$S^{n}, 24$	Cartesian product, 25
\mathbb{R}^n , 24	Cartesian robot, 431
	Cayley–Rodrigues parameters, 68, 582
acceleration ellipsoid, 280	center of mass, 283
Ackermann steering, 524	center of rotation (CoR), 473
actuator, 11, 303	centripetal force, 276
Ad, 100	Chasles–Mozzi theorem, 105
adjoint map, 100	chassis, 513
admittance, 442	Christoffel symbols of the first kind,
ambiguity, 495	278
angular velocity, 76	closed-chain mechanism, 18, 245
body, 78	collision–detection routine, 362
spatial, 77	sphere approximation, 363
apparent inertia, 310	commutation, 306
associativity, 70	commutativity, 71
atan2, 219	condition number, 199
atlas, 27	configuration, 12
axis-angle representation, 79	configuration space, see C-space
	connected component, 358
back-emf, 308	connectivity, 368
backlash, 2, 446	constrained dynamics, 301
bang-bang trajectory, 340	constraint
Barrett Technology's WAM, 150	active, 466
bifurcation point, 257	artificial, 439
body frame, 61	holonomic, 30
C 19	homogeneous, 469
C-space, 12	impenetrability, 465
free, 353	integrable, 31
obstacle, 358	natural, 438
representation, 25	nonholonomic, 32
topologically equivalent, 24	Pfaffian, 31, 439
topology, 23	, ,

rolling, 466 contact frictionless point, 472 kinematics, 463 point with friction, 472 roll-slide, 465, 466 sliding, 466 sliding, 466 soft, 472 contact label, 469 contact mode, 469 proportional (P), 414 rolling, 466 contact setpoint, 414 stiffness, 442 task-space motion control, 433 control vector field, 522 control-affine system, 531 control-affine system, 531 controllable robot, 529 coordinate chart, 27 coordinate free, 60 Coriolis force, 276 Coriolis matrix, 279 contact normal, 464 control D-H parameters, 140, 585 D-H parameters and product of expo-
frictionless point, 472 kinematics, 463 point with friction, 472 roll-slide, 465, 466 rolling, 466 sliding, 466 soft, 472 control vector field, 522 control-affine system, 531 controllable robot, 529 sliding, 466 coordinate chart, 27 soft, 472 coordinate free, 60 contact label, 466 contact mode, 469 contact normal, 464 control stiffness, 442 task-space motion control, 433 control vector field, 522 control
kinematics, 463 point with friction, 472 roll-slide, 465, 466 rolling, 466 sliding, 466 soft, 472 control vector field, 522 control-affine system, 531 controllable robot, 529 sliding, 466 coordinate chart, 27 soft, 472 coordinate free, 60 contact label, 466 contact mode, 469 contact normal, 464 control D-H parameters, 140, 585
point with friction, 472 roll-slide, 465, 466 rolling, 466 sliding, 466 soft, 472 controllable robot, 529 sliding, 466 contact label, 466 contact label, 466 contact mode, 469 contact normal, 464 control control co
roll-slide, 465, 466 rolling, 466 sliding, 466 sliding, 466 controllable robot, 529 sliding, 466 coordinate chart, 27 soft, 472 coordinate free, 60 Coriolis force, 276 contact label, 466 Coriolis matrix, 279 contact normal, 464 control D-H parameters, 140, 585
rolling, 466 controllable robot, 529 sliding, 466 coordinate chart, 27 soft, 472 coordinate free, 60 contact label, 466 Coriolis force, 276 contact mode, 469 Coriolis matrix, 279 contact normal, 464 control D-H parameters, 140, 585
sliding, 466 soft, 472 coordinate chart, 27 coordinate free, 60 contact label, 466 contact mode, 469 contact normal, 464 control coordinate chart, 27 coordinate free, 60 Coriolis force, 276 Coriolis matrix, 279
soft, 472 coordinate free, 60 contact label, 466 Coriolis force, 276 contact mode, 469 Coriolis matrix, 279 contact normal, 464 control D-H parameters, 140, 585
contact label, 466 Coriolis force, 276 contact mode, 469 Coriolis matrix, 279 contact normal, 464 control D-H parameters, 140, 585
contact mode, 469 Coriolis matrix, 279 contact normal, 464 control D-H parameters, 140, 585
contact normal, 464 control D-H parameters, 140, 585
control D–H parameters, 140, 585
D II 1 1 0
adaptive, 448 nentials
admittance-controlled robot, 443 comparison, 595
centralized, 432 da Vinci S Surgical System, 238
compliance, 442 damped natural frequency, 411
computed torque, 429 damping
decentralized, 431 critical, 411
feedback, 414 overdamped solution, 411
feedforward, 414 underdamped solution, 411
feedforward–feedback, 418 damping ratio, 410
force, 403, 434 DC motor, 305
gain, 414 brushed, 306
hybrid motion–force, 403, 437 brushless, 306
impedance, 403, 441 degrees of freedom (dof), 12
impedance-controlled robot, 443 Delta robot, 22, 245
inverse dynamics, 429 Denavit–Hartenberg parameters, see D–
iterative learning, 448 H parameters
linear, 414 diff-drive robot, 523
motion, 403 differential equation
motion, with torque or force in- homogeneous, 407
puts, 420 nonhomogeneous, 407
motion, with velocity inputs, 413 direct-drive robot, 313
open-loop, 414 distance-measurement algorithm, 362
proportional-derivative (PD), 423 dof, 12
proportional-integral (PI), 415 Dubins car, 537
proportional-integral-derivative (PID)ynamic grasp, 496
422 dynamics of a rigid body, 283

classical formulation, 283	friction angle, 484
twist-wrench formulation, 288	friction coefficient, 484
dynamics of open chains, 271	friction cone, 484
Lagrangian formulation, 272	
Newton-Euler recursive formula-	gantry robot, 431
tion, 291	gearing, 310
Newton-Euler recursive formula-	harmonic drive, 314
tion with gearing, 312	generalized coordinates, 272
	generalized forces, 272
Eclipse mechanism, 267	GJK algorithm, 362
elbow-down (righty) solution, 219	Grübler's formula, 17
elbow-up (lefty) solution, 219	graph, 364
electrical constant, 308	directed, 364
end-effector, 11	undirected, 364
equations of motion, 271	unweighted, 364
error dynamics, 406	visibility, 368
error response, 406	weighted, 364
Euclidean space, 24	graph edge, 364
Euler angles, 68, 575	graph node, 364
Euler's equation for a rotating body,	grasp metric, 482
284	group closure, 70
Euler–Lagrange equations, 273	
exceptional objects, 479	homogeneous coordinates, 90
exponential coordinates	homogeneous transformation matrix, 89
for rigid-body motion, 104	homotopic path, 398
for rotation, 79, 82	. 1
6 1 1 1 20	impedance, 441
five-bar linkage, 20	inadmissible state, 339
fixed frame, 61	inconsistent problem, 495
force closure, 489	inertia matching, 323
force ellipsoid, 176, 199	inertia matrix
form closure, 469, 478	rotational, 284
forward dynamics, 271	spatial, 288
forward kinematics, 137	inertial measurement unit (IMU), 560
parallel mechanisms, 247	integrator anti-windup, 425
four-bar linkage, 18	inverse dynamics, 271
free vector, 60	inverse kinematics, 219
friction, 484	analytic, 221
Coulomb, 484	numerical, 226
static, 314	parallel mechanisms, 247
viscous, 314	inverse velocity kinematics, 232

isotropic manipulability ellipsoid, 198	manipulability ellipsoid, 173, 197 mass ellipsoid, 280
Jacobi identity, 322	mass matrix, 271, 275, 277, 279
Jacobian, 171	matrix
analytic, 188	rotation, 28
body, 178, 185	matrix exponential, 80
constraint, 252	for rigid-body motion, 105
geometric, 188	for rotations, 84
space, 178, 180	
jamming, 500	matrix Lie group, 70
joint, 11	matrix logarithm
cylindrical, 16	for rigid-body motion, 106
helical, 16	for rotation, 85
	mecanum wheel, 514
prismatic, 16	meter-stick trick, 498
revolute, 16	mobile manipulation, 548
screw, 16	moment, 108
spherical, 16	pure, 109
universal, 16	moment labeling, 488
Valman vanit condition 500	motion planning, 353
Kalman rank condition, 528	anytime, 356
kinetic energy, 272	approximate, 355
Krasovskii–LaSalle invariance principle,	complete, 356
458	complete planners, 368
Lagrange multiplier, 234, 302, 440, 598	computational complexity, 356
Lagrangian function, 272	exact, 355
law of cosines, 220	grid methods, 369
lefty solution, 219	multiple query, 356
•	nonlinear optimization, 392
Lie algebra, 77, 98	offline, 355
of vector fields, 534	online, 355
Lie bracket	optimal, 355
of twists, 289	path planning, 355
of vector fields, 532	piano mover's problem, 355
Lie product, 533	PRM algorithm, 384
linear program, 480	probabilistically complete, 356
linear system, 406	RDT algorithm, 380
linearly controllable, 528	resolution complete, 356
link, 11	RRT algorithm, 379
loop-closure equation, 28, 29	bidirectional, 382
Manhattan distance 370	RRT* algorithm, 383

sampling methods, 378 satisficing, 355	body form, 149 space form, 142
single query, 356	product of exponentials and D–H pa-
smoothing, 394	rameters
virtual potential fields, 386	comparison, 595
wavefront planner, 370	pseudoinverse, 229
wheeled mobile robot, 374	left, 229
MoveIt, 353	right, 229
multi-resolution grid, 372	PUMA-type arm, 221
-	* -
natural frequency, 410	quadtree, 373
navigation function, 389	quasistatic, 496
neighborhood, 529	quaternion, unit, 581
neighbors	reachability, 368
4-connected, 369	reachable set, 529
8-connected, 369	reciprocal wrench and twist, 466
Newton–Raphson root finding, 227	redundant actuation, 246
no-load speed, 308	redundant actuation, 240 redundant constraint, 14
	redundant constraint, 14 redundant robot, 190, 234
octree, 373	
odometry, 546	Reeds–Shepp car, 538 reflected inertia, 310
omniwheel, 514	repelling wrench and twist, 466
Open Motion Planning Library, 398	representation
open-chain mechanism, 18	implicit, 28
overshoot, 406	right-handed reference frame, 62
parallel mechanisms, 245	righty solution, 219
parallel-axis theorem, 287	rigid body
parametrization	planar, 15
explicit, 27	spatial, 15
passivity property, 279	rigid-body motion, 89
path, 325	roadmap, 368
peg insertion, 500	Robot Operating System (ROS), 152,
phase plane, 339	354
polyhedral convex cone, 469	Rodrigues' formula, 84
polyhedral convex set, 469	roll-pitch-yaw angles, 68, 580
polytope, 469	root locus, 416
potential energy, 272	rotation, 68
principal axes of inertia, 285	rotation matrix, 68
principal moments of inertia, 285	rotor, 305
product of exponentials, 140	rviz, 354

SCARA, 34	spatial force, 109
screw axis, 102	spatial momentum, 289
body-frame, 149	spatial relocity
space-frame, 142	in body frame, 97
screw pitch, 103	
- · · · · · · · · · · · · · · · · · · ·	in space frame, 99
SE(3), 89	special Euclidean group $(SE(3))$, 89
se(3), 98	special orthogonal group $(SO(3))$, 70
search	speed-torque curve, 308
$A^*, 365$	stability of an assembly, 499
breadth-first, 367	stable dynamics, 408
Dijkstra's algorithm, 367	stall torque, 308
suboptimal A^* , 367	standard second-order form, 410
serial mechanism, 18	Stanford-type arm, 225
series elastic actuator, 446, 459	state, 354
settling time, 406	stator, 305
shortest paths, car with reverse gear,	steady-state error, 406
538	steady-state response, 406
shortest paths, forward-only car, 537	Steiner's theorem, 287
singularity, 21, 27, 172	Stephenson six-bar linkage, 20
actuator, 256	Stewart–Gough platform, 22, 245
actuator, degenerate, 259	strain gauge, 405, 435, 446
actuator, nondegenerate, 259	Stribeck effect, 314
C-space, 256, 258	Swedish wheel, 514
end-effector, 256, 261	
kinematic, 191	$T^{n}, 25$
skew-symmetric matrix, 77	tangent vector, 522
slider–crank mechanism, 18	tangent vector field, 522
small-time locally accessible (STLA),	task space, 32
529	task-space dynamics, 300
small-time locally controllable (STLC),	Taylor expansion, 227, 531
529	time constant, 409
so(3), 77	time scaling, 326
SO(2), 70	cubic, 329
SO(3), 70	quintic, 330
space frame, 61	S-curve, 333
span	time-optimal, 336
conical, 462	trapezoidal, 330
convex, 462	time-optimal trajectories, diff-drive, 540
linear, 462	torque, 108
positive, 462	torque constant, 306
positive, 402	1 1

```
trajectory, 326
    point-to-point, 326
    through via points, 334
trajectory tracking, nonholonomic mo-
         bile robot, 543
transformation matrix, 89
transient response, 406
tree, 364
    child node, 364
    leaf node, 364
    parent node, 364
    root node, 364
twist, 97
    body, 98
    spatial, 99
unit quaternions, 68
Universal Robot Description Format (URDF),
         152, 303
Universal Robots' UR5, 147
unstable dynamics, 408
variable-impedance actuator, 449
variable-stiffness actuator, 449
vector field, 522
velocity limit curve, 339
Watt six-bar linkage, 20
wedging, 501
wheeled mobile robot, 513
    canonical, 526
    car-like, 524
    diff-drive, 523
    nonholonomic, 514
    omnidirectional, 514
    unicycle, 521
workspace, 33
wrench, 108
    body, 110
    spatial, 110
zero-inertia point, 338, 344
```

May 2017 preprint of Modern Robotics, Lynch and Park, Cambridge U. Press, 2017. http://modernrobotics.org