300, 309 feedback linearization, 162 integrator windup, 306, 307 linearization, 158 pole/zero cancellation, 248 robustness, 18, 347, 348, 354 Curtiss seaplane, 19, 20 cybernetics, 11, see also robotics D/A converters, see digital-to-analog converters damped frequency, 184 damping, 28, 36, 41, 96, 265, 266 damping ratio, 184, 185, 188, 300 DARPA Grand Challenge, 20, 21 DC gain, 155, see also zero frequency gain dead zone, 23, 24 decision making, higher levels of, 8, 12, 19 delay, see time delay delay compensation, 292, 375

delay margin, 281 delta function, see impulse function derivative action, 24, 25, 293, 296-298, 310, 330 filtering, 297, 308, 311, 312 setpoint weighting, 309, 312 time constant, 294 versus lead compensator, 330 describing functions, 288-290 design of dynamics, 18-19, 109, 124–125, 131, 167, 177, 182 diabetes, see insulin-glucose dynamics diagonal systems, 105, 139 Kalman decomposition for, 222 transforming to, 106, 129, 138 Dickmanns, E., 20 difference equations, 34, 37-41, 61, 157, 224, 312 differential algebraic equations, 33, see also algebraic loops differential equations, 28, 34-37, 95-98 controlled, 29, 133, 235 equilibrium points, 100-101 existence and uniqueness of solutions, 96-98 first-order, 32, 298 isolated solution, 101 periodic solutions, 101-102, 109 qualitative analysis, 98-102 second-order, 99, 183, 298 solutions, 95, 96, 133, 137, 145, 263 stability, see stability transfer functions for, 236 differential flatness, 221 digital control systems, see computer implementation, controllers digital-to-analog converters, 4, 82, 224, 225, 311 dimension-free variables, 48, 61 direct term, 34, 38, 147, 211,

250 discrete control, 56 discrete-time systems, 38, 61, 128, 157, 165, 311 Kalman filter for, 215 linear quadratic regulator for, 192 disk drives, 64 disturbance attenuation, 4, 176, 323-324, 358-359 design of controllers for, 319, 320, 327, 337, 345, 369 fundamental limits, 336 in biological systems, 257, 297 integral gain as a measure of, 296, 324, 359 relationship to sensitivity function, 323, 335, 345, 358 disturbance weighting, 372 disturbances, 4, 29, 32, 244, 248, 315, 318, 319 generalized, 371 random, 215 Dodson, B., 1 dominant eigenvalues (poles), 187, 300, 301 double integrator, 137, 168, 236 Doyle, J. C., xii, 344, 374 drug administration, 85-89, 94, 151, 186, see also compartment models duality, 207, 211 Dubins car, 53 dynamic compensator, 196, 213 dynamic inversion, 163 dynamical systems, 1, 27, 95, 98, 126 linear, 104, 131 observer as a, 201 state of, 175 stochastic, 215 uncertainty in, 347-349 see also differential equations dynamics matrix, 34, 38, 105, 142 Dyson, F., 27

e-commerce, 13 e-mail server, control of, 39, 157 economic systems, 14-15, 22, 62 ecosystems, 16-17, 89, 181, see also predator-prey system eigenvalue assignment, 176, 178, 180-182, 188, 212, 300, 313 by output feedback, 213 for observer design, 208 eigenvalues, 105, 114, 123, 142, 232 and Jordan form, 139-141, 165 distinct, 128, 129, 138, 144, 222 dominant, 187 effect on dynamic behavior, 183, 185-187, 233 for discrete-time systems, 165 invariance under coordinate transformation, 106 relationship to modes, 142-145 relationship to poles, 239 relationship to stability, 117, 140, 141 eigenvectors, 106, 129, 142, 143 relationship to mode shape, 143 electric power, see power systems (electric) electrical circuits, 33, 45, 74, 131, 236, see also operational amplifier electrical engineering, 6-7, 29-31, 155, 275 elephant, modeling of an, 27 Elowitz, M. B., 59 encirclement, 271, see also Nyquist criterion entertainment robots, 12 environmental science, 3, 9, 17 equilibrium points, 90, 100, 105, 132, 159, 168 bifurcations of, 121 discrete time, 62

for closed loop system, 176, 195 for planar systems, 104 region of attraction, 119-121, 128 stability, 102 error feedback, 5, 293, 294, 309, 317 estimators, see oservers387 Euler integration, 41, 42 exponential signals, 230-235, 239, 250 extended Kalman filter, 220 F/A-18 aircraft, 8 Falb, P. L., 167 feedback, 1-3 as technology enabler, 3, 19 drawbacks of, 3, 21, 308, 352, 359 in biological systems, 1-3, 16, 25, 297, see also biological circuits in engineered systems, see control in financial systems, 3 in nature, 3, 15-17, 89 positive, see positive feedback properties, 3, 5, 17-23, 315, 320, 347 robustness through, 17 versus feedforward, 22, 296, 320 feedback connection, 243, 287, 288 feedback controller, 244, 315 feedback linearization, 161-163 feedback loop, 4, 267, 315, 358 feedback uncertainty, 349, 356 feedforward, 22, 219-222, 244, 315, 319, 321 Fermi, E., 27 filters active, 154 for disturbance weighting, 373 for measurement signals, 21, 225, 359

see also band-pass filters; high-filters; low-pass filters financial systems, see economic systems finite escape time, 97 finite state machine, 69, 76 first-order systems, 134, 165, 236, 252, 253 fisheries management, 94 flatness, see differential flatness flight control, 8, 18, 19, 53, 163 airspace management, 9 F/A-18 aircraft, 8 X-29 aircraft, 337 X-45 aircraft, 8 see also vectored thrust aircraft flow, of a vector field, 29, 99 flow in a tank, 126 flow model (queuing systems), 54, 292, 313 flyball governor, see centrifugal governor force feedback, 10, 11 forced response, 133, 231 Forrester, J. W., 15 Fourier, J. B. J., 61, 262 frequency domain, 229-231, 267, 285, 315 frequency response, 30, 43, 44, 152-157, 230, 290, 303, 322 relationship to Bode plot, 250 relationship to Nyquist plot, 270, 272 second-order systems, 185, 256 system identification using, 257 fully actuated systems, 240 fundamental limits, see control: fundamental limitations Furuta pendulum, 130 gain, 24, 43, 73, 153, 154, 186, 230, 234, 239, 250, 278, 285-288, 347

390

 H_{∞} , 286, 287, 371 observer, see observer gain of a system, 285 reference, 195 state feedback, 176, 177, 180, 195, 197 zero frequency, see zero frequency gain see also integral gain gain crossover frequency, 279, 280, 322, 326, 332, 351, 365 gain crossover frequency inequality, 332, 334 gain curve (Bode plot), 250-254, 282, 326 gain margin, 278-281 from Bode plot, 279 reasonable values, 281 gain scheduling, 220, 373 gain-bandwidth product, 74, 237, 361 Gang of Four, 317, 344, 358 Gang of Six, 317, 322 gene regulation, 16, 58, 59, 166, 256 genetic switch, 64, 114, 115 global behavior, 103, 120-124 Glover, K., 344, 374 glucose regulation, see insulin-glucose dynamics Golomb, S., 65 governor, see centrifugal governor *H*_∞ control, 371–374, 376 Harrier AV-8B aircraft, 53 heat propagation, 238 Heaviside, O., 163 Heaviside step function, 150, 163 Hellerstein, J. L., 13, 25, 81 high-frequency roll-off, 327, 359, 366 high-pass filter, 255, 256 Hill function, 58 Hoagland, M. B., 1 Hodgkin-Huxley equations, 60 homeostasis, 3, 58 homogeneous solution, 133,

136, 137, 239

Honeywell thermostat, 6

Horowitz, I. M., 226, 343, 369, 374 human-machine interface, 65, 69 hysteresis, 23, 24, 289

identification, see system identification impedance, 236, 309 implementation, controllers, see analog implementation; computer implementation impulse function, 146, 164, 169 impulse response, 135, 146, 147, 261 inductor, transfer function for, 236 inertia matrix, 36, 163 infinity norm, 286, 372 information systems, 12, 54-58, see also congestion control; web server control initial condition, 96, 99, 102, 132, 137, 144, 215 initial condition response, 133, 136-139, 142, 144, 147, 231 initial value problem, 96 inner loop control, 341, 343 input sensitivity function, see load sensitivity function input/output models, 5, 29, 31, 132, 145-158, 229, 286, see also frequency response; steady-state response; step response and transfer functions, 261 and uncertainty, 51, 349 from experiments, 257 relationship to state space models, 32, 95, 146 steady-state response, 149 transfer function for, 235 inputs, 29, 32 insect flight control, 46-47 instrumentation, 10-11, 71 insulin-glucose dynamics, 2, 88-89

integral action, 24-26, 195-198, 293, 295-296, 298, 324 for bias compensation, 227 setpoint weighting, 309, 312 time constant, 294 integral gain, 24, 294, 296, 299 integrator windup, 225, 306-307, 314 conditional integration, 314 intelligent machines, see robotics internal model principle, 214, 221 Internet, 12, 13, 75, 77, 80, 93, see also congestion control Internet Protocol (IP), 77 invariant set, 118, 121 inverse model, 162, 219, 320 inverse response, 284, 292 inverted pendulum, 37, 69, 100, 108, 118, 121, 128, 130, 276, 337, see also balance systems Jacobian linearization, 159-161 Jordan form, 139-142, 165, 188 Kalman, R. E., 167, 197, 201, 223, 226 Kalman decomposition, 222-224, 235, 262, 264 Kalman filter, 215-218, 226, 370 extended, 220 Kalman-Bucy filter, 217 Kelly, F. P., 80 Kepler, J., 28 Keynes, J. M., 14 Keynesian economic model, 62, 166 Krasovski-Lasalle principle, 118 LabVIEW, 123, 164 lag, see phase lag lag compensation, 327, 328 Laplace transforms, xi, 259-262

Laplacian matrix, 58 Lasalle's invariance principle, see Krasovski-Lasalle principle lead, see phase lead lead compensation, 328-331, 341, 346 limit cycle, 91, 101, 109, 111, 122, 288, 289 linear quadratic control, 190-194, 216, 226, 369-371 linear systems, 30, 34, 74, 104, 131-164, 222, 231, 235, 262, 286 linear time-invariant systems, 30, 34, 134, 261 linearity, 133, 250 linearization, 109, 117, 132, 158-163, 220, 347 Lipschitz continuity, 98 load disturbances, 315, 359, see also disturbances load sensitivity function, 317 local behavior, 103, 109, 118, 120, 159 locally asymptotically stable, 103 logistic growth model, 89, 90, 94 loop analysis, 267, 315 loop shaping, 270, 326-331, 343, 369 design rules, 327 fundamental limitations, 331-340 see also Bode's loop transfer function loop transfer function, 267-270, 278-280, 287, 315, 318, 326, 327, 329, 336, 344, see also Bode's loop transfer function Lotus Notes server, see e-mail server low-order models, 298 low-pass filter, 255, 256, 308 LQ control, see linear quadratic control LTI systems, see linear time-invariant systems Lyapunov equation, 114, 128

118, 124 existence of, 113 Lyapunov stability analysis, 43, 110-120, 126 discrete time, 128 manifold, 120 margins, see stability margins Mars Exploratory Rovers, 11, 12 mass spectrometer, 10 materials science, 9 Mathematica, 41, 123, 164 MATLAB, 26, 41, 123, 164, 200 acker, 181, 211 dlge, 216 dlqr, 194 hinfsyn, 372 jordan, 139 linmod, 160 lqr, 191 place, 181, 189, 211 trim, 160 matrix exponential, 136-139, 143, 145, 163, 164 coordinate transformations. 148 Jordan form, 140 second-order systems, 138, 164 maximum complementary sensitivity, 354, 365 maximum sensitivity, 323, 352, 366 measured signals, 31, 32, 34, 95, 201, 213, 225, 316, 318, 371 measurement noise, 4, 21, 201, 203, 215, 217, 244, 308, 315-317, 327, 359 response to, 324-326, 359 mechanical systems, 31, 36, 42, 51, 61, 163 mechanics, 28-29, 31, 126, 131 minimal model (insulin-glucose), 88, 89,

Lyapunov functions, 111-114,

design of controllers using,

120, 127, 164

see also insulin-glucose dynamics minimum phase, 283, 290, 331 modal form, 130, 145, 149 Modelica, 33 modeling, 5, 27-33, 61, 65 control perspective, 31 discrete control, 56 discrete-time, 37-38, 157-158 frequency domain, 229-231 from experiments, 47-48 model reduction, 5 normalization and scaling, 48 of uncertainty, 50-51 simplified models, use of, 32, 298, 348, 354, 355 software for, 33, 160, 163 state space, 34-43 uncertainty, see uncertainty modes, 142-144, 239 relationship to poles, 240 motion control systems, 51-54, 226 motors, electric, 64, 199, 228 multi-input, multi-output systems, 286, 318, 327, see also input/output models multiplicative uncertainty, 349, 356 nanopositioner (AFM), 281, 366 natural frequency, 184, 300 negative definite function, 111 negative feedback, 18, 22, 73, 176, 267, 297 Nernst's law, 60 networking, 12, 45, 80, see also congestion control neural systems, 10, 47, 60, 297 neutral stability, 102-104 Newton, I., 28 Nichols, N. B., 163, 302, 343 Nichols chart, 369, 370 Nobel Prize, 10, 11, 14, 61, 81 noise, see disturbances; measurement noise noise attenuation, 257, 324-326

INDEX

noise cancellation, 124 noise sensitivity function, 317 nonlinear systems, 31, 95, 98, 101, 108, 110, 114, 120-125, 202, 220, 286-288 linear approximation, 109, 117, 159, 165, 347 system identification, 62 nonminimum phase, 283, 284, 292, 331-333, see also inverse response nonunique solutions (ODEs), 97 normalized coordinates, 48-50, 63, 161 norms, 285-286 Nyquist, H., 267, 290 Nyquist criterion, 271, 273, 275, 278, 287, 288, 303 for robust stability, 352, 376 Nyquist D contour, 270, 276 Nyquist plot, 270-271, 278, 279, 303, 324, 370 observability, 32, 201-202, 222, 226 rank condition. 203 tests for, 202-203 unobservable systems, 204, 222-223, 265 observability matrix, 203, 205 observable canonical form, 204, 205, 226 observer gain, 207, 209-211, 213, 215-217 observers, 201, 206-209, 217, 220 block diagram, 202, 210 see also Kalman filter ODEs, see differential equations Ohm's law, 60, 73, 236 on-off control, 23, 24 open loop, 1, 2, 73, 168, 245, 267, 306, 315, 323, 349 open loop gain, 237, 278, 322 operational amplifiers, 71-75, 237, 309, 356 circuits, 92, 154, 268, 360 dynamic model, 74, 237

input/output characteristics, 72 oscillator using, 92, 128 static model, 72, 237 optimal control, 190, 215, 217, 370 order, of a system, 34, 235 ordinary differential equations, see differential equations oscillator dynamics, 92, 96, 97, 138, 184, 233, 236 normal form, 63 see also nanopositioner (AFM); spring-mass system outer loop control, 341-343 output feedback, 211, 212, 226, see also control: using estimated state; loop shaping; PID control output sensitivity function, see noise sensitivity function outputs, see measured signals overdamped oscillator, 184 overshoot, 151, 176, 185, 322 Padé approximation, 292, 333 paging control (computing), 56 parallel connection, 243 parametric stability diagram, 122, 123 parametric uncertainty, 50, 347 particle accelerator, 11 particular solution, 133, 152, see also forced response passive systems, 287, 336 passivity theorem, 288 patch clamp, 10 PD control, 296, 328 peak frequency, 156, 322 pendulum dynamics, 113, see also inverted pendulum perfect adaptation, 297 performance, 76 performance limitations, 331, 336, 365, 373 due to right half-plane poles and zeros, 283 see also control: fundamental limitations performance specifications, 151, 175, 315, 322-327,

358, see also overshoot; maximum sensitivity; resonant peak; rise time; settling time periodic solutions, see differential equations; limit cycles persistence, of a web connection, 76, 77 Petri net, 45 pharmacokinetics, 85, 89, see also drug administration phase, 43, 153, 154, 186, 230, 234, 250, 288, see also minimum phase; nonminimum phase minimum vs. nonminimum, 283 phase crossover frequency, 279, 280 phase curve (Bode plot), 250-252, 254 relationship to gain curve, 282.327 phase lag, 153, 154, 256, 283, 332, 333 phase lead, 153, 256, 330, 346 phase margin, 279, 280, 327, 329, 332, 346, 375 from Bode plot, 279 reasonable values, 281 phase portrait, 28, 29, 98-100, 120 Philbrick, G. A., 75 photoreceptors, 297 physics, relationship to control, 5 PI control, 17, 25, 65, 68, 296, 301, 328 first-order system, 300, 364 PID control, 24-25, 235, 293-313, 330 block diagram, 294, 296, 308 computer implementation, 311 ideal form, 293, 313 implementation, 296, 308-312 in biological systems, 297 op amp implementation, 309-311

tuning, 302-306 see also derivative action; integral action pitchfork bifurcation, 130 planar dynamical systems, 99, 104, see also second-order systems pole placement, 176, 361, 365-366, see also eigenvalue assignment robust, 361 pole zero diagram, 240 pole/zero cancellations, 247-249, 265, 365, 366 poles, 239, 240 dominant, 301, see also dominant eigenvalues (poles) fast stable, 364, 366 pure imaginary, 270, 276 relationship to eigenvalues, 239 right half-plane, 240, 276, 283, 331, 333-334, 336, 346, 366 population dynamics, 89-91, 94, see also predator-prey system positive definite function, 111, 112, 114, 118 positive definite matrix, 114, 191 positive feedback, 16, 21-23, 129.296 positive real (transfer function), 336 power of a matrix, 136 power systems (electric), 6-7, 63, 101, 127 predator-prey system, 38, 90-91, 121, 181 prediction, in controllers, 24, 25, 220, 296, 375, see also derivative action prediction time, 297 principle of the argument, see variation of the argument, principle of process control, 9, 10, 13, 45 proportional control, 24, 293, see also PID control

proportional, integral,

control protocol, see congestion control; consensus pulse signal, 146, 147, 187, see also impulse function pupil response, 258, 297 pure exponential response, 232 O-value, 63, 186, 254 quantitative feedback theory (QFT), 369 quarter car model, 265 queuing systems, 54-56, 63 random process, 54, 215, 228 reachability, 32, 167-175, 197, 222 rank condition, 170 tests for, 169 unreachable systems, 171, 199, 222-223, 265 reachability matrix, 169, 173 reachable canonical form, 35, 172-175, 178, 180, 198 reachable set, 167 real-time systems, 5 reference signal, 23, 175, 176, 229, 244, 293, 309, 317, 319, see also command signals; setpoint effect on observer error, 212, 219, 224 response to, 322, 345 tracking, 175, 219, 220, 327, 360 reference weighting, see setpoint weighting region of attraction, see equilibrium points: regions of attraction regulator, see control law relay feedback, 289, 305 Reno (protocol), see Internet; congestion control repressilator, 59-60 repressor, 16, 59, 64, 114, 166, 257 reset, in PID control, 295, 296 resonant frequency, 186, 286 resonant peak, 156, 186, 322, 355

derivative control, see PID

resource usage, in computing systems, 13, 55, 57, 75, 76 response, see input/output models retina, 297, see also pupil response Riccati equation, 191, 217, 372, 374 Riemann sphere, 351 right half-plane poles and zeros, see poles: right half-plane; zeros: right half-plane rise time, 151, 176, 185, 322 robotics, 8, 11-12, 163 robustness, 17-18, 322, 349, 374 performance, 358-361, 369-374 stability, 352-358 using gain and phase margin, 281, 326 using maximum sensitivity, 323, 326, 353, 375, 376 using pole placement, 361-368 via gain and phase margin, 280 see also uncertainty roll-off, see high-frequency roll-off root locus diagram, 123 Routh-Hurwitz criterion, 130 rush-hour effect, 55, 64 saddle (equilibrium point), 104 sampling, 157, 224, 225, 311 saturation function, 45, 72, 311, see also actuators:

sampling, 157, 224, 225, 311 saturation function, 45, 72, 311, *see also* actuators: saturation scaling, *see* normalized coordinates scanning tunneling microscope, 11, 81 schematic diagrams, 44, 45, 71 Schitter, G., 84 second-order systems, 28, 164, 183–187, 200, 253, 301

Segway Personal Transporter, 35, 170 self-activation, 129 self-repression, 166, 256

INDEX

394

semidefinite function, 111 sensitivity crossover frequency, 324 sensitivity function, 317, 324-326, 336, 352, 360, 366 and disturbance attenuation, 323, 336, 345 sensor matrix, 34, 38 sensor networks, 57 sensors, 3, 4, 9, 202, 224, 283, 311, 315, 318, 333, 334, 371 effect on zeros, 284, 334 in computing systems, 75 see also measured signals separation principle, 201, 213 series connection, 243 service rate (queuing systems), 55 setpoint, 293 setpoint weighting, 309, 312 settling time, 151, 165, 176, 185.322 similarity of two systems, 349-352 simulation, 40-42, 51 SIMULINK, 160 single-input, single-output (SISO) systems, 95, 132, 133, 159, 204, 286 singular values, 286, 287, 376 sink (equilibrium point), 104 small gain theorem, 287-288, 355 Smith predictor, 375 software tools for control, x solution (ODE), see differential equations: solutions Sony AIBO, 12 source (equilibrium point), 104 spectrum analyzer, 257 Sperry autopilot, 19 spring-mass system, 28, 40, 42, 43, 82, 127 coupled, 144, 148 generalized, 36, 71 identification, 47 normalization, 49, 63 see also oscillator dynamics

stability, 3, 5, 18, 19, 42, 98, 102-120 asymptotic stability, 102, 106 conditional, 275 in the sense of Lyapunov, 102 local versus global, 103, 110, 120, 121 Lyapunov analysis, see Lyapunov stability analysis neutrally stable, 102, 104 of a system, 105 of equilibrium points, 42, 102, 104, 111, 117 of feedback loop, see Nyquist criterion of limit cycles, 109 of linear systems, 104-107, 113, 140 of solutions, 102, 110 of transfer functions, 240 robust, see robust stability unstable solutions, 103 using eigenvalues, 117, 140, 141 using linear approximation, 107, 117, 160 using Routh-Hurwitz criterion, 130 using state feedback, 175-194 see also bifurcations; equilibrium points stability diagram, see parametric stability diagram stability margin (quantity), 279, 281, 323, 346, 353, 372 reasonable values, 281 stability margins (concept), 278-282, 291, 326 stable pole, 240 stable zero, 240 Stark, L., 258 state, of a dynamical system, 28, 31, 34 state estimators, see observers state feedback, 167-197, 207, 212, 219-221, 224-226,

362, 370, see also eigenvalue assignment; linear quadratic control state space, 28, 34-43, 175 state vector, 34 steady-state gain, see zero frequency gain steady-state response, 26, 42, 149-157, 165, 176, 185, 230, 231, 233, 257, 262 steam engines, 2, 17 steering, see vehicle steering Stein, G., xii, 1, 315, 337 step input, 30, 135, 150, 239, 302 step response, 30, 31, 47, 48, 135, 147, 150, 151, 176, 184, 185, 302 stochastic cooling, 11 stochastic systems, 215, 217 summing junction, 45 superposition, 30, 133, 147, 164, 230 supervisory control, see decision making: higher levels of supply chains, 15 supremum (sup), 286 switching behavior, 22, 64, 117, 373 system identification, 47, 62, 257 tapping mode, see atomic force microscope TCP/IP, see Internet; congestion control Teorell, T., 85, 89 thermostat, 5, 6 three-term controllers, 293, see also PID control thrust vectored aircraft, see vectored thrust aircraft time constant, first-order

three-term controllers, 293, st also PID control thrust vectored aircraft, see vectored thrust aircraft time constant, first-order system, 165 time delay, 5, 13, 235, 236, 281, 283, 302, 311, 332–334 compensation for, 375 Padé approximation, 292, 332 time plot, 28

time-invariant systems, 30, 34, 126, 134–135 tracking, see reference signal: tracking trail (bicycle dynamics), 70 transcriptional regulation, see gene regulation transfer functions, 229-262 by inspection, 235 derivation using exponential signals, 231 derivation using Laplace transforms, 261 for control systems, 244, 264 for electrical circuits, 236 for time delay, 235 frequency response, 230, 250 from experiments, 257 irrational, 236, 239 linear input/output systems, 231, 235, 264 transient response, 42, 150, 151, 153, 168, 188, 231, 232 Transmission Control Protocol (TCP), 77 transportation systems, 8 Tsien, H. S., 11 tuning rules, 314, see Ziegler-Nichols tuning two degree-of-freedom control, 219, 294, 319, 321, 343, 345 uncertainty, 4, 17-18, 32, 50-51, 195, 347-352

component or parameter variation, 4, 50, 347 disturbances and noise, 4, 32, 175, 244, 315

unmodeled dynamics, 4, 50, 348.353 see also additive uncertainty; feedback uncertainty; multiplicative uncertainty uncertainty band, 50 uncertainty lemon, 50, 51, 68, 74,84 underdamped oscillator, 97, 184, 185 unit step, 150 unmodeled dynamics, see uncertainty: unmodeled dynamics unstable pole, see poles: right half-plane unstable pole/zero cancellation, 248 unstable solution, for a dynamical system, 103, 104, 106, 141, 240 unstable zero, see zeros: right half-plane

variation of the argument, principle of, 277, 290 vector field, 29, 99 vectored thrust aircraft, 53-54, 141, 191, 217, 264, 329, 340 vehicle steering, 51-53, 160, 177, 209, 214, 221, 245, 284, 291, 321, 362 ship dynamics, 51 vehicle suspension, 265, see also coupled spring-mass system vertical takeoff and landing, see vectored thrust aircraft vibration absorber, 266 Vinnicombe, G., 344, 351, 374

Vinnicombe metric, 349-352, 372 voltage clamp, 10, 11, 61 waterbed effect, 336, 337 Watt governor, see centrifugal governor Watt steam engine, 3, 17 web server control, 75-77, 192 web site, companion, x Whipple, F. J. W., 71 Wiener, N., 11, 12 winding number, 277 window size (TCP), 78, 80, 104 windup, see integrator windup Wright, W., 18 Wright Flyer, 8, 19

X-29 aircraft, 337 X-45 aircraft, 8

Youla parameterization, 356–358

zero frequency gain, 155, 177, 180, 186, 239 zeros, 239 Bode plot for, 264 effect of sensors and actuators on, 284, 334 for a state space system, 240 right half-plane, 240, 283, 331-334, 337, 346, 365 signal-blocking property, 239 slow stable, 362, 363, 365 Ziegler, J. G., 302, 312 Ziegler-Nichols tuning, 302-305.312 frequency response, 303 improved method, 303 step response, 302

396