5 DOF maneuvering model, 115	attitude and heading reference systems, 528
4 DOF maneuvering model, 158	automatic pretrimming, 78
6 DOF equations of motion, 167	autopilot
	acceleration feedback, 384
Abkowitz's model, 138	backstepping, 508
absolute damping factor, 366	cross-tracking, 385
acceleration feedback, 365, 369	heading, 377, 525
accelerometer, 329	history, 230
Adams-Bashford's integration method, 546	Kalman filter, 300
adaptive	linear quadratic optimal, 429
feedback linearization, 455	LOS path-following, 387
weather optimal control, 499	model, 142
added mass, 91	nondimensional models, 148
definition, 92	path-following, 512
energy approach, 117	PID, 379
forces and moments, 118	pitch and depth, 526
hydrodynamic derivatives, 129	sliding mode control, 518
potential coefficient, 111	AUV, autonomous underwater vehicle, 3
property of the system inertia matrix, 118	average wave period, 202
system inertia matrix, 118	average zero-crossings period, 202
AHRS, attitude and heading reference system,	
328	backstepping, 457
anemometer, 191	integral action, 469
angle of attack, 41	integrator augmentation technique, 472
angular velocity transformation, 24, 29	MIMO mass-damper-spring system, 475
anti-rolling tanks, 433	robots, 478
Archimedes, 59	ships, 480
attitude	SISO mass-damper-spring system, 465
control, 452	weather optimal control, 500
dynamics, 48	ballast systems, 74
observer, 336	semi-submersible, 77

bandwidth, 373	craft, 3
Beaufort number, 190, 203	cross-tracking, 385
Bech's reverse spiral maneuver, 146, 354,	cross-flow drag, 127, 136, 156
363	cross-product operator, 20
Bernoulli equation, 83	cross-track error, 258
bilge keels, 433	cruise condition, 175
bis system, 148	cubic splines, 267
boat, definition, 3	Cummins equation, 96
BODY, body-fixed reference frame, 17	current angle of attack, 155
body-fixed vector representation, 167	current coefficients
Bretschneider spectrum, 202	area-based, 156
buoyancy, 59	DP, 153
buoyancy force	relationship to cross-flow drag and surge
floating vessels, 62	resistance, 156
submerged vehicle, 59	surge damping, 127
Butterworth filter, 289	
	D'Alambert's paradox, 122
carrier DGPS, 305	damped oscillator, 365
CB, center of buoyancy, 18, 59	damping
centripetal forces, 53	frequency-dependent, 95
CF, center of flotation, 18, 68	matrix, 123
CG, center of gravity, 18	dead-reckoning, 299
CO, body axes coordinate origin, 17	decoupling
commanded acceleration, 451–2	body-fixed reference frame, 451
compass, 300, 331	NED reference frame, 452
computed torque, 450	degrees-of-freedom
configuration space, definition, 236	definition, 235
constant bearing guidance, 244	model classification, 5
continuous-time Kalman filter, 298	notation, 15
control allocation, 398, 414	density
constrained, 405	air, 189
unconstrained, 404	describing function, 95
control bandwidth, 373	DGPS, differential GPS, 305
control design model, 6	Dieudonné's spiral maneuver, 146, 362
control Lyapunov function, definition,	diffeomorphism, 459
458	directional stability, 344, 346
controllability, definition, 418	discrete-time Kalman filter, 296
coordinate	discretization of continuous-time systems,
form, 18	541
free vector, 18	displacement vessel, 4
systems, 16	DOF, degrees-of-freedom, 235
transformation matrix, 20	DP
Coriolis and centripetal forces	backstepping control system, 480
maneuvering, 115	brief history, 391
seakeeping, 99	control allocation, 411
Coriolis and centripetal matrix	definition, 391
definition, 53	Kalman filter, 304
property, 54, 170	linearized model, 157
corrector–predictor representation, 299	nonlinear model, 153
course angle, definition, 39	nonlinear separation principle, 487

optimal control system, 445	equation, 83
passive observer, 310	forward, 544
PID control system, 393	parameters, 27
position mooring, 396	Euler angles from quaternions, 33
roll and pitch damping, 391	Euler's
setpoint chasing, 393	axioms, 46
weather optimal control system, 491	integration method, 544
drag coefficient, 127	theorem on rotation, 21
drift angle, definition, 40	extended
Dubins path, 255	thrust configuration matrix, 402
dynamic positioning, see DP, 391	
dynamic stability	feedback linearization, 450, 463
on course, 352	body-fixed reference frame, 451
straight-line motion, 347	NED reference frame, 452
dynamic straight-line stability, theorem,	filter
351	low-pass, 288
dynamically positioned vessel, definition,	notch, 290
391	fin stabilizers, 434
	flat Earth navigation, 35
Earth rotation, 47	flow
ECEF, Earth-centered Earth-fixed frame,	axes, 39
16	control, 76
ECI, Earth-centered inertial frame, 16	irrotational, 83
effective metacentric height, 73	potential, 83
ellipsoidal height, 36	fluid
energy dissipation, 122	kinetic energy, 117
environmental forces, 187	memory effects, 81, 96, 104
equations of motion	viscous, 82
1 DOF, 142	force RAO, 211
3 DOF, 133	forced oscillations, 90
4 DOF, 158	forward shift operator, 541
6 DOF, 167	forward speed model, 140
classical model, 7	four-quadrant arctangent, 33
DP, 152	free-surface
expressed in BODY, 167	correction, 73
expressed in NED, 168	effect, 73
lateral, 185	frequency
longitudinal, 184	damped system, 367
maneuvering, 109, 133	encounter, 210
nondimensional, 148	natural, 365
nonlinear, 167	frequency-domain model, 89
rigid-body, 51	frequency-independent
seakeeping, 96	model, 113
vectorial representation, 13	potential coefficients, 111
equations of relative motion, 188	frictional forces, 122
equilibrium heading, 86	Froude number, definition, 3
equivalent linearization, 95	FSC, free-surface correction, 73
Euler	•
angles, 22	GALILEO, European Union Global Positioning
backward, 545	System, 230, 305
	· · · · · · · · · · · · · · · · · · ·

Gauss–Markov process, 223	ships, 62
generalized	submerged vehicles, 59
coordinates, 116	
eigenvalue problem, 70	IKEDA damping, 95
inverse, 404	IMU, inertial measurement unit, 328
geodetic latitude, 36	inclination, 331
GLONASS, GLObalnaya NAvigatsionnaya	incompressible fluid, 82
Sputnikovaya Sistema, 230, 305	inertia matrix, definition, 48
GM, metacenter height, 65	INS, inertial navigation system, 328
GNSS, Global Navigation Satellite Systems, 230,	integrator backstepping, 457
305	interceptor, 243
GPS, NAVSTAR Global Positioning System,	irrotational
230, 305	flow, 83
gravitational force	ocean currents, 103
floating vessels, 62	irrotational constant ocean currents, 129
submerged vehicle, 59	irrotational ocean currents, 55, 109
guidance, 241	ITTC resistance, 125
closed-loop, 232	
constant bearing, 244	JONSWAP, Joint North Sea Wave Project
line-of-sight, 243	spectrum, 205
open-loop, 232	5 <b>500000000000000000000000000000000000</b>
pure pursuit, 243	Kalman filter
guidance, navigation and control, definitions,	autopilot, 300
232	continuous-time, 297
gyroscope, 229, 329	corrector–predictor representation, 299
gyroscopic compass, 301	discrete-time, 296
gyroscopic compass, 501	DP, 304
heading angle, definition, 39	extended, 298
heave, definition, 15	Kempf's zigzag maneuver, 354, 359
Helmholtz-Kirchhoff plate, 192	kinematic viscosity, 122
Hermite interpolant, 267	kinematics, 15
Heun's integration method, 547	kinetics, 15, 45
Hoerner's curve, 127	Kirchhoff's equations, 54, 116
Huygens–Steiner theorem, 50	I
hydrodynamic	Lagrange equations, 115
code, 84	Laplace equation, 83
Coriolis and centripetal matrix, property,	lateral model, 183
120	latitude, definition, 34
damping, 122	LCF, longitudinal center of flotation, 18
derivatives, 118, 129	LF, low-frequency motion, 285
forces, 128	lift and drag, 122
mass-damper-spring, 128	line-of-sight
system inertia matrix, property, 118	guidance, 243
hydrodynamics	path following, 254
computation programs, 84	linear damping formula for mass-damper-spring
potential theory, 82	system, 367
hydrostatics, 59	linear equations of motion
box-shaped vessels, 64	linear, 173
floating vessels, 62	linear-quadratic optimal control, 418
semi-submersibles, 62	linear-quadratic regulator, 418

linear velocity transformation, 22, 28	marine craft, 3
linear viscous damping, 123	mariner class vessel
linearized	Kalman filter, 303
Coriolis and centripetal forces, 57	Nomoto models, 144
DP model, 157	nonlinear least-squares, 357
equations of motion, 56	pivot point, 147
maneuvering model, 140	turning circle, 355
load condition, 67	mass-damper-spring system, 345, 365
long-crested irregular sea, 208	mean wave drift force, 95
longitude, definition, 34	measure of maneuverability, 353
longitudinal model, 183	metacenter height
LOS, line-of-sight, 243	lateral, 65
low-aspect ratio wing theory, 165	transverse, 65
low-frequency motion, 286	metacenter stability, definition, 67
low-pass filter, 288	metacenter, definition, 62
low-speed model, 173	modal
LQ	frequency, 201
fin and rudder-roll damping, 433	period, 201
heading autopilot, 429	modal analysis, 69
optimal control, 418	model representations, 9
trajectory-tracking, 421	models, 6
LOG, 449	modified Pierson-Moskowitz spectrum,
Luenberger observer, 293	204
,	moments of area, definition, 66
magnetic	moments of inertia, 48
compass, 301	Moore-Penrose pseudo-inverse, 77, 169
field, 331	Morison's equation, 122
magnetometer, 331	motion
maneuver	RAO, 213
Bech's spiral maneuver, 363	sickness criteria, 443
Kempf's zigzag maneuver, 359	Munk moment, 142
pull-out maneuver, 361	
turning circle, 354	natural
maneuverability, 343, 353	frequency, 68, 113, 345, 365
maneuvering	period, 68
coefficients, 128	natural frequency model, definition, 113
equations, 128	Navier–Stokes equation, 82
kinematics, 85	navigation systems, 286
theory, 9, 81, 109	NED, North-East-Down reference frame, 17
zero-frequency model, 113	Neumann spectrum, 202
maneuvering control, definition, 266	neutrally buoyant, 61
maneuvering model	Newton's second law, 45
3 DOF, 133	Newton-Euler formulation, 45
4 DOF, 158	Newton-Raphson method, 68
including ocean currents, 225	Nomoto model
ITTC and cross-flow drag, 136	first-order, 143
linearized, 140	nonlinear extension, 144
odd functions, 138	normalization, 151
potential theory representation, 141	second-order, 143
second-order modulus, 136	nondimensional equations of motion, 148
· · · · · · · · · · · · · · · · · · ·	*

nonlinear	heading autopilot, 319
constrained optimization, 273, 405	path
observer, 310	cubic splines, 269
PID control, 469	parametrized, 266
normalization, 149	straight lines and circular arcs, 255
normalization forms, 148	path-following guidance, 254
notch filter, 290	peak period, 200
numerical	period
differentiation, 547	peak, 200
integration, 544	wave, 200
	zero-crossing, 200
observability, definition, 292	perturbation coordinates, 86, 111
observer	PID control
design model, 7	acceleration feedback, 369
fixed-gain, 292	cross-tracking, 385
IMU and GNSS, 328	curved-path path following, 389
Luenberger, 293	dynamic positioning, 391
passive, 319	heading autopilot, 377
ocean currents, 188	LOS path-following, 387
2-D, 224	mass-damper-spring system, 365
3-D, 224	MIMO nonlinear systems, 375
direction, 223	position mooring systems, 396
equations of relative motion, 221	pitch
irrotational, 222	definition, 15
models, 221	period, 185
speed, 223	ratio, 411
wind generated, 221	pitch-controlled propeller, 411
odd functions, 138	pivot point, definition, 146
optimal control, 418	planning vessel, 4
dynamic positioning, 445	PM spectrum, 203
fin and rudder-roll damping, 433	PMM, 10, 140
heading autopilot, 429	pole placement, 319
regulator, 418	polynomial interpolation, 267
roll damping, 435	position
trajectory-tracking, 421	control, 452
weather optimal, 491	mooring systems, 396
optimal trajectory generation, 253	positional motion stability, 344
optimization	potential
control allocation, 405	coefficients, 91, 111, 129
guidance, 273	damping, 91, 111, 122, 129
orthogonal matrix, 19	theory, 82
<b>3</b> , .	potential coefficients
P number, 354	properties, 102
panel methods, 84	speed-dependent, 101
parallel navigation, 244	zero-speed, 100
parallel-axes theorem, 50	predictor–corrector representation, 299
parametrization, 456	pretrimming, 76
parametrized path, definition, 266	Prime system, 148
passive observer	principal rotation, 22
dynamic positioning, 310	principle of superposition, 187
, i	1 1 1 /

products of inertia, 48	robot, 478
projected area, 189	roll
propeller, 411	damping, 434
proportional navigation, 244	definition, 15
pull-out maneuver, 354, 361	period, 72, 186
pure pursuit guidance, 243	roll and sway-yaw subsystems, 159
	rotation matrix, 19, 32
quadratic	rotation matrix differential equation, 25
drag, 122	rotation point
programming, 276, 406	yaw, 146
quaternions	rotational motion, 48, 50
definition, 27	Routh stability criterion, theorem, 350
from Euler angles, 32	ROV, remotely operated vehicle, 3
from rotation matrix, 32	RRD, rudder-roll damping, 434
IMU and GNSS, 341	RTK, real-time kinematic, 305
	rudder-roll damping, 160, 434
radiation force, 91	Runge–Kutta integration methods, 547
radius of gyration, 72	
RAO	sea state
force, 199, 211	codes, 202
motion, 199, 213	definition, 200
reference frame	seakeeping
body-fixed, 17	coordinates, 86
Earth-centered Earth-fixed, 16	equations of motion, 93
Earth-centered inertial, 16	kinematics, 85
flow axes, 39	theory, 11, 81
North-East-Down, 17	second-order modulus functions, 138
seakeeping, 85	second-order modulus terms, 128
Serret–Frenet, 278	second-order system, 365
reference model, 247, 377	second-order wave forces and moments, 199
nonlinear damping, 251	semi-displacement vessel, 4
position and attitude, 249	semi-empirical methods, 85
velocity, 249	semi-submersible
regressor, 456	ballast control, 78
regulation, 418	dynamic positioning control system, 391
relative	dynamic positioning system, 445, 487
damping ratio, 345, 365	optimal setpoint chasing, 393
speed, 39	position mooring control system, 396
velocity, 188	roll and pitch damping, 391
response amplitude operator (RAO), 199	weather optimal control system, 491
restoring	separation principle
forces, 59, 129	linear, 449
matrix, 69	nonlinear, 487
retardation functions, 12, 90, 97	Serret–Frenet frame, 278
Reynolds number, 122, 125	service speed, 148
rig, 77	setpoint regulation, 233
rigid-body kinetics	ship
maneuvering, 110	acceleration feedback, 384
Newton–Euler, 45	control allocation, 411
seakeeping, 90	cross-tracking control system, 385

ship (Continued)	steering and roll, 162
curved-path path-following control, 389	steering autopilot, 525
definition, 3	steering criteria, 430
dynamic positioning control system, 391	stopping trials, 354
dynamic positioning system, 445, 487	straight-line stability, 344, 346
fin and rudder-roll damping systems, 433	strip theory, 84
heading autopilot, 377, 429, 454, 508, 525	submarine
LOS path-following control, 387	definition, 3
optimal setpoint chasing, 393	model, 183
path-following control, 512	submerged vehicles
position mooring control system, 396	hydrostatics, 59
weather optimal control system, 491	model, 183
ShipX, 84	superposition, 187
short-crested irregular sea, 209	surface vessels
sideslip angle, definition, 40	hydrostatics, 62
significant wave height, 200, 202	surge
similarity transformation, 542	damping, 125
simple rotation, definition, 21	definition, 15
simulation model, 6	resistance, 125, 136, 156
singularity, 25	sway, definition, 15
skew-symmetry, 20	symmetry properties of inertia, 171
skin friction, 122	system inertia matrix
slack tank, 73	property, 170
sliding-mode control	system inertia matrix, definition, 52
eigenvalue decomposition, 522	system transformation matrix, definition, 177
heading autopilot, 525	•
pitch and depth control, 526	tanks, 76
SISO systems, 518	target, 243
SNAME notation, 15	target tracking, 242
Son and Nomoto's model, 162	Taylor series, 138
special orthogonal group, 19	thrust allocation, 414
spectrum	thrust configuration matrix, 411
Bretschneider, 202	time differentiation, moving reference frame, 47
JONSWAP, 205	Torsethaugen spectrum, 206
modified Pierson-Moskowitz, 204	trajectory generation, 267
Neumann, 202	trajectory tracking, definition, 246
Pierson–Moskowitz, 203	trajectory-tracking control, 233
Torsethaugen, 206	transit, 175
spiral maneuver, 354	translational motion, 47, 50
spreading function, 209	turning
SS(3), set of skew-symmetric matrices, 20	circle, 354
stability	index, 353
axes, 41	
directional, 346	undamped oscillator, 365
index, 349	underactuated
on course, 346	control, 247
open-loop, 343	marine craft, 235
stabilizing function, 460	underwater vehicle
state feedback linearization, 450	acceleration feedback, 384
stationkeeping model, 173	added mass and damping, 112

cross-tracking control system, 385	wave drift damping, 122
curved-path path-following control, 389	wave excitation force, 95
definition, 3	wave filter
heading autopilot, 377, 429, 454, 508, 525	autopilot, 301, 319
lateral model, 185	dynamic positioning, 304, 311
longitudinal model, 184	wave filtering, definition, 286
LOS path-following control, 387	wave spectrum
path-following control, 512	Bretschneider, 202
pitch and depth control, 526	JONSWAP, 205
restoring forces, 59	maximum value, 204
underway replenishment, 245	modified Pierson-Moskowitz, 204
unified	Neumann, 202
model, 103	Torsethaugen, 206
theory, 12	wave spectrum moments
unit quaternions, 27	moments, 201
normalization, 31	wave-frequency motion, 199, 214, 286
UNREP, underway replenishment, 245	wave-induced forces, 187
UUV, unmanned underwater vehicle, 3	waypoint
	representation, 255
vectorial mechanics, 45	tracking, 232
velocity	weather optimal position control, 491
control, 451	weather routing, 277
velocity transformation	weight, 59
angular, 24, 29	WF, wave-frequency motion, 199, 214, 285
linear, 22, 28	WGS-84, World Geodetic System, 17
VERES, 84	wind
vessel parallel coordinates, definition, 173	angle of attack, 188
vessel, definition, 3	axes, 41
viscous	coefficients, 188
damping, 122, 129	container ship, 191
damping matrix, 95	direction, 189
volume of displaced fluid, 59	forces on marine craft at rest, 188
voyage planning systems, 277	forces on moving craft, 191
VRU, vertical reference unit, 340	large tankers, 195
	merchant ships, 194
WAMIT, 84, 211	models, 188
water plane area moment, 65	moored ships and floating structures, 195
water tanks, 76	offshore vessels, 191
wave	relative angle of attack, 191
first-order forces and moments, 199	relative speed, 191
force RAO, 211	speed, 188
force, no spreading function, 212	tunnel, 191
force, spreading function, 213	wind-generated waves, 202
models, 202	workspace, definition, 237
period, 200	
response, 214	yaw, definition, 15
second-order forces and moments, 199	
state-space model, 215	zero-frequency model, definition, 113
wave amplitude response model, 208	zero-speed model, 103