

## APPENDIX A

### A WORD ON KALMAN FILTERS

The most widely used method for sensor fusion in mobile robot applications is the Kalman filter. This filter is often used to combine all measurement data (e.g., for fusing data from different sensors) to get an optimal estimate in a statistical sense. If the system can be described with a linear model and both the system error and the sensor error can be modeled as white Gaussian noise, then the Kalman filter will provide a unique statistically optimal estimate for the fused data. This means that under certain conditions the Kalman filter is able to find the best estimates based on the “correctness” of each individual measurement.

The calculation of the Kalman filter is done recursively, i.e., in each iteration, only the newest measurement and the last estimate will be used in the current calculation, so there is no need to store all the previous measurements and estimates. This characteristic of the Kalman filter makes it appropriate for use in systems that don't have large data storage capabilities and computing power. The measurements from a group of  $n$  sensors can be fused using a Kalman filter to provide both an estimate of the current state of a system and a prediction of the future state of the system.

The inputs to a Kalman filter are the system measurements. The a priori information required are the system dynamics and the noise properties of the system and the sensors. The output of the Kalman filter is the estimated system state and the innovation (i.e., the difference between the predicted and observed measurement). The innovation is also a measure for the performance of the Kalman filter.

At each step, the Kalman filter generates a state estimate by computing a weighted average of the predicted state (obtained from the system model) and the innovation. The weight used in the weighted average is determined by the covariance matrix, which is a direct indication of the error in state estimation. In the simplest case, when all measurements have the same accuracy and the measurements are the states to be estimated, the estimate will reduce to a simple average, i.e., a weighted average with all weights equal. Note also that the Kalman filter can be used for systems with time-variant parameters.

The extended Kalman filter is used in place of the conventional Kalman filter if the system model is potentially numerically unstable or if the system model is not approximately linear. The extended Kalman filter is a version of the Kalman filter that can handle non-linear dynamics or non-linear measurement equations, or both [Abidi and Gonzalez, 1992].

## APPENDIX B

### UNIT CONVERSIONS AND ABBREVIATIONS

To convert from	To	Multiply by
<b>(Angles)</b>		
degrees (°)	radian (rad)	0.01745
radian (rad)	degrees (°)	57.2958
milliradians (mrad)	degrees (°)	0.0573
<b>(Length)</b>		
inch (in)	meter (m)	0.0254
inch (in)	centimeter (cm)	2.54
inch (in)	millimeter (mm)	25.4
foot (ft)	meter (m)	30.48
mile (mi), (U.S. statute)	meter (m)	1,609
mile (mi), (international nautical)	meter (m)	1,852
yard (yd)	meter (m)	0.9144
<b>(Area)</b>		
inch <sup>2</sup> (in <sup>2</sup> )	meter <sup>2</sup> (m <sup>2</sup> )	$6.4516 \times 10^{-4}$
foot <sup>2</sup> (ft <sup>2</sup> )	meter <sup>2</sup> (m <sup>2</sup> )	$9.2903 \times 10^{-2}$
yard <sup>2</sup> (yd <sup>2</sup> )	meter <sup>2</sup> (m <sup>2</sup> )	0.83613
<b>(Volume)</b>		
foot <sup>3</sup> (ft <sup>3</sup> )	meter <sup>3</sup> (m <sup>3</sup> )	$2.8317 \times 10^{-2}$
inch <sup>3</sup> (in <sup>3</sup> )	meter <sup>3</sup> (m <sup>3</sup> )	$1.6387 \times 10^{-5}$
<b>(Time)</b>		
nanosecond (ns)	second (s)	$10^{-9}$
microsecond (μs)	second (s)	$10^{-6}$
millisecond (ms)	second (s)	$10^{-3}$
second (s)		
minute (min)	second (s)	60
hour (hr)	second (s)	3,600
<b>(Frequency)</b>		
Hertz (Hz)	cycle/second (s <sup>-1</sup> )	1
Kilohertz (KHz)	Hz	1,000
Megahertz (MHz)	Hz	$10^6$
Gigahertz (GHz)	Hz	$10^9$

To convert from	To	Multiply by
<b>(Velocity)</b>		
foot/minute (ft/min)	meter/second (m/s)	$5.08 \times 10^{-3}$
foot/second (ft/s)	meter/second (m/s)	0.3048
knot (nautical mi/h)	meter/second (m/s)	0.5144
mile/hour (mi/h)	meter/second (m/s)	0.4470
mile/hour (mi/h)	kilometer/hour (km/h)	1.6093
<b>(Mass, Weight)</b>		
pound mass (lb)	kilogram (kg)	0.4535
pound mass (lb)	grams (gr)	453.59
ounce mass (oz)	grams (gr)	28.349
slug (lbf · s <sup>2</sup> /ft)	kilogram (kg)	14.594
ton (2000 lbm)	kilogram (kg)	907.18
<b>(Force)</b>		
pound force (lbf)	newton (N)	4.4482
ounce force	newton (N)	0.2780
<b>(Energy, Work)</b>		
foot-pound force (ft · lbf)	joule (J)	1.3558
kilowatt-hour (kW · h)	joule (J)	$3.60 \times 10^6$
<b>(Acceleration)</b>		
foot/second <sup>2</sup> (ft/s <sup>2</sup> )	meter/second <sup>2</sup> (m/s <sup>2</sup> )	0.3048
inch/second (in./s <sup>2</sup> )	meter/second <sup>2</sup> (m/s <sup>2</sup> )	$2.54 \times 10^{-2}$
<b>(Power)</b>		
foot-pound/minute (ft · lbf/min)	watt (W)	$2.2597 \times 10^{-2}$
horsepower (550 ft · lbf/s)	watt (W)	745.70
milliwatt (mW)	watt (W)	$10^{-3}$
<b>(Pressure, stress)</b>		
atmosphere (std) (14.7 lbf/in <sup>2</sup> )	newton/meter <sup>2</sup> (N/m <sup>2</sup> or Pa)	101,330
pound/foot <sup>2</sup> (lbf/ft <sup>2</sup> )	newton/meter <sup>2</sup> (N/m <sup>2</sup> or Pa)	47.880
pound/inch <sup>2</sup> (lbf/in <sup>2</sup> or psi)	newton/meter <sup>2</sup> (N/m <sup>2</sup> or Pa)	6,894.8
<b>(Temperature)</b>		
degree Fahrenheit (°F)	degree Celsius (°C)	$^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times 5 / 9$
<b>(Electrical)</b>		
Volt (V); Ampere (A); Ohm ( $\Omega$ )		

## APPENDIX C SYSTEMS-AT-A-GLANCE TABLES

Name	Computer	Onboard Equipment	Accuracy-position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
General			0.01%-5% of traveled distance		100-10,000 or analog	Error accumulation	Unlimited, internal, local	[Parish and Grabbe, 1993] Omnitech Robotics, Inc.
TRC Labmate	486-33MHz	Each quad-encoder pulse corresponds to 0.012 mm wheel displacement	4×4 meters bidirectional square path <sup>†</sup> : 310 mm	On smooth concrete*: 6° With ten bumps*: 8°	Very high ~ 1 KHz	Short wheelbase	Unlimited	[TRC] Transition Research Corp.
Cybermotion	Onboard proprietary	Drive and steer encoders	4×4 meters bidirectional square path*: 63 mm	On smooth concrete*: 1 to 3.8° With ten bumps*: 4°		Synchro-drive design		Cybermotion
Blanche	MC68020	Uses a pair of knife-edge non-load-bearing wheels for odometry						[Cox, 1991] NEC Research Institute
Model-reference adaptive motion control	386-20 MHz TRC Labmate	Wheel encoders and sonars for orientation measurements	Average after a 2×2 m square path: 20 mm	Average after 2×2 m square path: 0.5°	20 Hz	Can only compensate for systematic error	Unlimited	[Feng et al., 1994] Univ. of Michigan
Multiple robots		Two cooperative robots: one moves and one stays still and measures the motion of the moving one	Simulation: 8 mm after 100 meters movement at 2 m step			Capable of maintaining good position estimate over long distance	Unlimited	[Sugiyama, 1993] NTT Communication Science Lab.
CLAPPER: Dual-drive robot with internal correction of Odometry	486-33 MHz	Two TRC Labmates, connected by a compliant linkage; two absolute rotary encoders, one linear encoder	4×4 m square path: no bumps: 22 mm With 10 bumps <sup>†</sup> : 44 mm	On smooth concrete*: 22° With 10 bumps*: 0.4°	25 Hz	Capable of compensating for random disturbance	Require additional robot or trailer	[Borenstein, 1994] Univ. of Michigan
UMBmark calibration for reduction of systematic odometry errors	486-33 MHz or any onboard computer	Any differential-drive mobile robot; tests here performed with TRC LabMate	4×4 m square path: average return position error: 30-40 mm		25 Hz	Designed for reduction of systematic odometry errors; this calibration routine can be applied to any differential-drive robot, requires no special tooling or instrumentation		[Borenstein and Feng, 1995a,b, c] Univ. of Michigan
Fluxgate magnetometer				±1 - ±4°	10-1000 or analog	External, global, \$100-2000 Prone to magnetic disturbance	Unlimited	[Parish and Grabbe, 1993] Omnitech Robotics, Inc.

\* This result is based on running the University of Michigan Benchmark (UMBmark) test for dead-reckoning accuracy. This test is described in detail in [Borenstein and Feng, 1994].

Name	Computer	Onboard Equipment	Accuracy-position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
Angular rate gyro (laser or optical fiber)		Very accurate models available at \$1K-5K Problems are time dependent drift, and minimum detectable rate of rotation Gyro will not "catch" slow rotation errors		0.01%-5% of full scale rate.	10-1000 or analog	Internal, local, \$1K-20K.	Unlimited	[Parish and Grabble, 1993] Omnitech Robotics, Inc.
Radar velocimeter (Doppler)			0.01%-5% of full scale rate		100-1000 or analog	Internal, local, \$1K-10K	Unlimited	[Parish and Grabble, 1993] Omnitech Robotics, Inc.
Filtered/inertial sensor suite (direction gyros and accelerometer based)			0.01%-5% of distance traveled, also time dependent drift		10-1000 or analog	Internal, local, \$3K-\$150K+	Unlimited	[Parish and Grabble, 1993] Omnitech Robotics, Inc.
MiniRover MKI	Underwater vehicle	Fluxgate magnetic sensor		Accuracy: $\pm 2\%$ max. Resolution: $2^\circ$	analog		$0^\circ - 359^\circ$	[BENTHOS] BENTHOS, Inc.
Futaba model helicopter gyro FP-G154	Output: pulse-width modulated signal			Drift: $>1^\circ/s$	20 ms	\$150		[TOWER]
Gyration GyroEngine	RS232 interface			Drift: $9^\circ/\text{min}$		\$300	Unlimited	[GYRATION] Gyration, Inc.
Murata Gyrostar ENV-05H	Analog interface	Piezoelectric triangular prism. Drift: $9^\circ/\text{sec}$ (maximum rated by manufacturer. Actual drift is lower)		Measured drift: $3-15^\circ/\text{min}$		small, light (42 gr), \$300	Unlimited	[Murata]
Angular rate gyros, general (Laser or Optical Fiber)		Very accurate models available at \$1K-5K Problems are time dependent drift, and minimum detectable rate of rotation Gyro will not "catch" slow rotation errors		0.01%-5% of full scale rate.	10-1000 or analog	Internal, local, \$1K-20K.	Unlimited	[Parish and Grabble, 1993], Omnitech Robotics, Inc.
Hitachi OFG-3	RS232 interface or TTL	Originally designed for automotive navigation systems		Drift: $0.0028^\circ/s$	100 Hz		Unlimited	Komoriyama and Oyama [1994], [HITACHI]
Andrew Autogyro and Autogyro Navigator	RS232 interface	Quoted minimum detectable rotation rate: $\pm 0.02^\circ/s$ Actual minimum detectable rate limited by deadband after A/D conversion: $0.0625^\circ/s$		Drift: $0.005^\circ/s$	10 Hz	\$1000	Unlimited	[ANDREW] Andrew Corporation
Complete inertial navigation system including ENV-05S Gyrostar solid state rate gyro, the START solid state gyro, one triaxial linear accelerometer and two inclinometers			Position drift rate 1 to 8 cm/s depending on the freq. of acceleration change	Gyro drift $5-15^\circ/\text{min}$ . After compensation: drift $0.75^\circ/\text{min}$	100-1000 or analog	Internal, global	unlimited	[Barshan and Durrant-Whyte, 1993, 1995]; [GEC]; [MURATA]
Non-Wire Guidance System for AGV's	VCC-2 vehicle control computer	Solid state gyroscope, position code reader	Position codes (landmarks)					[CONTROL] Control Engineering Company

Name	GPS Type	Static position error mean [m (feet)]	Static position error standard dev. [m (feet)]	Time to first fix [min]	City driving: Percent of time navigation data available	Manufacturer
Magnavox 6400 (10-year old system, out-dated)	2-channel sequencing receiver	33.48 (110)	23.17 (76)	~30	no nav. data: 10.3% only 2-D data: 0.2% full 3-D data: 89.4%	[MAGNAVOX] Magnavox Advanced Products and Systems
Magellan OEM GPS Module	5-channel GPS receiver, OEM type	22.00 (72)	16.06 (53)	~1 to 2	no nav. data: 0.0% only 2-D data: 25.8% full 3-D data: 74.2%	[MAGELLAN] Magellan Systems Corp.
Magnavox GPS Engine	5-channel GPS receiver, OEM type	30.09 (99)	20.27 (67)	~1 to 2	no nav. data: 3.4% only 2-D data: 5.3% full 3-D data: 91.2%	[ROCKWELL] Rockwell International
Rockwell NavCore V	5-channel GPS receiver, OEM type	28.01 (92)	19.76 (65)	~1 to 2	no nav. data: 0.0% only 2-D data: 1.1% full 3-D data: 98.9%	[MAGNAVOX] Magnavox Advanced Products and Systems
Trimble Placer	5-channel GPS receiver, OEM type	29.97 (98)	23.58 (77)	~1 to 2	no nav. data: 0.0% only 2-D data: 5.2% full 3-D data: 94.8%	[TRIMBLE] Trimble Navigation

Name	Computer	Onboard Components	Stationary Components	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling rate [Hz]	Features	Effective Range	Manufacturer
CONAC (computerized opto-electronic navigation and control)	486-33 MHz	Structured opto-electronic acquisition beacon (STROAB)	Networked opto-electronic acquisition datum (NOAD)	Indoor $\pm 1.3$ mm outdoor $\pm 5$ mm	Indoor and outdoor $\pm 0.05^\circ$	25 Hz	3-D - At least 3 NOADS for one acre. Networkable for unlim. area	Need line-of-sight for at least three NOADS	[MacLeod, 1993] (MTI)
ROBOSENSE		Scanning laser rangefinder	Retroreflective targets	System measures direction and distance to beacons with accuracy $< 0.17^\circ$ and $< 20$ mm, respectively Accuracy for robot location and orientation not specified		10-40 Hz	2-D - Measure both angle and distance to target	0.3-30 m	[SIMAN] SIMAN Sensors & Intelligent Machines Ltd.
NAMCO LASERNET beacon tracking system	RS-232 serial interface provided	Rotating mirror pans a near-infrared laser beam through a horizontal arc of $90^\circ$	Retroreflective targets of known dimensions	Angular accuracy is within $\pm 0.05\%$ with a resolution of $0.006^\circ$ Accuracy for robot location and orientation not specified.		20 Hz	Derives distance from computing time of sweep over target of known width	15 meters (50 ft)	[NAMCO, 1989]
TRC beacon navigation system	6808 integrated computer, RS232 interface	Rotating mirror for scanning laser beam	Retroreflective targets, usually mounted on stand-alone poles	Resolution is 120 mm (4-3/4 in) in range and $0.125^\circ$ in bearing for full $360^\circ$ coverage in a horizontal plane		1 Hz	Currently limited to single work area of $80 \times 80$ ft	24.4 m (80 ft)	[TRC]
LASERNAV	64180 micro-computer	Laser scanner	Retroreflective bar codes. Up to 32 can be distinguished.	$\pm 1$ in moving at 2 ft/sec; $\pm 0.5$ in stationary	$\pm 0.03^\circ$ .	90 Hz	2-D - Measures only angles to reflectors	30 meters (100 ft) With active reflectors: up to 183 m	[Benayad-Cherif, 1992] and [DBIR]
Odyssey	Hand-held	Pole- or wand-mounted receiver	Two laser-beam transmitters	Horizontal: $\pm 1$ mm Vertical: $\pm 1$ mm		5 Hz	~\$90,000	Indoor: 75m (250ft) outdoor: 150m (500ft)	[SPSi] Spatial Positioning Systems, inc
BNS (beacon navigation system); 30.5 m		Optical IR detector ( $\pm 10^\circ$ field of view in horizontal and vertical axes)	Infrared beacon transmitter (uniquely identifiable, 128 codes)		$0.3^\circ$ in the $\pm 5^\circ$ central area and $\pm 1^\circ$ out to the periphery of the sensitive area	10 Hz		500 ft suitable for long corridors	[Benayad-Cherif, 1992] (Denning)
Laser scanner + corner cubes	8086	Laser scanner	Three corner cubes	LN-10: $\pm 500$ LN-20: $\pm 20$ LN-30: $\pm 500$ LN-40: $\pm 20$	LN-10: $\pm 1^\circ$ LN-20: $\pm 0.1^\circ$ LN-30: $\pm 1^\circ$ LN-40: $\pm 0.1^\circ$	0.5 Hz		LN-10 50 m LN-20 50 m LN-30 200 m LN-40 200 m	[Nishide et al., 1986]. Tokyo Aircraft Instrument Co., Ltd.
Laser scanner + bar code		Laser scanner	Barcoded target			0.033 Hz			[Murray, 1991] Caterpillar
Magnetic markers			Magnetic markers buried under path (50 ft apart)						[Murray, 1991] Eaton-Kenway



Name	Computer	Onboard Components	Stationary Components	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling rate [Hz]	Features	Note	Researchers &References
Three object triangulation	486-33 MHz	Computer vision system		Mean error (I) x=234, y=225 (G) x=304, y=301 (N) x=17, y=17 (C) x=35, y=35	Mean error (I) 4.75° (G) 141.48° (N) 2.41° (C) 5.18°	Mean time (I) 3048.7 (G) 3.8 (N) 33.5 (C) 4.8	Computer simulation for comparative study of four triangulation algorithms Accuracies are sensitive to landmark location	(I) Iterative Search (G) Geometric triangulation (N) Newton-Raphson (C) Circle intersection	[Cohen and Koss, 1992] Univ. of Michigan
Laser beam + corner cube	8086	Four laser transceivers (transmitter and receiver)	Two corner cube reflectors on both sides of the path	x=30 y=2		10 Hz			[Tsumura et al., 1988]
Ultrasonic beacons		Eight sonar receiver array (45° apart)	Six sonar beacons in a 12 m <sup>2</sup> space	Measured standard dev. of path error of 40 mm		150 ms			[Kleeman, 1992]
Infrared beacons		One optical infrared scanner	Infrared beacons	25 m <sup>2</sup> test area, beacons (0,0), (5,0) and (5,4); worst error = 70	±0.2°				[McGillem and Rappaport, 1988]
Laser scanner + corner cube	Z80	Laser scanner	Retro-reflector 45×45 m space, 3 reflectors at A(0,0), B(45,0), C(0,45)	Inside DABC: Mean=57, σ=25 Outside DABC: mean=140, σ=156 On line AB or AC mean=74, σ=57	Inside DABC: mean=0.07 σ=0.06 Outside DABC: mean=0.13 σ=0.16 On line AB or AC: mean=0.12 σ=0.05				[Tsumura and Hashimoto, 1986]
Vision camera + retro-reflectors		Vision camera + light source	Retro-reflectors on the path	Path error within 10mm, at 1m/s		10 Hz			[Takeda et al., 1986]
Three target triangulation		Detector	Active beacon	100 with very noisy measurement			Optimize using all beacon data, reweighted least square criterion		[Durieu et al., 1989]
Direction measure of several identical beacons		Laser scanner	Strips of reflective tapes	At 0.3 m/s, error <2 cm At 1 m/s, is stable At 1.5 m/s, instable			Can navigate on wet rainy field, even when the drive wheels were spinning		[Larsson et al, 1994] University of Lulea
Triangulation with more than 3 landmarks			3 to 20 beacons.	6.5 cm in 10×10 m area.	Simulation results only, but simulation includes model of large measurement errors When many beacons available, system can identify and discard outliers (i.e., large errors in the measured angles to some of the beacons)				[Betke and Gurvitz, 1994], MIT

Name	Computer	Onboard Components	Features used	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
Camera vision robot position and slippage control system	PC	Vision camera	Rectangular ceiling lights, concentric circle	<100 mm		>1 Hz			Cyberworks, Inc. [CYB]
Absolute positioning using a single image	68030, 25 MHz	Fixed vision camera (6 m high) discretization 9.5×6.0 mm for one pixel	Known pattern composed of coplanar points (IR diodes) Test pattern: 1.0×2.8 m. 84 uniformly distributed points	Accuracy: mean=2,max:10 repeatability X: mean=0.7,max: 2 $\sigma=0.8$ Y: mean: 2 max: 5, std. 2	Repeatability mean: 0.3° max: 0.7° std. 0.4°	4 Hz	Can monitor robot operation at the same time. 3-D operation.		[Fleury and Baron, 1992] Laboratoire d'Automatique et d'Analyse des Systemes
Real-time vision-based robot localization	Sun 4/280 computer Karlsruhe mobile robot (KAMRO)	780×580 CCD-camera, f=8 mm VISTA real-time image processing system	Vertical edges matching using stored map	15 mm	0.1°	2 Hz	Correspondence between observed landmarks and a stored map, give bond on the localization error	2-D operation	[Atiya and Hager, 1993] University of Karlsruhe
Robot localization using common object shapes	Sun workstation	640×400×4b CCD camera, PC-EYE imaging interface	Objects with a polygon-shaped top and a lateral surface perpendicular to the top	<5%			Sensitive at certain orientations		[Chen and Tsai, 1991] National Chiao Tung University
Omnidirectional vision navigation with beacon recognition		Vision camera with fish-eye lens	A light array (3x3)	40 mm	0.3°				[Cao et al., 1986] University of Cincinnati
Vision algorithm for mobile vehicle navigation	TRC Labmate	Vision camera	Two sets of four coplanar points are necessary	7 m distance 10%					[D'Orazio et al., 1991] Istituto Elaborazione Segnali ed Immagini
Adaptive position estimation	Litton S-800 486 control MC68000 positioning	Camera, strobe, landmark	Two circles of different radii	5 mm			Convergence 120 measurements	Adapt system model using maximum likelihood algorithm	[Lapin, 1992] Georgia Institute of Technology
Guidance system using optical reflectors	Sun	Camera, strobe light, (only on 0.3 s)	Reflector pattern mounted on the ceiling 2 m high						[Mesaki and Masuda, 1992] Secom Intelligent Systems Laboratory
Positioning using a single calibrated object		Camera	A sphere with horizontal and vertical calibration great circles	5%	5°		3-D angle error increases as great circles approach the edge of the sphere Distance error increases with the distance between the robot and landmark		[Magee and Aggarwal, 1984] University of Texas

Name	Computer	Onboard Components	Features used	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
Model based vision system	TRC LabMate 68040	512×512 gray-level CCD camera, f=6 mm	Corners of the room	100 mm middle error 2%	±3°			3-D orientation error <0.5°. if the corner is in the center of the image Large error when corner is off image center and angle coefficients of L and R are too small	[D'Orazio et al., 1993] Istituto Elaborazione Segnali ed Immagini
Pose estimation	9200 image processor	Fairchild 3000 CCD camera (256×256), f=13mm Perceptics	Quadrangular target s12=77.5,s13=177.5 s14=162,s23=160 s24=191,s34=104	At 1500 mm: 11 mm	At 1500 mm: 1.5°.			3-D volume measurement of tetrahedra composed of feature point triplets extracted from an arbitrary quadrangular target and the lens center	[Abidi and Chandra, 1990] University of Tennessee
Positioning using standard pattern			Relative displacement pattern: circle, half white & half black Identification pattern: bar code	At 5000 mm: 2.2%	Largest error: 2°			Errors increase with increasing distance, angle between landmark and camera too small or too large	[Kabuka and Arenas, 1987] University of Miami
TV image processing for robot positioning			Diamond shape, 90° angle and 23 cm each side	At 4000 mm: 70 mm	At 4000 mm: ±2°	90 s processing time	2-D	Errors increase with distance and angle too small or too large	[Fukui, 1981] Agency of Industrial Science and Technology
Single landmark navigation	ARCTEC Gemini robot	Infrared detector (angular resolution ±4°)	Infrared beacons	At 4000 mm: 400 mm At 2400 mm: 200 mm			2-D, error increases with the increase of distance between the vehicle and beacon	Running fix: using dead-reckoning info to use measurement obtained at t(k-1) at time t(k)	[Case, 1986] US Army Construction Eng. Research Lab.
Robot positioning using opto-electronic processor	386 PC Image-100 image processing board	256×256 camera, f=16 mm Hough transform filter (128×128)	Circle (R=107mm)	At 2000 mm 35 mm		30 Hz	2-D, the result is the fusion of dead reckoning and observed	Errors are function of the distance and angle	[Feng et al., 1992] University of Michigan
Global vision		Camera mounted at fixed points in the environment					Large range over which obstacles can be detected, allows global path planning	Main problems: how many cameras and where to put them?	[Kay and Luo, 1993] North Carolina State University
Robot localization using a single image		Sony CCD camera, f=8.5mm resolution = 0.12°/pixel at image center	Vertically oriented parts of fixed objects, e.g., doors, desks and wall junctions Stored map		Min. distance to landmark: 1000 mm. orientation 0.2°		2-D	Utilizes the good angular resolution of a CCD camera, avoids feature correspondence and 3-D reconstruction	[Krotkov, 1991] Laboratoire d'Automatique et d'Analyse des Systemes
Autonomous robot for a known environment (ARK)	Two VME-based cards	CCD camera, IR spot laser range-finder, custom-made pan/tilt table	"Natural" landmarks, e.g., semi-permanent structures, doorways)	On the order of centimeters				On the order of <10 m.	[AECL]

Name	Computer	Onboard Components	Features used	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
Scanning laser rangefinder				0.5%-5%		1 to 10 kHz or analog	External, local, \$10K-100K	300 m	[Parish and Grabble, 1993], Omnitech Robotics, Inc.
Scanning IR rangefinder				1%-10%		100-1000 or analog	External, local, \$5K-20K	5-50 m	[Parish and Grabble, 1993], Omnitech Robotics, Inc.
Scanning (or arrayed) ultrasonic rangefinder				1%-10%		1-100	External, local, \$100-5K	1-10 m	[Parish and Grabble, 1993], Omnitech Robotics, Inc.
Visual				1%-20%		0.1-100	External, local, \$500-50K	1-10000	[Parish and Grabble, 1993], Omnitech Robotics, Inc.
Navigation by multi-sensory integration	TRC Labmate	Cohu CCD camera, f=16 mm dead reckoning					Integrates position estimates from vision system with odometry using Kalman filter framework		[D'Orazio et al., 1993] CNR-IESI
Laserradar and sonar based world modeling	Tricycle robot	24 sonars, four laser rangefinders, rotate at 360°/s, each scan 720 range points					Utilizes heterogeneous info from laser radar and sonars		[Buchberger et al., 1993] Kaiserslautern University
Vision directed navigation	Sun Sparc for vision, Micro-VAX as host, ROBMAC100 tricycle type vehicle	Vision camera	Doors, columns	±5.0 cm	2.0°	2 Hz Convex and concave polygons	3-D		University of Waterloo [Wong and Gao, 1992]
Robot localization by tracking geometric beacons	Sun-3 for localization Sun-4 vehicle control	One rotating sonar or six fixed sonars	Geometric beacon - naturally occurring environment feature			1 Hz	EKF utilizes matches between observed geometric beacons and a priori map of beacon locations		[Leonard and Durrant-Whyte, 1991] University of Oxford
Position estimation using vision and odometry	Differential-drive vehicle 386 PC	756×581 CCD camera f=12.5 mm	Vertical edges and stored map	40 mm	0.5°		2-D - Realistic odometry model and its uncertainty is used to detect and calculate position update fused with observation	Extended Kalman filter to correct the vehicle pose from the error between the observed and estimate angle to each landmark	[Chenavier and Crowley, 1992] LETI-DSYS

Name	Computer	Onboard Components	Features used	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
Recognize world location with stereo vision		Stereo cameras	Long, near vertical stereo features				1000 real-world data recognition test, under 10% false negative, zero false positive	Least-squares to find the best fit of model to data and evaluate that fit	[Braunegg, 1993] MITRE Corp.
Environment learning using a distributed representation	Omnidirectional three-wheeled base	a ring of 12 sonars and a compass	Left wall, right wall, corridors				Dynamic landmark detection utilizing robot's motion	Learn the large-space structure of environment by recording its permanent features	[Mataric, 1990] MIT
Localization in structured environment	Motorola M68020	A ring of 24 sonars	Classify objects into edges, corners, walls, and unknown objects			0.1 Hz	Positions resulting from all possible mappings are calculated and then analyzed for clusters The biggest cluster is assumed to be at the true robot position	Each mapping of two model objects onto two reference objects correspond to a certain robot position	[Holenstein et al., 1992] Swiss Federal Inst. of Technology
Localization using sonar	SUN 4	Linear array of three sonars: A. reduce the angular uncertainty, B. help identify the target's class	Local map: feature map (extended reflectors, e.g., wall, and point reflectors)	<10 mm	<1°		Local map: feature extraction Matching: least squares EKF for estimating the geometric parameters of different targets and related uncertainty		[Sabatini and Benedetto, 1994] Scuola Superiore di Studi Universitari
Sonar-based real-world mapping	Neptune mobile robot	Sonars	Probability based occupancy grid map	Map with 3000 6 in cells made from 200 well spaced readings of a cluttered 20x20 ft room can be matched with 6 in displacement and 3° rotation in 1 s of VAX time			Map matching by convolving them It gives the displacement and rotation that best brings one map into registration with the other, with a measure of the goodness of match		[Elfes, 1987] Carnegie-Mellon University
Comparison of grid-type map building by index of performance (IOP)	Cybermotion K2A synchro-drive robot 386 20 MHz PC	A ring of 24 sonars	Histogramic in-motion mapping (HIMM) and heuristic probability function	HIMM results in a sensor grid in which entries in close proximity to actual object locations have a favorable (low) Index of performance value			Index of performance (IOP) computes the correlation between the sensed position of objects, as computed by the map-building algorithm, and the actual object position, as measured manually The IOP gives quantitative measure of the differences in the sensor grid maps produced by each algorithm type		[Raschke and Borenstein, 1990] University of Michigan
Comparison of position estimation using occupancy grid			Local map: grid map Global map: grid map	Best result obtained by matching segment to segment			Grid to segment matching: generating a mask for the segment and correlating it with the grid map	Segment to segment matching: A. orientation B. collinearity C. overlap	[Schiele and Crowley, 1994] LIFIA

Name	Computer	Onboard Components	Features used	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
Blanche	MC68020 Tricycle-type mobile robot	Optical range-finder, res.=1 in at 5 ft, 1000 samples/rev. in one s. Odometry	24 line-segment environments map for a 300×200 in room	6 in path following		Position update every 8 s for a 180 points image and a map of 24 lines. 2-D map.	(1) Least-square for data and model matching (2) Combine odometry and matching for better position estimate using maximum likelihood	Segments Assume the displacement between the data and model is small	[Cox, 1991] NEC Research Institute
Range map pose estimation	SPARC1+	1-D Laser range finder 1000 points/rev	Line segment, corner	Mean error Feature-based: 60 Iconic estimator: 40 In a 10×10 m space	Max under 1.2° for both	Feature-based: 0.32 s Iconic: 2 s	1000 points/rev. Iconic approach matches every range data point to the map rather than condensing data into a small set of features to be matched to the map		[Schaffer et al., 1992] CMU
Positioning using model-based maps		A rotatable ring of 12 polaroid sonars	Line segments	3-5 cm Coverge if initial estimate is within 1 meters of the true position			Classification of data points Weighted voting of correction vectors	Clustering sensor data points. Line fitting.	[MacKenzie and Dudek, 1994] McGill University
Positioning using optical range data	INMOS-T805 transputer	Infrared scanner	Line segment	The variance never exceeds 6 cm			Kalman filter position estimation Line fitting Matching, only good matches are accepted	When scans were taken from erroneous pos. matches consistently fail	[Borthwick et al., 1994] University of Oxford
World modeling and localization using sonar ranging		A ring of 24 sonars	Line segments	x=33 mm covariance: 1 y=17 mm covariance: 1	0.20° covariance: 17.106	A model for the uncertainty in sonars, and the projection of range measurement into external Cartesian coordinate	Extracting line segments from adjacent collinear range measurements and matching these line segments to a stored model	Matching includes: orientation, collinearity, and overlap by comparing one of the parameters in segment representation	[Crowley, 1989] LIFIT(IMAG)
2-D laser range-finder map building	Sun Sparc	Cyclone 2-D laser rangefinder accuracy ±20 cm, range 50 m	Local map: line segment map Global map: line segments	Max. 5 cm average 3.8 cm		On SUN Sparc, 80 ms for local map building and 135 ms for global map update	Matching: remove segment already in the global map from local map, add new segment	Local map: clustering clustering segmentation line fitting	[Gonzalez et al., 1994] Universidad de malaga

Name	Computer	Onboard Components	Features used	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Notes	Reference
Iconic position estimator	Locomotion emulator, all-wheel drive and all-wheel steer, Sun Sparc 1	Cyclone laser range scanner, resolution =10 cm range = 50m 1000 readings per rev.	In general, has a large number of short line segments	Max. 36 mm mean 19.9 mm	Max. 1.8° mean 0.73°		Iconic method works directly on the raw sensed data, minimizing the discrepancy between it and the model	Assume small displacement between sensed data and model Two parts: sensor to map data correspondence & error minimization	[Gonzalez et al., 1992] Carnegie Mellon University
Environment representation from image data			Geometrical relationships between observed features rather than their absolute position				A graph where the nodes represent the observed features and edges represent the relationships between features	The recognition problem can be formulated as a graph matching problem	[Taylor, 1991] Yale University
Localization via classification of multi-sensor maps		Sonars Lateral motion vision Infrared proximity sensor	Local map: multi-sensor 100×100 grid maps, cell 20×20 cm	Using datasets from 10 rooms and hallways, estimate a 94% recognition rate for rooms, and 98% for hallways		Local grid maps Feature-level sensor fusion by extracting spatial descriptions from these maps	Positioning by classifying the map descriptions to recognize the workspace region that a given map represents	Matching: K-nearest neighbor and minimum Mahalanobis distance	[Courtney and Jain, 1994] Texas Instruments, Inc.

## Systems-at-a-Glance Tables

## Other Navigation Techniques

Name	Computer	Onboard Components	Maps and Features	Accuracy - position [mm]	Accuracy - orientation [°]	Sampling Rate [Hz]	Features	Effective Range, Nnotes	Reference
Guide path sensor (magnetic, optical, inductive, etc.)				0.01-0.1 m		100-1000 or analog	External, local, or waypoint indication, \$100-\$5K	0.01-0.2 m	[Parish and Grable, 1993] Omnitech Robotics, Inc.
Odor trails for navigation		Applicator for laying volatile chemicals on the floor; olfactory sensor						Unlimited	[Russell et al., 1994] Monash University
Thermal path following		Quartz halogen bulb and pyroelectric sensor				0.833	No need to remove markers after use	Unlimited	[Kleeman and Russell, 1993] Monash University

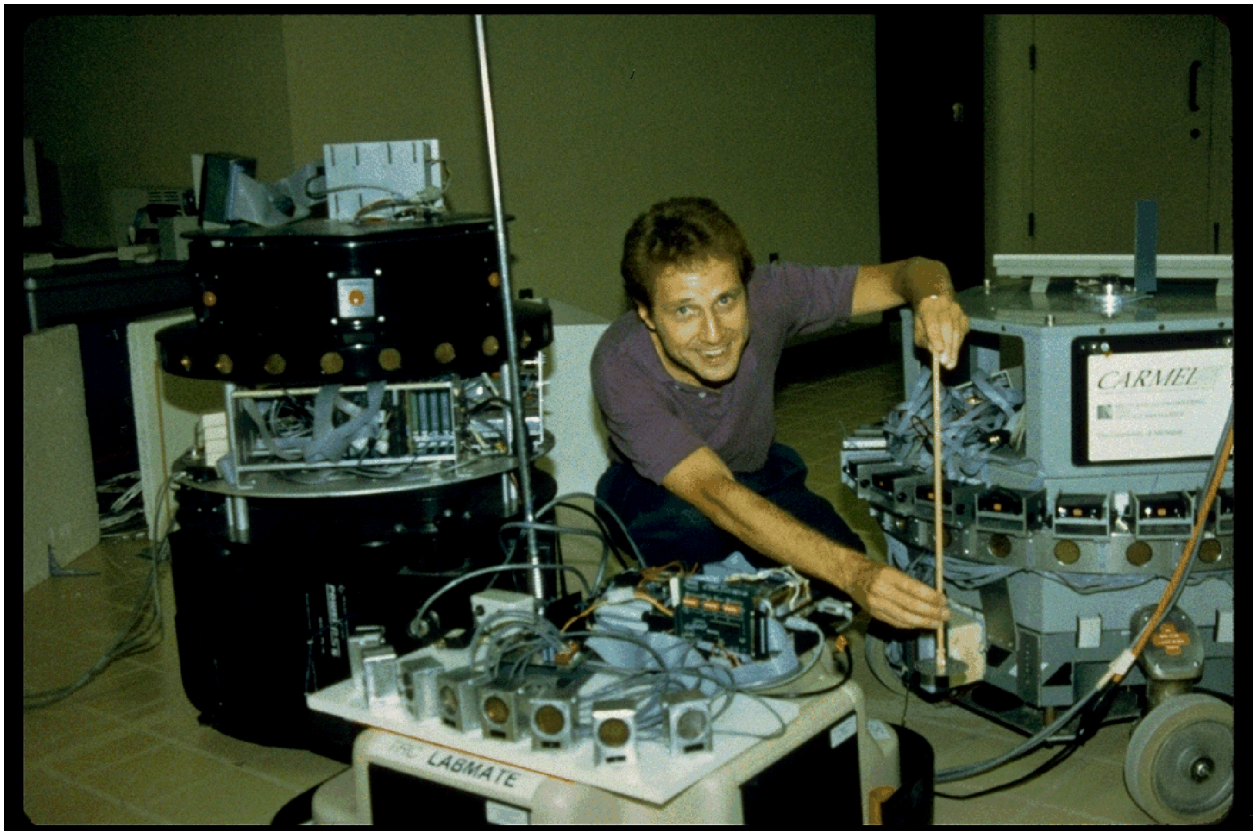


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# References

## Subject Index

## Author Index



University of Michigan grad. student Ulrich Raschke verifies the proper alignment of ultrasonic sensors. All three robots in this picture use 15°-angular spacing between the sensors. Many researchers agree that 15 ° spacing assures complete coverage of the area around the robot.

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## SUBJECT INDEX

- AC ..... 47, 59, 65, 81, 82, 103, 226, 246  
acceleration ..... 10, 73, 146, 220, 223  
accelerometer ..... 146, 147, 223  
accumulate ..... 131  
AccuRange ..... 117-119  
Ackerman ..... 21, 22, 138  
acoustic ..... 115, 247  
acousto-optical ..... 115  
acquisition ..... 71, 82, 111, 159, 164, 166, 173, 201, 254, 259  
active ..... 10, 11, 35, 36, 38, 39, 42, 62, 65, 68, 93, 95, 99, 151, 152, 155, 158, 163, 169, 170, 172, 176, 183, 197, 198, 217, 225, 226  
active/passive ..... 93  
actuators ..... 62, 169, 248, 255  
AGC ..... 116  
AGV ..... 15, 21, 160, 161, 165, 176, 178, 246, 252  
airborne ..... 17, 107  
aircraft ..... 42, 65, 76, 145  
airplanes ..... 10, 33, 151  
air-core ..... 53  
algorithm ..... 12, 26, 57, 107, 144, 152-154, 175, 187, 190, 191, 193, 194, 198, 199, 203-205, 209-212, 214, 227, 232, 241  
alignment ..... 23, 32, 46, 57, 61, 166, 200, 212, 235  
all-solid-state ..... 43  
all-terrain ..... 22  
almanac ..... 71, 93  
alphanumeric ..... 175  
altimeters ..... 107  
altitude ..... 70  
amorphous ..... 60  
amplitude ..... 63, 95, 101, 112, 113, 117, 118, 121-123, 240  
    -induced ..... 121  
    -modulated ..... 42, 95, 123, 255  
AMR ..... 59  
analog ..... 34, 35, 42-44, 47, 52, 54-59, 62, 63, 98, 101, 103, 108, 113, 118, 161, 222, 223, 230  
analog-to-digital ..... 101  
Andros ..... 28, 29, 139  
annealed ..... 62  
antenna ..... 67, 79-81, 83, 91, 93, 125, 126  
ARK ..... 174, 175, 229, 246  
Army ..... 103, 228, 249, 257  
arrays ..... 109, 110, 159, 160, 207  
arsenide ..... 57, 58, 92  
ASCII ..... 93  
associative location ..... 69  
asynchronous ..... 16, 88  
atmospheric ..... 72, 73, 77  
atom ..... 71  
attention ..... 59, 79, 207  
attenuation ..... 41, 79  
attractive ..... 10, 42, 43, 146  
audible ..... 126  
Case ..... 153  
AutoCad ..... 169  
autocalibration ..... 69  
AUTOGYRO ..... 43, 44, 223  
autonomous ..... 22, 28, 29, 45, 66, 102, 116, 143, 146, 163, 171, 179, 180, 229, 238-246, 248-250, 252, 253, 255, 259, 260  
AutoSense ..... 104-106  
auto-compensation ..... 57  
availability ..... 73, 75, 78, 93, 97, 109  
backscatter ..... 38, 107  
balanced-mirror ..... 118  
balanced-mixer ..... 126  
bandwidth ..... 14, 43, 44, 59, 127  
bar-code ..... 176, 178  
baseline ..... 65, 216  
base-station ..... 76  
baud ..... 56, 57, 92, 93  
beacon ..... 15, 65, 69, 118, 151-153, 155, 158-160, 163-166, 169, 172, 176, 183, 195, 225-228, 230, 240, 260  
beam ..... 13, 16, 18, 36-38, 42, 61-63, 96, 100, 102-105, 107-109, 112, 114-119, 123, 125, 152, 159, 160, 163, 165-167, 170, 178, 225, 226, 253  
beamwidth ..... 97, 98, 121, 126  
bearing ..... 46, 70, 75, 76, 119, 138, 143, 158, 161, 163, 164, 175, 222, 225  
belt-drive ..... 23  
benchmark ..... 132, 134, 222, 239  
bias ..... 42-44, 49, 62, 137, 147, 148, 178  
bias-free ..... 137  
bidirectional ..... 134, 136, 142, 222  
binary ..... 16, 17, 92, 93, 110, 111  
    -coded ..... 16, 17, 176  
binoculars ..... 107  
bipolar ..... 121, 248  
bistatic ..... 97, 98, 127  
Blanche ..... 198, 199, 222, 232  
blank ..... 100  
blind ..... 125-128, 244  
blockages ..... 84, 93  
boron ..... 62  
bounded ..... 11, 77, 187, 210  
break-beam ..... 13, 16  
broadcast ..... 65, 93  
buffer ..... 115, 116

- building . . . . . 95, 164, 185, 186, 193, 194, 202-204,  
207, 214-216, 232, 233, 244, 250-252, 256,  
258
- bumper . . . . . 127
- bursts . . . . . 101
- bus . . . . . 116, 126, 254
- B-field . . . . . 49, 51, 58
- B-H curve . . . . . 48, 49
- C100 . . . . . 56, 57, 256
- calculation . . . . . 30, 70, 95, 161, 188, 218
- calibrated . . . . . 60, 121, 209, 228, 248
- CALMAN . . . . . 171
- camera . . . 99, 109-111, 116, 174, 175, 207-213, 216,  
226-231, 236, 247, 248, 252, 253, 255
- camera-calibration . . . . . 211
- camphor . . . . . 182
- cantilever . . . . . 63
- canyon . . . . . 88-91, 258
- capacitor . . . . . 93, 101, 113
- capacity . . . . . 185
- CARMEL . . . . . 12, 129, 241
- carrier . . . . . 19, 66, 73, 76, 77, 123, 174, 193  
-phase-differential . . . . . 77
- carrying . . . . . 134
- Cartesian . . . . . 199, 203
- castor . . . . . 131, 137
- Caterpillar . . . . . 176, 178, 225, 255
- CCD . . . . . 110, 111, 174, 175, 207, 227-231
- ccw . . . . . 30, 134, 135, 137, 139, 140
- CDMA . . . . . 69
- ceiling . . . . . 157, 174, 183, 227  
-mounted . . . . . 19, 52, 56, 158, 165, 166, 170
- cells . . . . . 58, 188, 197, 231, 248
- centroid . . . . . 154, 186
- cesium-clock . . . . . 71
- cesium . . . . . 71, 72, 76
- chained . . . . . 166
- channel . . . . . 14, 15, 47, 51, 67, 78, 155, 224
- checksum . . . . . 157
- chemical . . . . . 62, 182
- chip . . . . . 15, 58, 71, 72, 76, 244
- chirp . . . . . 99
- CLAPPER . . . . . 143, 222, 238, 239
- classification . . . . . 105, 203, 232, 233, 241
- Class-I . . . . . 178
- clean-room . . . . . 23, 39
- cliffs . . . . . 88, 237
- closed-loop . . . . . 15, 35-37, 42, 50, 59
- closed-ring . . . . . 51
- coalition . . . . . 73
- coarse-to-fine . . . . . 175, 216
- coaxial . . . . . 114, 116, 118
- code . . . . . 12, 16, 17, 69, 71-73, 76, 77, 176, 178,  
212, 223, 225, 228
- codeless . . . . . 77
- code-division-multiple-access . . . . . 69
- coil . . . . . 42, 43, 47, 49, 50, 52, 53, 56, 57, 59, 62
- collapsed . . . . . 208
- collimated . . . . . 116, 117
- collinear . . . . . 75, 165, 199, 233
- collision . . . . . 97, 107, 125-127, 240, 245, 247, 254
- columnar . . . . . 83
- compact . . . . . 101, 163
- compass . . . 31, 45-47, 52-59, 61, 77, 182, 229, 231,  
244, 248, 254, 256
- compensation . . . 24, 57, 69, 142, 150, 157, 223, 240
- compliant . . . . . 27, 28, 143, 144, 222, 238, 239
- complimentary . . . . . 17, 159
- composite . . . . . 76, 111, 185, 200
- compressible . . . . . 138
- CONAC . . . . . 166, 225
- concealed . . . . . 134
- concentrators . . . . . 57, 63
- conductor . . . . . 17, 57, 166
- cone-shaped . . . . . 152, 155
- congruence . . . . . 198
- constant-slope . . . . . 148
- constrained . . . . . 28, 40, 164, 187, 198, 215
- consumption . . . . . 24, 47, 52, 53, 55, 59, 93, 100,  
126, 163, 164
- contamination . . . . . 92, 179
- continuous-wave . . . . . 66, 114, 115, 121
- contour . . . . . 217
- contrast . . . . . 25, 41, 58, 73, 137, 139, 153, 173, 175-  
177, 183, 196, 207, 211
- convoy . . . . . 76
- cooperative . . . . . 102, 108, 114, 163, 222
- core-cladding . . . . . 40
- Coriolis . . . . . 33, 34
- correction . . . 30, 46, 57, 60, 76, 139, 141, 143-145,  
156, 157, 159, 178, 180, 186-188, 192, 198-  
200, 232, 238, 239, 242
- correlation . . . . . 71, 175, 188, 192, 216, 232, 254
- correspondence . . . 27, 110, 185, 187, 189, 199, 209,  
211, 213, 214, 216, 227, 248, 253
- covariance . . . . . 194, 200, 201, 218, 232
- cranes . . . . . 107
- crosstalk . . . . . 38, 96, 97, 123, 158
- cross-correlation . . . . . 192
- cross-referenced . . . . . 66
- cryogenically . . . . . 63
- cryptographic . . . . . 72
- crystal . . . . . 54, 60, 61, 71, 182
- CT . . . . . 119, 163, 258
- current-loop . . . . . 108
- curvature . . . . . 141
- CW . . . . . 30, 115, 134, 135, 137, 139, 140
- C-band . . . . . 68
- daisy . . . . . 166
- data-gathering . . . . . 108

- Datums ..... 166  
 DC ..... 15, 33, 49, 51, 57-60, 81, 82, 179, 249, 252  
 dead-reckoning ..... 17, 19, 21, 28, 45, 54, 130, 131,  
     133, 137, 146, 167, 179, 195, 203, 222, 228,  
     238, 239, 243, 247, 253  
 degradation ..... 23, 73  
 degree-of-freedom ..... 25-28, 46, 56, 239  
 depth ..... 14, 36, 78, 111, 200, 202, 261  
 derivation ..... 141  
 Desert Storm ..... 73  
 detection ..... 11, 41, 59, 69, 70, 95-97, 100, 101,  
     104-106, 109-116, 118, 119, 125-128, 155-  
     157, 159-161, 163, 166, 173-177, 183, 186,  
     188, 200, 202, 231, 236, 243, 245, 246, 258,  
     260  
 detection/gating ..... 111  
 detector ..... 16, 35, 96, 101, 103-105, 107, 112,  
     121, 126, 158, 160, 172, 225, 226, 228  
 DGPS ..... 75-77, 249  
   -capable ..... 76  
 diagnostic ..... 71  
 diaphragm ..... 99  
 dielectric ..... 126  
 differential ..... 14, 19, 21, 23-25, 27, 28, 49, 75-77,  
     82, 92-94, 112, 114, 132-134, 137-139, 179,  
     181, 182, 222, 231, 243, 249  
   -capable ..... 76  
   -drive ..... 19, 21, 23-25, 27, 28, 132-134, 138,  
     222, 238, 239, 243, 244  
 differentially ..... 138, 143  
   -steered ..... 21, 22  
 digital ..... 13, 14, 33, 35, 42, 44, 47, 54-57, 66,  
     69, 98, 101, 103, 108, 109, 116, 126, 213-  
     215, 244  
 diode ..... 41, 101, 103, 104, 107, 115, 117, 120,  
     125, 241, 252  
 DIP ..... 46, 167  
 dipoles ..... 60, 61  
 direct-memory-access ..... 116  
 distinguishable ..... 159, 175, 184, 204, 209, 210  
 distort ..... 191  
 distribution ..... 23, 54, 86, 134, 139, 181, 191, 197,  
     210, 216  
 disturbance ..... 136, 146, 222  
 dither ..... 38, 73  
 divergence ..... 107-109, 118, 119, 163  
 dock ..... 158, 159  
 docking ..... 15, 158, 159, 168  
 dock-mounted ..... 158  
 domain ..... 212  
 doorway ..... 120, 175  
 DOP ..... 75, 79-81, 83, 86-88, 91  
 doppler ..... 17-19, 73, 114, 124-126, 223  
 dots ..... 176, 198  
 dot-matrix ..... 15  
 double-sided ..... 158  
 downlink ..... 158  
 downloading ..... 71  
 drift ..... 17, 30-34, 42-44, 56, 59, 77, 145-148, 223  
 drive ..... 16, 19-28, 49-51, 53, 54, 62, 132-134, 137-  
     139, 143, 179, 222, 226, 231-233, 237-239,  
     243, 244, 251, 255-258  
   -motor ..... 15, 160  
 DSP ..... 126  
 dual  
   -axis ..... 32, 37, 38, 43, 51, 52, 56, 58, 59, 61,  
     119, 147, 169, 201, 236  
   -frequency ..... 65, 77, 112, 121, 159  
 duty ..... 24, 99, 117, 127  
 dynamic ..... 11, 34, 42, 78-84, 88, 90-92, 94, 96,  
     118, 146, 197, 231  
 earth ..... 17, 30-32, 45-47, 70-72, 245  
   -based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69,  
     71, 76, 95, 96, 101, 109, 112, 115, 121, 125,  
     146, 150, 163, 172-174, 183-188, 194-199,  
     203, 206, 207, 231, 232, 236, 242, 248, 252,  
     259, 260  
 EEPROM ..... 57, 92, 126  
 efficiency ..... 143  
 EKF ..... 147, 148, 230, 231  
 elasticity ..... 60, 63  
 electro  
   -optics ..... 101-106, 257, 258  
   optical ..... 115, 164  
 electrostatic ..... 62, 63, 99, 257  
 elimination ..... 166  
 elongation ..... 62  
 emergency ..... 67  
 emission ..... 38, 110, 155  
 emitter ..... 17, 103, 117, 158, 159  
 emitter/detectors ..... 158, 159  
 enable/disable ..... 103  
 encoder ..... 13-17, 20, 21, 24, 25, 28, 35, 103,  
     117, 130, 131, 138, 139, 143-145, 166, 222,  
     238,  
     243, 245  
 encoding ..... 13, 16, 109-111  
 encryption ..... 72  
 endurance ..... 194  
 end-effector ..... 156  
 engine ..... 22, 56, 67, 78-80, 83-88, 90-92, 224, 256  
 ENSIGN ..... 73  
 envelope ..... 96, 103, 155, 258  
 Ephemeris ..... 71, 73, 93  
 equator ..... 31, 46, 58, 70  
 error ..... 10, 17, 30, 44, 46, 53, 54, 59, 66, 72-77,  
     80, 82-88, 91, 95, 96, 106, 121, 130-149,  
     152-156, 162, 171, 179, 180, 185-187, 194,  
     196-199, 201, 203, 206, 210, 216, 218, 222,  
     226-228, 231-233, 259

- inducing ..... 59
- ESP ..... 116, 117, 121, 122, 189, 256
- estimation ..... 11, 76, 77, 91, 97, 130, 131, 148-150, 157, 175, 185, 187, 189, 197, 202, 203, 213-218, 227, 228, 232, 236, 240, 241, 245, 247, 252-254, 261
- etched ..... 13, 62, 125, 126, 153, 154, 187, 232, 233, 244
- array ..... 125, 126
- Ethernet ..... 119
- ETL ..... 77
- Euclidean ..... 199
- Evaluation ..... 4, 51, 57, 77-79, 240, 243
- excitation ..... 47, 49-53, 59, 63
- exclusive-or ..... 113
- experimental ..... 92, 134, 138, 143-145, 150, 171, 181, 189, 194, 195, 201, 204, 253, 254
- experimenter ..... 132, 133
- extrinsic ..... 208, 211, 213
- eye ..... 103, 107, 116, 120, 163, 164, 174, 227
- safe ..... 103, 116, 120, 163, 164
- Falcon ..... 68, 257
- fan-shaped ..... 103-105, 163
- fast-growing ..... 143, 144
- feature-based ..... 183, 187, 194, 195, 232
- feature-level ..... 186, 204, 233
- feature ..... 126, 157, 159, 164, 174, 181, 183, 185-188, 193-195, 204, 208, 211, 212, 215, 216, 228-233, 237, 253
- ferrite ..... 57, 58, 180
- ferromagnetic ..... 60
- ferrous ..... 49
- fertilizer ..... 17
- FET ..... 121
- fiber ..... 10, 32, 34-36, 39-44, 61, 62, 108, 146, 148, 150, 223, 236, 243, 247, 248, 250, 252, 254
- optic ..... 10, 32, 34-36, 39, 41-43, 61, 62, 146, 150, 236, 237, 240, 248
- optically ..... 108
- fiberglass ..... 104
- field-of-view ..... 110, 161
- filter ..... 56, 76, 107, 116, 123, 147, 148, 150, 181, 210, 216, 218, 228, 230-232, 241
- Fischler ..... 212, 243
- fixed
  - length ..... 40, 135
  - location ..... 66-68, 96, 154, 156, 157, 165, 166, 169, 260
  - reference ..... 65, 222, 243
- flexible ..... 92, 93
- floating ..... 46, 56, 93
- fluctuating ..... 54
- fluid ..... 46, 56
- flux ..... 45-52, 57, 58, 63
- gathering ..... 50, 108
- fluxgate ..... 45, 47-49, 51-57, 59, 222, 223, 236, 250
- flywheel ..... 30
- FM ..... 42, 76, 95, 123, 124, 165
- FMCW ..... 125, 127, 128
- fog ..... 178
- foliage ..... 77, 79, 88, 90, 93
- force ..... 23, 26, 27, 30, 34, 46-49, 52, 71, 73, 138, 220, 251
- forward-looking ..... 17
- FP-G154 ..... 33
- fractional ..... 114, 155
- free
  - ranging ..... 115, 163, 178, 246
  - running ..... 97
  - space ..... 199
- frequency
  - modulated ..... 42, 95, 123, 255
  - modulation ..... 125
  - to-voltage ..... 118
- Fresnel ..... 116
- frictional ..... 24
- fringe ..... 41
- front
  - mounted ..... 19, 52, 56, 158, 165, 166, 170
  - surfaced ..... 119
- fuel ..... 67
- full-duplex ..... 158
- fusing ..... 46, 149, 216, 218, 254
- fusion ..... 69, 148, 185, 186, 204, 206, 216, 218, 228, 233, 236, 249, 254, 260
- GaAlAs ..... 115
- GaAs ..... 103
- gain ..... 11, 38, 100, 113, 116, 117, 121
- Gallium ..... 92
- gamma ..... 45
- gasoline ..... 22
- gate ..... 113
- gated ..... 103, 110
- gateways ..... 204
- gating ..... 47-49, 110, 111, 250
- Gauss ..... 45, 57-59, 61-63
- Gaussian ..... 210, 216, 218
- GDOP ..... 75, 76, 87
- GE9300-C ..... 33
- gear ..... 15, 20, 23, 24, 179
- drive ..... 19, 21, 23-25, 27, 28, 132-134, 138, 222, 238, 239, 243, 244
- generator ..... 59
- Genghis ..... 155
- geodetic ..... 65, 77
- geographical ..... 45
- geomagnetic ..... 45-47, 51, 52, 57-59
- gimbal-mounted ..... 52, 56
- gimbal ..... 31, 46, 52, 56



- glass ..... 13, 37, 39, 40, 58, 62  
   -ceramic ..... 37  
   -epoxy ..... 58  
 global ..... 11, 65, 69, 70, 72, 76, 151, 153, 164,  
   176, 177, 184, 187-189, 196, 198, 199, 203,  
   206, 222, 223, 229, 232, 233, 242, 244, 246,  
   249, 252  
 globe ..... 31, 46  
 glycerine ..... 46  
 GMR ..... 59  
 gold-film ..... 63  
 GPS .... 65, 69-88, 90-92, 151, 154, 224, 236, 241,  
   244, 245, 247, 255, 256  
 GPS/INS ..... 76, 245  
 gravitational ..... 34, 146, 251  
 gravity ..... 21, 32, 42, 135, 146  
 grid ..... 66, 67, 186, 188, 189, 196-199, 203, 204,  
   231-233, 250  
   -based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69,  
   71, 76, 95, 96, 101, 109, 112, 115, 121, 125,  
   146, 150, 163, 172-174, 183-188, 194-199,  
   203, 206, 207, 231, 232, 236, 242, 248, 252,  
   259, 260  
   -map ..... 198, 199  
 grill ..... 125  
   -mounted ..... 19, 52, 56, 158, 165, 166, 170  
 ground ..... 17-19, 21, 22, 65, 66, 68-71, 73, 81, 83,  
   131, 138, 139, 145, 236, 245, 253, 259  
   -based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69,  
   71, 76, 95, 96, 101, 109, 112, 115, 121, 125,  
   146, 150, 163, 172-174, 183-188, 194-199,  
   203, 206, 207, 231, 232, 236, 242, 248, 252,  
   259, 260  
   -speed ..... 14, 16, 18, 69, 101, 146  
   -wave ..... 14, 35, 49, 59, 60, 66, 113-115, 117,  
   121, 125  
 grounding ..... 121, 123  
 guidance .... 165, 180, 223, 227, 237, 241, 244, 245,  
   248-251, 253, 254, 259-261  
 gyro ..... 30-42, 44, 55, 56, 146-150, 223, 229,  
   236, 237, 240, 254  
 gyrocompass ..... 31, 32, 55, 179  
 GyroEngine ..... 33, 223  
 GyroPoint ..... 33  
 gyroscope ... 30-34, 43, 44, 147, 148, 223, 241, 247,  
   248, 252  
 Gyrostar ..... 33, 34, 147, 148, 223  
 hairpin ..... 168  
 Hall ..... 45, 47, 57-59, 233, 237, 240, 248, 259  
   -effect ..... 19, 45, 47, 57-59  
 halogen ..... 181, 234  
 handshake ..... 16  
 hand-held ..... 170, 225  
 hard-wired ..... 103, 155  
 harmonic ..... 51, 52  
 hazardous ..... 65, 126, 237  
 HCTL ..... 15, 16  
 He ..... 52, 107, 118, 160, 199, 210  
 heading .... 15, 21, 22, 24, 30, 45-47, 53, 54, 57, 58,  
   66, 80, 143, 144, 148, 150, 153, 159, 163-  
   166, 169, 187, 214, 247, 253  
 helicopter ..... 33, 103, 258  
 helium-neon ..... 36  
 HelpMate ..... 16  
 hemisphere ..... 30  
 hemispherical ..... 103  
 HERMIES-III ..... 26, 250, 251  
 heterodyne ..... 118  
 heterodyning ..... 112  
 heterogeneous ..... 186, 230  
 heuristic ..... 199  
 high  
   -accuracy ..... 33, 151, 154, 156, 242  
   -end ..... 145, 161  
   -frequency ..... 65, 77, 112, 121, 159  
   -performance ..... 38  
   -permeability ..... 63  
   -power ..... 57, 65  
   -precision ..... 32  
   -pulse-repetition-rate ..... 103  
   -resolution ..... 17, 60, 179, 250  
   -sensitivity ..... 61  
   -shock ..... 16  
   -speed ..... 14, 16, 18, 69, 101, 146  
   -temperature ..... 16  
   -to-low ..... 100  
   -tolerance ..... 39  
 highway ..... 88, 90, 91, 105, 167, 256  
 histogram ..... 189-192, 197, 238  
 histogrammic ..... 86, 232, 238  
 HMMWV ..... 23  
 hobbyists ..... 32  
 homing ..... 15  
 horizon ..... 66, 83, 178, 225  
 hospitals ..... 173, 242  
 host ..... 57, 116, 126, 166, 167, 230  
 hostile ..... 73  
 Hough ..... 176, 228  
 household ..... 136  
 humidity ..... 96, 155, 157  
 hybrid ..... 131, 155, 169, 175, 179  
 Hydro ..... 174  
 hyperbolic ..... 65, 66  
 hysteresis ..... 48-50, 87  
 H-field ..... 49, 50  
 IC ..... 58, 59, 92  
 iconic ..... 187, 232, 233, 244  
 icon-based ..... 187  
 IFOG ..... 40-43  
 illumination ..... 107, 166

- image . . . . 3, 105, 106, 109, 110, 120, 175, 176, 187,  
 188, 198, 199, 207-209, 211-217, 227, 228,  
 232, 233, 243, 244, 247, 248, 252, 253, 259,  
 260  
   -based . . . . 11, 13, 15, 17, 23, 30, 58, 65, 68, 69,  
 71, 76, 95, 96, 101, 109, 112, 115, 121, 125,  
 146, 150, 163, 172-174, 183-188, 194-199,  
 203, 206, 207, 231, 232, 236, 242, 248, 252,  
 259, 260  
 imaginary . . . . . 21, 22, 31  
 imbalances . . . . . 31  
 immobile . . . . . 177  
 immunity . . . . . 13, 17, 82  
 impact . . . . . 46, 136  
 Imperial . . . . . 165  
 impulse . . . . . 116  
 inaccuracies . . . . . 96, 130, 190, 203  
 incline . . . . . 21  
 incremetal . . . . . 180  
 index . . . . 14, 15, 38-40, 43, 57, 166, 232, 235, 250,  
 262, 279  
 indexed . . . . . 166  
 indium-antimonide . . . . . 57, 59  
 indium-arsenide-ferrite . . . . . 58  
 indoor . . . . 24, 46, 65, 67, 70, 97, 131, 166, 169, 171,  
 180, 184, 202, 203, 213, 225, 242, 251, 254,  
 261  
   indoors . . . . . 69  
 induced . . . . . 21, 36, 42, 52, 62, 71, 121  
 inductive . . . . . 13, 104, 234  
 inductor . . . . . 51  
 inert . . . . . 46, 56  
 inertia . . . . . 31  
 inertial . . . . . 10, 15, 17, 30, 31, 34, 35, 77, 145,  
 146, 150, 156, 207, 216, 223, 237, 251, 254  
 infogeometric . . . . . 69, 70, 245  
 infrared . . . . 104, 107, 116, 117, 151, 158-160, 163,  
 172, 179, 181, 186, 225, 226, 228, 232, 233  
 InGaAs . . . . . 101, 104  
 initialization . . . . . 15, 211  
 injecting . . . . . 42  
 INS . . . . . 76, 77, 145-147, 245  
 insecticides . . . . . 103  
 insensitivity . . . . . 42  
 instabilities . . . . . 14, 38  
 instantaneous . . . . . 21, 44, 51, 52, 62, 144  
 instrument-grade . . . . . 99  
 Intel . . . . . 100, 126  
 intelligent . . . 105, 153, 163-165, 225, 228, 236-239,  
 241-243, 246, 247, 249-254, 256, 258, 259  
 intensifiers . . . . . 110  
 intensity . . . . 34, 35, 42, 45, 59, 62, 96, 100, 106,  
 116, 121, 122, 181, 236  
 interferometer . . . . . 38, 61, 254  
 intersection . . . . . 153  
 interval . . . . . 14, 15, 20, 44, 66, 111, 113, 114, 124,  
 144, 155  
 inter-robot . . . . . 155  
 intolerance . . . . . 52  
 intrinsic . . . . . 208, 209, 211  
 IPEC . . . . . 143-145  
 IR . . . . . 174, 225, 227, 229, 230  
 iron . . . . . 46-48, 61, 62  
 irregularities . . . . . 131, 138, 162  
 J1455 . . . . . 99  
 jamming . . . . . 70  
 K2A . . . . . 15, 24, 25, 158, 174, 232  
 K2A+ . . . . . 174  
 K3A . . . . . 24  
 Kalman . . . . . 76, 147, 148, 150, 181, 185, 200, 210,  
 216, 218, 230-232, 239, 241  
   -filter-based . . . . . 76  
 Kaman . . . . . 66, 67, 256  
 kinematic . . . . . 19, 137, 138, 143, 238, 239  
 kinematics . . . . . 138  
 KMZ10B . . . . . 59  
 knife-edge . . . . . 222  
 LA . . . . . 155, 244, 247  
 LabMate . . . . . 16, 19, 27, 134, 136, 137, 157, 222,  
 227, 228, 230  
 Lambertian . . . . . 101  
 landmark . . . . 10, 11, 13, 15, 17, 23, 30, 58, 65, 68,  
 69, 71, 76, 95, 96, 101, 109, 112, 115, 121,  
 125, 130, 131, 146, 150, 153, 163, 172-176,  
 179, 180, 183-188, 194-199, 203, 206, 207,  
 209, 210, 217, 226-229, 231, 232, 236, 240,  
 242, 248, 249, 252, 259-261  
 lane . . . . . 104, 105, 258  
 large-diameter . . . . . 24  
 laser . . . . . 10, 34-39, 41-44, 61, 65, 66, 101-104,  
 107-112, 115-119, 125, 146, 152, 160, 163-  
 167, 169-172, 174-176, 178, 186, 191, 207,  
 216, 223, 225, 226, 229, 230, 232, 233, 236-  
 238, 240, 241, 244, 245, 247-249, 252-255,  
 257, 258, 261  
   -based . . . . 11, 13, 15, 17, 23, 30, 58, 65, 68, 69,  
 71, 76, 95, 96, 101, 109, 112, 115, 121, 125,  
 146, 150, 163, 172-174, 183-188, 194-199,  
 203, 206, 207, 231, 232, 236, 242, 248, 252,  
 259, 260  
   -diode . . . . . 104  
   -energy . . . . . 109  
   -guided . . . . . 66, 176  
   -radar . . . . . 19, 186, 245  
 LaserNav . . . . . 162, 163, 225  
 LASERNET . . . . . 160-162, 225  
 latch . . . . . 100  
 latency . . . . . 146  
 lateral . . . . . 22, 24, 30, 63, 66, 143, 144, 160, 177,  
 178, 180, 227, 233

- lateral-post ..... 177
- latitude ..... 30, 46, 66, 70, 80, 83, 84, 87
- lattice ..... 60, 61
- lawnmower ..... 171
- LCD ..... 54, 55, 82
- lead ..... 76, 82, 133
- leader/follower ..... 76
- learning ..... 188, 231, 242, 249, 260
- least-square ..... 232
- LED-based ..... 163
- LED ..... 116, 120, 126, 158, 159, 163, 176
- length-to-diameter ..... 49
- lenses ..... 104, 110, 158, 253
- lexan ..... 56
- lidar ... 101, 107, 118, 119, 121-123, 186, 189, 190
- light ..... 10, 13, 14, 16, 18, 34-37, 39-43, 61, 62, 68, 71, 95, 96, 101, 104, 107, 110, 111, 114-121, 123, 124, 158, 159, 163, 176, 181, 223, 226, 227, 236, 258
  - based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69, 71, 76, 95, 96, 101, 109, 112, 115, 121, 125, 146, 150, 163, 172-174, 183-188, 194-199, 203, 206, 207, 231, 232, 236, 242, 248, 252, 259, 260
  - weight ..... 107
- lighting ..... 119, 179, 183
- LightRanger ..... 120, 163
- linearity ..... 38, 58, 121, 122, 124, 125
- linearization ..... 199
- linearized ..... 153, 199
- line-of-position ..... 65
- line-of-sight ..... 66-68, 70, 76, 166, 167, 169, 225
- linkage ..... 27, 28, 50, 51, 143, 144, 222, 238, 239
- liquid ..... 54
- Lithium ..... 92, 93, 181
- live-fire ..... 66
- load-bearing ..... 138, 222
- localization ... 65, 173, 174, 176, 202, 203, 207-209, 211, 213, 215, 216, 227, 229-233, 236, 237, 241, 244, 245, 247, 248, 251, 253, 254, 259, 261
- lock-in ..... 38
- locomotion ..... 13, 233
- locus ..... 21
- longitude ..... 66, 70, 80, 83, 84, 87
- look-up ..... 57, 101
- loops ..... 66, 104
- Loran ..... 65-67
- Loran-type ..... 66
- low
  - accuracy ..... 33, 151, 154, 156, 242
  - coherence ..... 41
  - cost ..... 13, 32, 39, 42, 43, 47, 51, 52, 56, 59, 61, 97, 116, 119, 146, 154, 163, 166, 242, 244
  - friction ..... 31, 47
  - loss ..... 43, 69, 186, 204, 233
  - power ..... 57, 65
  - priced ..... 57
  - speed ..... 14, 16, 18, 69, 101, 146
- LSS390 ..... 109
- M113-based ..... 17
- Mach-Zender ..... 61
- magnet ..... 46, 47, 180
- magnetic ..... 13, 31, 37, 38, 45-54, 56-63, 71, 81, 123, 182, 222, 223, 225, 234, 242, 244, 245, 248, 251, 255
- magnetically ..... 62
- magnetite ..... 46
- magnetization ..... 49, 50, 59, 60
- magnetized ..... 46
- magnetizing ..... 47-49, 52
- magnetoelastic ..... 45, 60-63, 243
- magnetomechanical ..... 62
- magnetometer ... 47, 48, 50, 52, 58, 59, 61-63, 236, 243, 250, 255
- magnetoresistive ..... 45, 59, 61, 242, 247
- magnetostriction ..... 60, 61
- magnetostrictive ..... 60, 61
- manifold ..... 103
- manipulating ..... 33
- map ..... 11, 95, 111, 123, 150, 153, 164, 173, 174, 184-188, 190, 193, 194, 196-199, 201-204, 206, 207, 211, 214-217, 227, 229-233, 239, 242, 250-252, 260
  - based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69, 71, 76, 95, 96, 101, 109, 112, 115, 121, 125, 146, 150, 163, 172-174, 183-188, 194-199, 203, 206, 207, 231, 232, 236, 242, 248, 252, 259, 260
  - building ..... 185, 186, 193, 194, 232, 250
  - matching ..... 195, 198, 201, 203
- mapping ..... 65, 102, 130, 164, 186, 187, 231, 232, 238, 242, 244, 245, 259, 260
- marine ..... 46, 65, 68, 258
- maritime ..... 17, 76, 145
- marker ..... 177-179, 181, 182
- mask ..... 79, 188, 232
- master/slave ..... 66, 155, 159
- match/correction ..... 198
- matrix ..... 15, 156, 218
- Matthis ..... 216
- MC6809-based ..... 68
- MCP ..... 111
- MDARS ..... 176-178
- MDOF ..... 25-28, 143, 144
- mean ..... 38, 83, 84, 86, 123, 149, 226, 227, 232, 233
- mechanical ... 2, 14-16, 23, 30-34, 38, 44-47, 58, 62, 102, 118, 146, 179, 243, 248

- mechanical-scanner . . . . . 118
- median . . . . . 116
- medium-resolution . . . . . 17
- Melboy . . . . . 149, 150
- membrane . . . . . 97
- memory . . . . . 57, 93, 116, 126, 173, 184, 253
- metal . . . . . 13, 17, 54, 99, 107, 179, 180, 200, 229
- metallic . . . . . 54, 60, 62
- METGLAS . . . . . 62, 63
- Mexico . . . . . 78
- Michigan . . . . . 2, 4, 25, 27-29, 34, 56, 129, 134, 139, 143-146, 152, 222, 235, 239, 243, 249, 255, 259
- micro . . . . . 18, 62, 78, 186, 187, 225, 230, 251, 256
  - machining . . . . . 62
- microchannel . . . . . 110
- microprocessor-controlled . . . . . 56
- microprocessor . . . . . 54-57, 100, 107, 119, 126, 164, 182
- microwave . . . . . 17-19, 127, 242, 252
- mid-air . . . . . 167, 168
- military . . . . . 23, 56, 72, 77
- millimeter-wave . . . . . 125
- minivan . . . . . 127
- Mini-Ranger . . . . . 68, 257
- mirror . . . . . 35, 37-39, 103, 105, 115, 117-119, 121, 158, 160, 225
- misalignment . . . . . 32, 131
- missiles . . . . . 145
- MIT . . . . . 36, 65, 226, 231, 243, 246
- mixer . . . . . 113, 124, 126
- Mobility . . . . . 19, 26, 27, 248, 254, 258
- Mobot . . . . . 189, 190, 240
- modality . . . . . 186
- model-based . . . . . 213, 214
- modified-FMCW . . . . . 127
- modular . . . . . 166
- modulated . . . . . 42, 95, 112, 116, 117, 121, 123, 223, 254, 255, 258
- modulation . . . . . 38, 71, 112-114, 119, 123-125, 158, 240, 254
- module . . . . . 78, 91, 92, 97-101, 125, 164, 174, 175, 215, 224, 256, 257
- moment . . . . . 21, 49, 75, 186
- momentum . . . . . 30
- monolithic . . . . . 37, 58, 59, 244
- monostatic . . . . . 97-99
- motorized . . . . . 108
- motor-driven . . . . . 103
- multi
  - axis . . . . . 32, 37, 38, 43, 51, 52, 56, 58, 59, 61, 119, 147, 169, 201, 236
  - degree-of-freedom . . . . . 25-28, 46, 56, 239
  - faceted . . . . . 105
  - mode . . . . . 40, 79, 83, 86, 88, 91, 101
  - path . . . . . 40, 70, 72, 73, 75, 77, 132, 134, 139, 140, 142
  - room . . . . . 23, 39, 154
  - target . . . . . 121, 248
  - turn . . . . . 39, 42
- multibus . . . . . 116
- multiple . . . . . 16, 26, 40, 43, 66, 69, 96, 100, 101, 109-111, 154, 155, 166, 169, 197, 202-204, 207, 208, 211, 212, 222, 237, 260, 261
  - echo . . . . . 101
- multiplying . . . . . 71, 76, 95, 113
- multisensory . . . . . 186
- mumetal . . . . . 47, 48, 57, 58
- Mylar . . . . . 13, 17
- narrow . . . . . 62, 109, 125, 159, 239
  - band . . . . . 68
  - beam . . . . . 13, 16, 159, 225
- National . . . . . 2, 4, 26, 78, 79, 84, 227, 240, 245, 247, 250, 251, 260
- NAV . . . . . 158, 159, 224, 225, 255
- NavCore . . . . . 78, 80, 83-85, 87, 88, 90-93, 224
- Navmaster . . . . . 15, 24, 158, 177
- Navstar . . . . . 70-72, 154
- Navy . . . . . 27, 57
- network . . . . . 11, 69, 76, 166, 167, 204, 261
- networked . . . . . 154, 166, 167, 225
- network-level . . . . . 69
- Newton-Raphson . . . . . 153
- nickel . . . . . 48, 61
- NOAD . . . . . 166, 225
- nodding . . . . . 115
- node . . . . . 35, 203
- non
  - contact . . . . . 16
  - differential . . . . . 28, 77
  - interfering . . . . . 71
  - jammable . . . . . 146
  - line-of-sight . . . . . 66, 67, 76
  - linear . . . . . 38, 153, 199, 203, 218
  - load-bearing . . . . . 222
  - point . . . . . 24, 25, 57, 69, 131, 152, 213
  - radiating . . . . . 146
  - ranging . . . . . 115, 163, 178, 246
  - reciprocal . . . . . 40
  - reflective . . . . . 159
  - repetitive . . . . . 155
  - robotics . . . . . 65
  - systematic . . . . . 130-132, 134-137, 143, 149
  - vision . . . . . 176
  - volatile . . . . . 57
- nonlinear . . . . . 212, 213
- north . . . . . 30-32, 45, 46, 49, 66, 229, 246, 255, 257, 258
- northern . . . . . 30
- north-seeking . . . . . 31, 32

- NPN ..... 47  
 NRL ..... 62, 63  
 object ..... 95, 96, 101, 111, 114, 116, 124, 131,  
     143, 203, 207, 208, 211, 213, 215-217, 226,  
     228, 232, 240, 241, 248, 255  
 obstacle ..... 24, 127, 128, 184, 185, 202, 238, 239,  
     244, 258  
 obstructions ..... 79-81, 83, 88, 90, 91, 93, 103,  
     154, 179  
 occlusion ..... 164, 167, 178  
 occupancy ..... 188, 197, 198, 231, 242, 252  
 ocean ..... 2, 17, 242  
 odometry ..... 10, 13, 19-25, 28-30, 77, 80, 130-  
     135, 137-139, 143, 144, 148-150, 173-175,  
     178, 180, 188, 193, 194, 197, 198, 206, 216,  
     222, 229-232, 239, 240  
   -based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69,  
     71, 76, 95, 96, 101, 109, 112, 115, 121, 125,  
     146, 150, 163, 172-174, 183-188, 194-199,  
     203, 206, 207, 231, 232, 236, 242, 248, 252,  
     259, 260  
   -derived ..... 193  
 odor ..... 181, 182, 234, 251  
 Odyssey ..... 170, 171, 225  
 OEM ..... 78, 79, 91, 92, 99, 101, 102, 224  
 olfactory ..... 181, 182, 234, 251  
 omnidirectional ..... 25, 26, 69, 152, 155, 169, 227,  
     231, 246, 247, 250  
 onboard ..... 11, 13, 71, 103, 149, 151, 159, 164-  
     167, 171, 178, 179, 188, 222, 229  
 on-road ..... 76  
 on-site ..... 76  
 on-the-fly ..... 157  
 opaque/transparent ..... 13  
 open-collector ..... 47  
 open-loop ..... 35, 39, 42, 59  
 optical ..... 13-16, 30, 34-36, 38-44, 61, 95, 96,  
     103, 109, 110, 114-117, 120, 121, 125, 146,  
     148, 157-159, 164, 166, 170, 176, 180, 198,  
     207, 209, 213, 223, 225-227, 232, 236, 240,  
     247-249, 252, 254, 256, 258, 260, 261  
 opto-electronic ..... 166, 167, 225, 243, 257  
 orbital ..... 70, 71  
 ordnance ..... 28  
 oscillator ..... 53, 92, 97, 126  
 outdoor ..... 22, 65, 169, 171, 213, 215, 225, 247,  
     250  
 outliers ..... 154, 226  
 over-the-horizon ..... 66  
 package .. 13, 55, 56, 59, 92, 93, 106, 108, 125, 163  
 packaging ..... 39, 93  
 packet ..... 79, 92, 155  
 path-following ..... 148  
 PDOP ..... 75, 87  
 pendulous ..... 56  
 permalloy ..... 47, 48, 247  
 permanent-magnet ..... 47  
 permeability ..... 47-49, 63  
 pesticides ..... 103  
 phase ..... 14, 15, 24, 38, 41, 42, 53, 65-67, 77, 95-  
     97, 109-118, 120, 121, 123, 125, 127, 129,  
     143, 155-157, 169, 191, 192, 196, 203-205,  
     218, 236, 243  
   -detection ..... 95, 112-114, 116, 118, 125, 157  
   -lock-loops ..... 66  
   -measurement ... 65, 71, 114, 115, 123, 125, 155,  
     157  
   -measuring ..... 115  
   -quadrature ..... 14, 15  
   -shift ..... 67, 95, 109, 112, 115, 117, 123, 125  
 phenomenological ..... 186, 187  
 photodetector ..... 13, 115, 116, 160  
 photodiode ..... 101, 103, 105, 107, 115  
 photoelectric ..... 165  
 photogrammetry ..... 212, 252, 254  
 photograph ..... 189  
 photometric ..... 207, 216  
 photon ..... 39  
 photoplast ..... 13  
 photovoltaic ..... 16  
 Piezoelectric ..... 33, 34, 62, 99, 156, 159, 223  
 pin-hole ..... 211  
 pingers ..... 155  
 Pittsburgh ..... 30, 76, 163, 237, 239, 251, 255  
 pixel ..... 110, 116, 121, 122, 175, 227, 229  
 Pletta ..... 240, 250  
 point-to-point ..... 69  
 polarity ..... 49, 92  
 polarization ..... 40, 43  
 Polaroid ..... 99-101, 232, 237, 257  
 pose ... 185, 187, 207, 213, 214, 217, 228, 231, 232,  
     252  
 positioning ..... 2, 4, 10-12, 19, 30, 54, 65, 66, 68-  
     70, 72, 95, 129, 130, 146, 150-152, 157, 163,  
     164, 169-171, 173-175, 179, 183-185, 188,  
     194-198, 206, 207, 209-211, 214, 215, 217,  
     225, 228, 232, 233, 240, 242, 244, 246, 249,  
     252, 256, 258, 260  
 potentiometers ..... 13  
 predetermined ..... 76, 117, 161  
 predict ..... 194, 202, 214  
 prediction-verification ..... 176  
 prism ..... 33, 34, 103, 223  
 probabilistic ..... 176, 210  
 propagation .... 40, 65, 66, 70, 71, 95, 96, 107, 124,  
     152, 154, 155  
 Proxim ..... 155  
 proximity ..... 13, 54, 59, 75, 95, 167, 177-179,  
     232, 233, 260  
 PRSM ..... 40

- pseudo ..... 71, 72, 75, 144, 197  
   -code ..... 73, 76, 77, 176, 178  
   -probability ..... 197  
   -random ..... 71  
   -range ..... 72, 75, 169  
   -stable ..... 31  
 pulsed-Doppler ..... 126  
 pyroelectric ..... 181, 234  
 quadrature ..... 14, 15  
 quadrilateral ..... 163, 164  
 quadruples ..... 16, 210  
 quadruplet ..... 210  
 quartz ..... 63, 71, 107, 181, 182, 234  
   -crystal ..... 71  
   -stabilized ..... 107  
 radar ..... 18, 19, 65, 95, 101, 108, 109, 123, 125-127, 186, 223, 230, 237, 238, 240, 245, 260  
   -based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69, 71, 76, 95, 96, 101, 109, 112, 115, 121, 125, 146, 150, 163, 172-174, 183-188, 194-199, 203, 206, 207, 231, 232, 236, 242, 248, 252, 259, 260  
   -like ..... 57, 65, 72  
 radio ..... 10, 33, 65, 66, 70, 76, 96, 155, 166, 167  
   -control ..... 15, 33, 118  
   -controlled ..... 28, 33, 56, 160, 167  
   -frequency ..... 65, 77, 112, 121, 159  
 range  
   -lateration ..... 69  
   -measurement ... 65, 71, 114, 115, 123, 125, 155, 157  
   -points ..... 196  
   -rate ..... 103, 126, 148  
 rangefinder ..... 101, 102, 107, 108, 115, 116, 120, 164, 165, 174, 175, 191, 225, 230, 233, 244, 246, 248, 249, 257-259  
 ratiometric ..... 47  
 Raymond ..... 4, 78  
 rays ..... 40, 208-210, 212  
 real-time ..... 11, 66, 70, 71, 143, 170, 227, 242, 252, 254  
 reed-follower ..... 63  
 reflectance ..... 116, 249  
 reflection ..... 40, 73, 96, 104, 110, 116, 159  
 reflective ... 35, 37, 39, 96, 158, 159, 166, 176, 178, 226  
 reflectivities ..... 96, 106  
 reflectivity ..... 101, 116, 166  
 reflector ..... 155, 226, 227  
 refraction ..... 38, 40, 72, 73, 77  
 remote-controlled ..... 28  
 repeatability ..... 15, 57, 66, 67, 69, 125, 136, 227  
 resolver ..... 17, 53  
 resonance ..... 33, 36, 42  
 resonator ..... 36, 38, 39, 42, 252, 254  
 Reston ..... 170, 258  
 retentivity ..... 49, 50  
 retro-reflector ..... 226  
 RF ..... 17, 65, 67, 68, 80, 92, 95, 96, 112, 126, 155, 157  
 ringing ..... 100  
 ring-core ..... 50, 51, 56  
 Roamer ..... 193, 194  
 ROBART ..... 52, 53  
 ROBOSENSE ..... 164, 165, 225  
 round-trip ..... 36, 65, 95, 96, 107, 112, 114, 116, 124  
 running-average ..... 73  
 RVSI ..... 109  
 SA ..... 22, 73-75, 84, 94  
 saddles ..... 215  
 SAE ..... 99, 254  
 Sagnac ..... 34, 36, 40-42, 251, 254  
 Sandia ..... 4, 78-80, 84, 240, 247, 250  
 satellite ..... 11, 13, 15, 17, 23, 30, 58, 65, 68-73, 76, 77, 79, 83, 88, 95, 96, 101, 109, 112, 115, 121, 125, 146, 150, 163, 172-174, 183-188, 194-199, 203, 206, 207, 231, 232, 236, 242, 246, 248, 252, 255, 259, 260  
 saturable-core ..... 47  
 sawtooth ..... 51  
 SBIR ..... 27, 104  
 scanning ..... 62, 102-105, 108, 109, 115, 116, 119, 122, 157, 158, 160, 163-166, 177, 178, 208, 211, 225, 230, 240, 248, 258, 261  
 scatter ..... 83  
 Scooter ..... 167, 168  
 SCSI ..... 118  
 segmentation ..... 176  
 selective ..... 73, 75, 103, 111  
 self  
   -calibrating ..... 116  
   -contained ..... 10, 146  
   -mapping ..... 164  
   -organizing ..... 69  
 semiconductor ..... 57  
 semi-permanent ..... 175  
 SEP ..... 73, 76, 77, 249  
 sequencing ..... 78, 84, 88, 90, 224  
 servo-control ..... 15, 118  
 SFS ..... 257  
 shared-spectrum ..... 70  
 short  
   -lived ..... 181, 251  
   -pulse ..... 103, 107  
   -range ..... 72, 75, 169  
   -term ..... 56, 93, 130, 150  
 shot-noise-limited ..... 43  
 shuttering ..... 109, 110

- signal . . . . . 17, 31, 38, 42, 49, 50, 58-60, 62, 63, 66,  
     67, 69-72, 77, 79, 92, 95, 96, 100, 101, 104,  
     106, 112, 114, 116-118, 121-124, 126, 127,  
     146, 155, 160, 166, 181, 182, 223, 261  
     -coding . . . . . 71  
     -processing . . . . . 58  
     -to-noise . . . . . 70, 79, 96, 116, 146  
 signatures . . . . . 174  
 silicon . . . . . 58, 59, 62, 246, 248  
     -based . . . . . 11, 13, 15, 17, 23, 30, 58, 65, 68, 69,  
     71, 76, 95, 96, 101, 109, 112, 115, 121, 125,  
     146, 150, 163, 172-174, 183-188, 194-199,  
     203, 206, 207, 231, 232, 236, 242, 248, 252,  
     259, 260  
 silk . . . . . 46  
 simulation . . . . . 138, 144, 148, 153, 154, 210, 222,  
     226, 247  
 single  
     -axis . . . . . 32, 37, 38, 43, 51, 52, 56, 58, 59, 61, 119,  
     147, 169, 201, 236  
     -board . . . . . 12  
     -channel . . . . . 14, 78, 224  
     -DOF . . . . . 27, 102, 119, 156  
     -echo . . . . . 100, 101  
     -frequency . . . . . 65, 77, 112, 121, 159  
     -mode . . . . . 40, 79, 83, 86, 88, 91, 101  
     -word . . . . . 116  
 singularities . . . . . 157  
 sink . . . . . 47  
 six-legged . . . . . 115, 240  
 skid-steer . . . . . 28  
 sky-wave . . . . . 66  
 slippage . . . . . 17, 18, 21, 23, 24, 26-28, 130, 131, 137-  
     139, 227, 255  
 SLNM . . . . . 181  
 slow-growing . . . . . 143  
 smaller . . . . . 24, 39, 82, 99, 104, 136, 148, 149, 180,  
     193, 200, 206  
 small-area . . . . . 77  
 small-diameter . . . . . 39  
 SN28827 . . . . . 99, 100  
 solenoidal . . . . . 50, 62  
 solid-state . . . . . 42, 43, 55, 57, 146, 147, 254  
 sonar . . . . . 97, 101, 159, 177, 178, 186, 195, 200,  
     202, 204, 205, 226, 230-232, 237, 239, 244-  
     249, 251, 257  
 sonobuoys . . . . . 57  
 space-stable . . . . . 31  
 Spatial . . . . . 53, 170, 171, 185, 186, 204, 207, 225,  
     233, 258, 260  
 spiral . . . . . 119  
 spread-spectrum . . . . . 69, 70, 155  
 SPSi . . . . . 258  
 SQUID . . . . . 63  
 standing-wave . . . . . 35  
 Starguide . . . . . 47  
 step-index . . . . . 40  
 Stereo . . . . . 115, 197, 203, 211, 215-217, 231, 237,  
     249  
 stiction . . . . . 53  
 stiffness . . . . . 60  
 STROAB . . . . . 166, 167, 169, 225  
 structured-light . . . . . 158  
 super-luminescent . . . . . 41  
 suppression . . . . . 107  
 surveillance . . . . . 2, 17, 181, 241, 242, 245, 259  
 swing-needle . . . . . 46  
 synchros . . . . . 13  
 synchro-drive . . . . . 23, 25, 138, 222, 244  
 TACAN . . . . . 159  
 TACTIC . . . . . 66, 67  
 TAD . . . . . 68  
 telemetry . . . . . 66, 67, 71, 168  
 tele-operated . . . . . 23, 28, 29  
 temperature-nulled . . . . . 57  
 terrestrial . . . . . 43  
 thermal . . . . . 181, 234  
 three-wheel . . . . . 25, 26  
 tilt-compensated . . . . . 146  
 time  
     -division-multiple-access . . . . . 69, 155  
     -measurement . . . . . 65, 71, 114, 115, 123, 125, 155,  
     157  
     -of-arrival . . . . . 65, 66, 72, 155, 156  
     -of-flight . . . . . 95, 106, 114, 156, 175  
     -phase . . . . . 53, 77  
     -stamped . . . . . 69  
     -tagged . . . . . 69  
     -to-amplitude-conversion . . . . . 101  
     -variant . . . . . 181, 218  
     -walk . . . . . 96  
 timer . . . . . 118  
 topological . . . . . 11, 187, 196, 197, 203, 204, 247  
 toroidal . . . . . 51, 53, 56  
 tractable . . . . . 215  
 tractor-trailer . . . . . 144, 145  
 trailer . . . . . 138, 139, 144, 145, 222, 238, 243, 248  
 trajectory . . . . . 133, 140, 150, 196, 215, 216  
 Trak-Star . . . . . 18, 19  
 translation-invariant . . . . . 186  
 translation . . . . . 130, 162, 186, 191, 192, 211-215, 241,  
     244  
 transmitter-receiver . . . . . 68, 125, 152, 155  
 transponder . . . . . 68, 154, 158  
 TreeSense . . . . . 103, 104  
 triangulation . . . . . 95, 151-153, 160, 163, 165, 172,  
     177, 178, 226, 241  
 tricycle . . . . . 21, 138, 179, 230, 232  
 trinocular . . . . . 216  
 triplets . . . . . 211, 228

- tripods ..... 161, 170
- true-north ..... 32
- tunneling ..... 61-63, 255
- tunneling-tip ..... 61-63, 255
- two-dimensional .... 66, 79, 110, 169, 186, 209, 211, 213, 214
- two-wheel ..... 27
- ultrasonic ..... 12, 18, 19, 65, 95-100, 113, 151, 154-159, 172, 178, 179, 189, 193, 194, 199-202, 216, 226, 230, 235, 237, 239, 241-243, 247, 248, 251, 256, 257, 260
- ultrasound ..... 19, 154, 207
- UMBmark ..... 134-137, 139, 141, 222
- unibody ..... 38
- USMC ..... 23
- vacuum ..... 39, 41
- variable ..... 58, 111, 216
- variable-width ..... 58
- variance ..... 80, 83, 84, 121, 200, 210, 232
- VAX ..... 116, 230, 231
- VDOP ..... 75, 87
- very-large-area ..... 166
- vessel ..... 13, 46
- VH1 ..... 60
- VH2 ..... 60
- VHF ..... 67
- vibrating ..... 33, 34, 63
- vibration ..... 16, 34, 42, 52, 71, 99, 161
- vidicon ..... 109
- vision .. 109-111, 115, 174-177, 183, 186, 187, 203-205, 207, 210, 212-217, 226-231, 233, 236, 237, 240, 241, 244-248, 252, 253, 255, 261
- vision-based ..... 174, 207, 236
- visual ..... 126, 167, 188, 204, 207, 208, 213-216, 230, 249
- visualization ..... 35
- visualizes ..... 133
- VME ..... 116, 174, 229
  - based ..... 11, 13, 15, 17, 23, 30, 58, 65, 68, 69, 71, 76, 95, 96, 101, 109, 112, 115, 121, 125, 146, 150, 163, 172-174, 183-188, 194-199, 203, 206, 207, 231, 232, 236, 242, 248, 252, 259, 260
  - bus ..... 116
- volatile ..... 14, 57, 181, 182, 234
- waveform ..... 99, 117, 124
- waveguide ..... 39, 40
- wavelength ..... 35, 37, 40, 41, 43, 72, 102-104, 106, 109, 112, 114, 115, 118, 119, 125, 155, 157, 163
- wheel ..... 10, 13, 15-17, 19-28, 30, 44, 130-133, 136, 138-143, 179, 222, 233, 250
  - slippage ..... 131
- wheelbase ..... 20, 24, 131-133, 137, 140, 142, 222
- wideband ..... 117
- workspace ..... 154, 163, 176, 203, 204, 233, 253
- world-modeling ..... 189
- worst-case ..... 75, 107, 118, 131
- Y-code ..... 76, 77



## AUTHOR INDEX

- Abidi ..... 236  
Acuna ..... 236  
Adams ..... 121, 123, 131, 202, 236, 254, 258  
Adrian ..... 236  
Agent ..... 182, 236  
Aggarwal ..... 175, 176, 185, 187, 197, 214, 215,  
228, 248, 253, 260  
Aldon ..... 254  
Allen ..... 236, 257  
Amai ..... 250  
Arakawa ..... 245  
Aras ..... 246  
Arditty ..... 36, 38, 39, 41, 243  
Arenas ..... 176, 246  
Arimoto ..... 253  
Arkin ..... 99, 236  
Aronowitz ..... 36, 236  
Asada ..... 259  
Atiya ..... 211, 236, 245  
Attolico ..... 241  
Aviles ..... 236  
Avolio ..... 13, 236  
Ayache ..... 216, 237  
Baines ..... 237, 255  
Bains ..... 246  
Baker ..... 169, 237  
Banzil ..... 237  
Barbieri ..... 113, 157, 243  
Baron ..... 176, 227, 244  
Barrett ..... 60, 237  
Barshan ..... 34, 146-148, 237  
Barth ..... 261  
Benchetrit ..... 252  
Benedetto ..... 231, 251  
Benhabib ..... 260, 261  
Bennett ..... 44, 236, 237  
Besant ..... 165, 250  
Betke ..... 153, 210, 237  
Beveridge ..... 243, 259  
Beyer ..... 237  
Bhanu ..... 258  
Biber ..... 237  
Binger ..... 237  
Blais ..... 259  
Blaszyk ..... 40, 41, 250  
Bohlander ..... 259  
Bolles ..... 212, 243  
Boltinghouse ..... 116, 238, 247  
Bolz ..... 181, 234, 238  
Borenstein ..... 2, 15, 26, 96, 99, 132, 134-136,  
139, 142-144, 149, 176, 197, 232, 238, 239,  
243, 250  
Bourbakis ..... 259  
Brooks ..... 239  
Brown ..... 72, 239  
Brubacher ..... 255  
Brunner ..... 236  
Buchberger ..... 186, 239  
Buholz ..... 38, 240  
Bulkeley ..... 240  
Burke ..... 238  
Burns ..... 240  
Byrd ..... 115, 240  
Byrne ..... 2, 4, 18, 73, 74, 77, 78, 85, 130, 178,  
240, 250  
Byun ..... 260  
Cao ..... 240, 259  
Caponetti ..... 241  
Capozzo ..... 241  
Carlson ..... 50, 250  
Carroll ..... 246  
Carter ..... 240  
Case ..... 153  
Chandra ..... 228, 236  
Chao ..... 240  
Chelberg ..... 260  
Chen ..... 213, 240, 259  
Chenavier ..... 130, 210, 240  
Chesnoy ..... 38, 240  
Chi ..... 261  
Chiarella ..... 167, 248  
Chodorow ..... 38, 240, 254  
Chow ..... 36, 240  
Christian ..... 38, 241  
Clark ..... 241, 255  
Clergeot ..... 242  
Cohen ..... 129, 152, 172, 241  
Colvin ..... 271  
Dick ..... 271  
Congdon ..... 197, 241  
Conrad ..... 114, 241  
Cooper ..... 77, 241  
Courtney ..... 186, 197, 203, 204, 241  
Cox ..... 134, 198, 241  
Crowley ..... 20, 130, 185, 188, 189, 197, 199,  
210, 231, 232, 240, 241, 252, 259  
Curran ..... 259  
D'Orazio ..... 241  
Dahlin ..... 242  
DeCorte ..... 177, 241  
Depkovich ..... 101, 242  
Deveza ..... 181, 241  
DeVries ..... 115, 240  
Dibburn ..... 242

- Dickerson ..... 259  
Distante ..... 241  
Dodington ..... 242  
Domey ..... 259  
Doussis ..... 243  
Drake ..... 259, 260  
Duchnowski ..... 67, 242  
Dudek ..... 232, 260  
Dunlap ..... 242  
Durieu ..... 242  
Durrant-Whyte ..... 237, 241  
Dyott ..... 236  
Edlinger ..... 242  
Elfes ..... 99, 197, 242, 249  
Elgazzar ..... 252  
Ellin ..... 237  
Elowitz ..... 242  
Emge ..... 44, 237  
Engelson ..... 186, 187, 242  
Etersky ..... 244  
Evans ..... 130, 242  
Everett ..... 2, 4, 52, 53, 99, 176, 177, 242, 243  
Ewing ..... 244  
Ezekial ..... 36, 243  
Fainman ..... 243  
Fan ..... 103-105, 163, 243  
Faugeras ..... 216, 237  
Feiten ..... 216, 237, 248  
Feng ... 2, 34, 132, 134-136, 139, 141, 142, 149,  
176, 222, 239, 243  
Fenn ..... 63, 243  
Fennema ..... 214, 243, 259  
Figueroa ..... 156, 157, 243  
Fischler ..... 212, 243  
Fisher ..... 244  
Fleury ..... 244  
Flynn ..... 14, 246  
Fournier ..... 254  
Fox ..... 244  
Fraden ..... 244  
Frank ..... 16, 129, 250  
Frederiksen ..... 244  
Fujimura ..... 261  
Fujiwara ..... 253  
Fukui ..... 176, 244  
Gage ..... 243  
Gan ..... 226, 232, 255  
Ganapathy ..... 212, 244  
Gerver ..... 243  
Getting ..... 244  
Geyger ..... 244  
Gilbert ..... 46, 244  
Gilbreth ..... 242, 243  
Goldenberg ..... 260  
Goncalves ..... 261  
Gonzalez ..... 199, 218, 236, 244, 252  
Gothard ..... 244  
Gould ..... 244  
Gourley ..... 137, 244  
Grabbe ..... 146, 222, 250  
Green ..... 252  
Grenoble ..... 47, 244  
Gunther ..... 169, 245  
Gurvits ..... 153, 154, 210, 237  
Hager ..... 175, 211, 227, 236, 245  
Hall ..... 45, 47, 57-59, 233, 237, 240, 248, 259  
Hamanaka ..... 252  
Hammond ..... 97, 240, 245  
Hanawa ..... 249  
Hanson ..... 243, 259  
Harmon ..... 245, 259  
Haralick ..... 213, 245  
Harris ..... 69, 115, 237, 245, 256  
Hashimoto ..... 226, 253  
Haenderson ..... 241, 253, 254  
Henkel ..... 245  
Hine ..... 51, 245  
Hinkel ..... 189, 245  
Ho ..... 238  
Hockney ..... 243  
Holcombe ..... 259  
Holenstein ..... 245  
Holland ..... 23, 244-246  
Holle ..... 14, 245  
Hollingum ..... 130, 245  
Hong ..... 260  
Hongo ..... 138, 245  
Hoppen ..... 185, 245  
Hosoi ..... 253  
Howard ..... 244, 245  
Huang ..... 248, 259  
Huber ..... 129  
Hurn ..... 245  
Hwang ..... 72, 73, 239  
Hyypa ..... 248  
Ianigro ..... 241  
Inigo ..... 259, 260  
Ishida ..... 248  
Jacobus ..... 237  
Jaffe ..... 247  
Jain ..... 186, 197, 203, 204, 233, 241, 261  
Janet ..... 246  
Jasiobedzki ..... 246  
Jenkin ..... 246  
Johnson ..... 101, 243, 248  
Jones ..... 246  
Jörg ..... 186, 239, 246  
Kabuka ..... 176, 246  
Kadonoff ..... 246  
Kaiser ..... 246, 254



- Oyama . . . 44, 131, 132, 135, 146, 148-150, 223, 247
- Parish . . . . . 250
- Parker . . . . . 260
- Partaatmadja . . . . . 260
- Patterson . . . . . 250
- Pears . . . . . 261
- Pedrotti . . . . . 240
- Pellerin . . . . . 51, 236
- Pessen . . . . . 15, 250
- Petersen . . . . . 59, 242, 250
- Pin . . . . . 26, 97
- Polkowski . . . . . 260
- Pont . . . . . 237
- Prasad . . . . . 260
- Premi . . . . . 165, 250
- Price . . . . . 254
- Primdahl . . . . . 49, 50, 250
- Probert . . . . . 122, 123, 236, 261
- Purkey . . . . . 250
- Puttkamer . . . . . 186, 191, 239, 242, 245, 254
- Rappaport . . . . . 152, 226, 249, 260
- Raschke . . . . . 235, 250
- Reidy . . . . . 250
- Reignier . . . . . 20, 241
- Reina . . . . . 244
- Reister . . . . . 26, 250, 251
- Rencken . . . . . 185, 188, 193-196, 237, 251
- Reunert . . . . . 251
- Reynolds . . . . . 246
- Rioux . . . . . 259
- Riseman . . . . . 243, 259
- Roberts . . . . . 258
- Roning . . . . . 240
- Rosker . . . . . 38, 241
- Rudolph . . . . . 250
- Russel . . . . . 132, 181, 182, 234, 241, 247, 251
- Sabatini . . . . . 251
- Sagnac . . . . . 34, 36, 40-42, 251, 254
- Sammarco . . . . . 146, 251
- Sampson . . . . . 114, 241
- Sanders . . . . . 43, 240, 252
- Santos . . . . . 261
- Savage . . . . . 255
- Schaffer . . . . . 187, 252
- Schiele . . . . . 188, 189, 252
- Schleich . . . . . 240
- Schultz . . . . . 252
- Schwind . . . . . 261
- Scully . . . . . 240
- Sethi . . . . . 261
- Shafer . . . . . 216, 249
- Shenk . . . . . 237
- Shertukde . . . . . 261
- Shirai . . . . . 259
- Shirakawa . . . . . 253
- Shoval . . . . . 252
- Shufeldt . . . . . 13, 17, 145, 242
- Siegel . . . . . 202, 247
- Singh . . . . . 261
- Siuru . . . . . 252
- Slama . . . . . 212, 252
- Smith . . . . . 261
- Smurlo . . . . . 243
- Stella . . . . . 241
- Stentz . . . . . 244, 252
- Stokes . . . . . 252
- Stuart . . . . . 50, 252
- Stuck . . . . . 197, 252
- Sugihara . . . . . 209, 210, 252
- Sugimoto . . . . . 245
- Sugiyama . . . . . 143, 252
- Sulzberger . . . . . 254
- Sun . . . . . 260
- Sutherland . . . . . 215, 252, 261
- Suzuki . . . . . 253
- Tai . . . . . 252
- Takeda . . . . . 253
- Talluri . . . . . 185, 214, 215, 253
- Tange . . . . . 245
- Taylor . . . . . 203, 253
- Tchoukanov . . . . . 261
- Tetelman . . . . . 237
- Thiel . . . . . 241, 251
- Thompson . . . . . 215, 253, 261
- Thorpe . . . . . 97, 247
- Tonouchi . . . . . 253
- Tran . . . . . 242, 246
- Trivedi . . . . . 137, 244
- Tsai . . . . . 212, 213, 227, 240, 248, 253
- Tsubouchi . . . . . 253
- Tsuji . . . . . 259, 261
- Tsukahara . . . . . 248
- Tsumura . . . . . 253
- Tu . . . . . 260
- Tumanski . . . . . 59, 247
- Turpin . . . . . 254
- Tuve . . . . . 47, 238
- Udd . . . . . 36, 248, 250, 252, 254
- Unseren . . . . . 26, 251
- Vaganay . . . . . 254
- Valiquette . . . . . 253
- Vaz . . . . . 261
- Vestli . . . . . 254
- Vuylsteke . . . . . 254
- Wagner . . . . . 116, 117, 249
- Waltman . . . . . 246
- Watanabe . . . . . 97, 250
- Wax . . . . . 38, 254
- Wehe . . . . . 4, 239, 243

Weiman	183, 246	Woll	254
Weiß	191, 254	Wong	255
Wernersson	248	Woodbury	255
Wetzler	191, 254	Wormley	255
Weymouth	203, 204, 206, 247, 261	Wu	240, 260
Wienkop	197, 254	Xu	261
Wiley	239, 244, 250, 254	Yamamoto	245
Wilkinson	36, 254	Yoo	261
Wintz	186, 244	Yoshikawa	179, 180, 229, 249
Wolf	212, 254	Yuta	213, 255
Wolfe	101, 115, 242	Zell	248
		Zheng	261

## COMPANY INDEX

ACUITY	117-119, 255	MAGELLAN	78, 80, 83-85, 87-88, 91-92, 224, 256
ADL	19, 255	MAGNAVOX	76, 78-81, 83-88, 90-92, 224, 256
ANDREW	43, 223, 255	MASSA	109-111
BENTHOS	223, 255	MICRO-TRAK	18, 256
CATERPILLAR	176, 178, 225, 255	MOTOROLA	57, 58, 68, 110, 126, 231, 257
CYBERMOTION	24, 25, 132, 158, 174, 222, 232, 255	MURATA	166-169, 225, 257, 258
CYBERWORKS	183, 227, 255	NAMCO	160, 161, 225, 257
DBIR	163, 255	NASA	62, 257
DINSMORE	47, 255	NIKE	257
EATON	125, 126, 225, 254, 256, 258	POLAROID	99-101, 232, 237, 257
ERIM	255	REMOTEC	28, 29, 139, 257
ESP	116, 117, 121, 122, 189, 256	RIEGL	107-109, 257
FUTABA	33, 223, 256	SEO	101-104, 257, 258
GEC	256	SFS	78, 80, 81, 83-85, 87, 88, 90-93, 224, 257
GREYHOUND	126, 256	TOWER	258
GYRATION	33, 223, 256	TRC	16, 28, 118, 119, 134, 136, 137, 157, 163, 164, 222, 225, 227, 228, 230, 258
HP	256	UNIQUE	27, 258
HTI	69, 70, 256	VORAD	125, 126, 254, 258
ILC	256	WATSON	55, 56, 258
ISI	256	ZEMCO	52-54, 56, 258
ISR	155, 256		
KVH	56, 256		

## Bookmark Index

	Page
<b>PART I SENSORS FOR MOBILE ROBOT POSITIONING</b>	
Chapter 1 Sensors for Dead Reckoning .....	13
Chapter 2 Heading Sensors .....	30
Chapter 3 Ground-Based RF-Beacons and GPS .....	65
Chapter 4 Sensors for Map-Based Positioning .....	95
<b>PART II SYSTEMS AND METHODS FOR MOBILE ROBOT POSITIONING</b>	
Chapter 5 Odometry and Other Dead-Reckoning Methods .....	130
Chapter 6 Active Beacon Navigation Systems .....	151
Chapter 7 Landmark Navigation .....	173
Chapter 8 Map-based Positioning .....	184
Chapter 9 Vision-Based Positioning .....	207
Appendix A A Word on Kalman Filters .....	218
Appendix B Unit Conversions and Abbreviations .....	219
Appendix C Systems-at-a-Glance Tables .....	221
References .....	236
Subject Index .....	262
Author Index .....	274
Company Index .....	278
Bookmark Index .....	279
Video Index .....	280
Full-length Papers Index .....	281









## Video Index

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 <p>The University of Michigan: Multi-Degree-of-Freedom vehicle with compliant linkage. Duration: 3:15 minutes</p> <p>240x180                      360x240</p>	 <p>The University of Michigan: Internal Odometry Error Correction with the CLAPPER. Duration: 4:24 minutes</p> <p>240x180                      360x240</p>
 <p>Spatial Positioning Systems: Odyssey laser beacon positioning system Duration: 2:23 minutes</p> <p>240x180                      360x240</p>	 <p>MTI: CONAC laser beacon positioning system, applied in Scooter experiment Duration: 3:27 minutes</p> <p>240x180                      360x240</p>
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- Paper 01 Borenstein, J. and Koren, Y., 1985, "A Mobile Platform For Nursing Robots." IEEE Transactions on Industrial Electronics, Vol. 32, No. 2, pp. 158-165.
- Paper 02 Borenstein, J. and Koren, Y., 1987, "Motion Control Analysis of a Mobile Robot." Transactions of ASME, Journal of Dynamics, Measurement and Control, Vol. 109, No. 2, pp. 73-79.
- Paper 10 Borenstein, J. and Koren, Y., 1989, "Real-time Obstacle Avoidance for Fast Mobile Robots." IEEE Transactions on Systems, Man, and Cybernetics Vol. 19, No. 5, Sept./Oct., pp. 1179-1187.
- Paper 16 Borenstein, J. and Koren, Y., 1991, "The Vector Field Histogram – Fast Obstacle-Avoidance for Mobile Robots." IEEE Journal of Robotics and Automation, Vol. 7, No. 3., June 1991, pp. 278-288.
- Paper 18 Borenstein, J. and Koren, Y., 1991, "Histogramic In-motion Mapping for Mobile Robot Obstacle Avoidance." IEEE Journal of Robotics and Automation, Vol. 7, No. 4, 1991, pp. 535-539.
- Paper 30 Borenstein, J. and Raschke, U., 1992, "Real-time Obstacle Avoidance for Non-Point Mobile Robots." SME Transactions on Robotics Research Vol. 2, pp. 2.1-2.10, 1992.
- Paper 32 Borenstein, J. and Koren, Y., 1995, "Error Eliminating Rapid Ultrasonic Firing for Mobile Robot Obstacle Avoidance." IEEE Transactions on Robotics and Automation February 1995, Vol. 11, No. 1, pp 132-138.
- Paper 34 Borenstein, J., 1995, "Control and Kinematic Design for Multi-degree-of-freedom Mobile Robots With Compliant Linkage." IEEE Transactions on Robotics and Automation February 1995, Vol. 11, No. 1, pp. 21-35
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