

# Index

---

---

- Actuator command, 122-124
  - command error, 123, 132
- Actuator
  - dynamics, 120, 128
  - noise, 119-120, 128, 135
  - See also Motor
- Adaptation, 89
- Adaptive control, 113, 136
  - adaptive feedforward, 120
  - adaptive feedback, 120
- Adaptive observer, 155
- Adaptive processes, 113
- AdeptOne, 38-39
- Aluminum surface, 145, 160
  - force step response on, 160
  - stiffness estimation of, 145
- Amplifier, 10, 33, 44, 157, 110, 161, 197
  - bandwidth, 44, 157
  - commutation, 10, 44, 110, 159, 197
  - deadzone, 44, 99, 159, 161, 189
  - nonlinearity, 110, 197
  - PWM, 44
  - slew rate, 33
- Analog servo, 46, 101, 104, 111
- Angular velocity vector, 13, 56, 69
- Backlash, 10, 33, 34, 37, 41, 51, 94, 140
- Bandwidth, 33, 34, 44, 128, 156, 161, 166, 189
- Bias errors, 81, 145, 151, 161, 189
- Calibration (kinematic)
  - cube, 52
  - frame, 51, 61
- Cartesian-based force control
  - hybrid position/force, 25, 28, 168, 171, 176, 191
  - hybrid position/force feedforward, 8
  - impedance, 140, 141, 170
  - operational space, 168, 208
  - PD, 7
  - resolved acceleration, 28, 168, 181, 185, 193, 208
  - stiffness, 25, 140, 141, 168, 174, 184, 193
- Cartesian-based position control
  - feedforward controller, 25
  - resolved acceleration, 26, 168
  - PD, 25
- Center of mass (gravity), 13, 65, 69, 71-72, 75-77, 79, 84
- Centripetal torques, 22
- Closed form dynamics, 93, 204
- CMU Direct Drive Arm II, 39, 89
- Cogging, 10, 44, 159, 161
- Command disturbance, 123

- Command following, 161
- Commutation, 10, 44, 110, 159, 197
- Compliance, 81
- Compliant coverings, 148
- Computed torque control, 16, 19, 87, 101, 103, 107
- Continuous time, 124
- Control, 4
- Control algorithms: see
  - Cartesian-based force control
  - Cartesian-based position control
  - Joint-based force control
  - Joint-based position control
- Convergence, 130, 136
  - rate, 118-119
- Convolution, 131
- Coordinate frames, 52-54, 67, 90
- Coriolis torques, 22, 87
- Counter-balancing, 89
- Currents, 94
  
- Damping, 128, 131
- DDArm: see MIT Serial Link
  - Direct Drive Arm
- Deadzone, 44, 99, 159, 161, 189
- Delay, 17, 131, 132
- Denavit-Hartenberg parameters, 11, 41, 52, 61
- Differential kinematics, 11, 55
- Differentiating filter, 73, 127
- Digital servo, 46, 102
- Direct drive arm, 2, 49-64, 122
  - AdeptOne, 38-39
  - CMU Direct Drive Arm II, 39, 89
  - five-bar-linkage design, 38
  - MIT Serial Link Direct Drive Arm (DDArm), 2, 38, 44-50, 119, 124, 136
  - YEWBOT, 38, 40
- Direct-drive motor, 10, 37-38, 43-44, 99, 197-198
- ISI, 38, 43-44, 99, 110, 157, 196
- variable reluctance, 37-38, 40, 197
- Direct dynamics, 7, 122
- Direct kinematics, 5, 11, 54, 115
- Direct linear transformation (DLT), 52
- Discrete time, 124, 131
- Discretization, 135
- Disturbance, 119-120, 123, 127-128, 135-136
  - rejection, 161
- Dominant pole, 157-159, 188
- Dynamic estimation, 76, 79
- Dynamic instability, 23, 139-166
- Dynamic model, 19-21, 29, 114
- Dynamics
  - closed form, 93, 204
  - direct, 7, 122
  - inverse, 8, 15, 18, 22, 27, 102, 123, 176
  - Lagrangian, 88
  - linearized, 176
  - Newton-Euler, 13, 67-71, 90-92
  - See also Inertial parameters
- Eccentric cam, 165, 188-189
- Eigen-structure assignment, 139
- Eigenvalue problem, 59
- Eigenvalues, 118, 132, 133, 175
- Ellipsoid of inertia, 59
- Endpoint variation, 56
- Environment, 139, 142
  - environment stiffness, 148
- Feedback control: see control algorithms

- Feedforward command, 118-119, 122, 127, 130
  - error, 123, 130-135
  - initialization, 120, 122, 124, 128
  - memory, 122
  - modification, 123
  - update, 124
  - torques, 124
- Feedforward control, 7, 18
- Feedforward controller, 16, 18, 102, 104, 106
- Filter, 120, 136
  - differentiating, 73, 127
  - low-pass, 127, 157-160, 166
- Fingers, 148
- Finite learning interval
  - convergence test, 133
- Finite time convergence, 135
- Five-bar-linkage design, 38
- Fixed point theory, 117, 130
- Flexible link dynamics, 120
- Flexible modes, 144
- Force control, 22-30, 139-166, 167-194
- Force control algorithms: see
  - Cartesian-based force control
  - Dynamic instability
  - Joint-based force control
  - Kinematic instability
- Force resolution, 156
- Force step response, 160
- Force/torque sensor, 9, 14, 15, 43, 44, 65, 70, 73, 79, 89, 145, 156, 188
- Force vector, 6, 13, 25, 69, 71, 91, 168
- Forward kinematics: see Direct kinematics
- Friction, 10, 33, 34, 37, 41, 89, 94, 101, 102, 107, 110, 111, 140, 156, 180, 181
- Gain, 135
- Gears, 10, 33-35, 37, 38, 40, 43, 50, 103, 110, 156, 197
  - backlash, 10, 33, 34, 37, 41, 51, 94, 140
  - flexibility, 10, 33
- Global stability, 175
- Gravity
  - torques, 22, 75, 84, 104
  - vector, 69
- Hayati parameters, 53
- Height gauge, 63
- High gain feedback, 143, 144
- Hybrid analog/digital controller, 101, 104, 111
- Hybrid control, 170
  - See Hybrid position/force control
- Hybrid position/force feedforward controller, 8
- Hybrid position/force control, 25, 28, 168, 171, 176, 191
- Impedance control, 140, 141, 170
- Impulse response, 131-133
- Independent joint PD control, 128
  - See also PD control
- Inertia matrix, 22, 87, 128, 176, 181, 193
- Inertial parameters, 65, 87
  - CAD-modelled, 42, 94, 97-99
  - center of mass (gravity), 13, 65, 69, 71-72, 75-77, 79, 84
  - link estimation, 14-16, 87-100
  - load estimation, 12-14, 65-85
  - mass, 13, 65, 69
  - mass moment, 13, 71

- moments of inertia, 13, 65, 69-70, 84-85
  - principal axes, 69, 72
  - principal moments, 72
  - unidentifiability of, 89, 93, 97
- Infrared light-emitting diodes, 51
- Instability (in force control)
  - dynamic instability, 139-166
  - kinematic instability, 167-194
- Integral load estimation equations, 201
- Internal model, 113
- Inverse dynamics, 8, 15, 18, 22, 27, 102, 123, 176
- Inverse kinematics, 6, 115-116
- Inverse model, 113-119, 131-136
- Iterative learning, 114
- Iterative least squares (kinematics), 64
  
- Jacobian, 168
  - inverse, 6, 25, 118, 170, 175, 193
  - matrix, 6, 11, 25, 55-56, 118
  - transpose, 6, 28-29, 170, 175, 193
- Joint-based force control
  - PD, 7
  - Stiffness, 168
- Joint-based position control
  - computed torque controller, 16, 19, 87, 101, 103, 107
  - feedforward controller, 16, 18, 102, 104, 106
  - PD, 16, 102, 104, 106
- Joint compliance dynamics, 120
- Joint coordinates, 5
- Joint torque, 6, 92, 94, 97
  - control, 34, 37, 44, 111, 156, 188, 197
  - sensing, 34, 67, 88-89, 110, 156, 159
- Kinematic calibration
  - parametric, 11, 49, 87
  - nonparametric, 116
- Kinematic instability, 23, 167-195
- Kinematic learning, 114-115
  - convergence, 117
- Kinematic parameters: see Denavit-Hartenberg parameters
- Kinematic transformation, 167, 170
- Kinematics
  - direct, 5, 11, 54, 115
  - inverse, 6, 115
  - linearized, 11, 55, 117, 119
  - redundancy, 6, 115
  - singularity, 6, 115
- Lagrangian dynamics, 88
- Laplace transform, 122-123
  - error, 124
- Laser tracking system, 50
- Lateral-effect photodiodes, 52
- Learning algorithm, 114, 127-129
  - convergence, 118, 135
  - derivation, 136
  - failure, 135
  - performance, 135-136
- Learning efficiency, 113
- Learning from practice, 136
- Learning interval, 131-135
- Learning of non-repetitive tasks, 136
- Learning operator, 113, 117-119, 127-136
  - bandwidth, 135
  - convergence, 119
  - efficacy, 135

- impulse response, 131, 133
- Learning performance, 129, 136
- Least squares, 65, 72-73, 92, 150-151
- Levenberg-Marquardt algorithm, 62, 64
- Linear learning operator, 119
- Linearized dynamics, 176
- Linearized kinematics, 11, 55, 117, 119
- Link estimation, 14-16, 87-100
  - by adaptation, 89
  - unidentifiability, 89, 93, 97
- Load estimation, 12-14, 65-86
  - dynamic estimation, 76, 79
  - orientation, 69, 84
  - static identification, 75, 76
- Local stability, 175-176
- Loop gain, 156
- Low-pass filter, 127, 157-160, 166
- MACSYMA, 93
- Mass, 13, 65, 69
- Mass moment, 13, 71
- Measurement noise, 128, 135
- Memory, 118
- Minimum phase, 131
- MIT Serial Link Direct Drive Arm (DDArm), 2, 38, 44-50, 119, 124, 136
- Model
  - accuracy, 118
  - approximate, 124
  - bad, 124
  - errors, 87, 114, 116, 120, 123, 129, 136, 143, 206
  - imperfect, 116
  - perfect, 114, 119, 124
  - usefulness, 1, 110, 136, 193, 195
- Model (parametric)
  - kinematic parameters, 11, 49-64, 115
  - link inertial parameters, 14, 87-100
  - load inertial parameters, 12, 65-85
  - motor, 10, 44
- Model-based (trajectory) learning, 113-138
  - command refinement, 136
- Moments of inertia, 13, 65, 69-70, 84-85
- Motion tracking systems, 49-51
  - Laser tracking system, 50
  - Selspot system, 50
  - Watsmart system, 12, 51, 64
- Motor, 10-11, 31-48
  - cogging, 10, 44, 159, 161
  - currents, 156
  - model, 10, 44
  - torque, 33, 37, 44, 110, 197
  - See also Direct drive motor
- Newton-Euler equations, 13, 69, 88, 89
  - for load, 13, 67
  - for links, 90
- Noise, 71, 75, 81, 119-120, 123, 127
- Nonlinearity cancellation, 19
- Nonlinear convergence criteria, 129
- Nyquist criterion, 206
- Open-loop force control, 156
- Operational space control, 168, 208
- Optimal filter, 83
- Optimization, 113
- Orientation, 69, 84
- Parallel axis theorem, 70, 72
- Parameter estimation, 9

- PD control: see
  - Cartesian-based force control
  - Cartesian-based position control
  - Joint-based force control
  - Joint-based position control
- Performance measures, 161
- Persistently exciting trajectories, 100
- Perturbation, 117
- PID control, 101
- Planning, 4
- Plant dynamics, 120
- Polar manipulator, 173, 180
- Position control: see
  - Cartesian-based position control
  - Joint-based position control
- Position sensors, 127
  - See also Resolver
- Positive feedback, 173
- Practice, 113-127, 135
- Precision points, 49
- Principal axes, 69, 72
- Principal moments, 72
- PUMA, 73, 76, 83, 89, 128
- Recognition, 66
- Region of instability, 180
- Resolved acceleration
  - position control, 26, 168
  - force control, 28, 168, 181, 185, 193, 208
- Resolver, 43, 94, 110, 155, 197
- Resonant frequency, 157
- Ridge regression, 93, 95, 98
- Rigid body dynamics: see
  - Dynamics
- Robot hand, 66
- Robot model: see Model
- Root locus, 177
- Rotary manipulator, 171, 176
- Rotor inertia, 33-35, 37, 44, 89, 157
- Rubber surface, 145
  - stiffness estimation of, 145
- RMS error, 62
- Sampling frequency, 73, 79, 107-111, 131, 135, 151, 189
- Screw coordinates, 55
- Selection matrix, 28, 168, 172, 189
- Selspot system, 50
- Sensor noise, 119-120, 127, 135
- Sensor stiffness, 148
- Sensors
  - force/torque, 9, 14, 15, 43, 44, 65, 70, 73, 79, 89, 145, 156, 188
  - resolver, 43, 94, 110, 155, 197
  - tachometer, 41, 79, 94, 110
  - Watsmart system, 12, 51, 64
- Servo: see
  - Analog servo
  - Digital servo
- Signal to noise ratio, 76
- Similarity transform, 182
- Simplified models, 114, 127, 128
- Singular value decomposition, 93, 98
- Singularity, 6, 115, 173
- Sinusoidal trajectory, 161, 189
- Special test movements, 67, 77, 79, 88
- Stability, 119
- Stanford Arm, 181
- Static identification, 75, 76
- Statics, 6
- Steady state accuracy, 159, 161
- Step response, 160, 189
- Stereo camera system, 49

- Stiffness control, 25, 140, 141, 168, 174, 184, 193
- Stiffness matrix, 168, 174
- Straight line estimation, 57
- Strain gauges, 156
- System identification, 9, 113
  
- Tachometer, 41, 79, 94, 110
- Tactile sensors, 148
- Task coordinates, 4
- Theodolites, 49
- Toeplitz matrix, 132-133
- Torque: see
  - Joint torque
  - Motor torque
- Torque vector, 13, 69, 75, 91
- Trajectory
  - fifth order polynomial, 74, 83, 94, 105, 124
  - persistently exciting, 100
  - seventh order polynomial, 128
  - sinusoidal, 161, 189
  - special test, 67, 77, 79, 88
- Trajectory learning, 20, 113-138
  - algorithm, 119-124
  - convergence, 114, 119, 129, 131
  - convergence test, 133
  - implementation, 124
  - interval, 130
  - performance, 120
- Transfer function impulse response, 132
- Triangular path, 183, 185
  
- Ultrasonic range sensor, 49
- Unidentifiability (link inertial parameters), 89, 93, 97
- Unmodeled dynamics, 81, 127, 143
  - in learning, 127
  - in load estimation, 81
  - in force control, 143
- Variance accounted for, 62
- Velocity sensors, 127
  - See also Tachometer
- Verification, 66
- Vibration, 83
- Vision system, 115
  
- Watsmart system, 12, 51, 64
- Wrench, 91
  - transmission matrix, 91
- Wrist force sensing, 156, 159
  - See also Force/torque sensor
  
- YEWBOT, 38, 40