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 instable 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
(Angles)		
degrees (°)	radian (rad)	0.01745
radian (rad)	degrees (°)	57.2958
milliradians (mrad)	degrees (°)	0.0573
(Length)		
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
(Area)		
$inch^2$ (in^2)	$meter^2$ (m^2)	6.4516×10^{-4}
$foot^2$ (ft^2)	$meter^2$ (m^2)	9.2903×10^{-2}
$yard^2$ (yd^2)	$meter^2$ (m^2)	0.83613
(Volume)		
$foot^3$ (ft^3)	$meter^3$ (m^3)	2.8317×10^{-2}
$inch^3$ (in^3)	$meter^3$ (m^3)	1.6387×10^{-5}
(Time)		
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
(Frequency)		
Hertz (Hz)	cycle/second ($s\text{-}^1$)	1
Kilohertz (KHz)	Hz	1,000
Megahertz (MHz)	Hz	10^6
Gigahertz (GHz)	Hz	10^9

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

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*: 310 mm	On smooth concrete*: 6° With ten bumps*: 8°	Very high ~ 1 KHz	Short wheelbase	Unlimited	[TRC] Transition Research Corp.
Cybermotion	Onboard proprietory	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	Umlimited	[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[1]: 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 sytematic odometry errors	486-33 MHz or any onboard computer	Any differential-drive mobile robot; tests here performed with TRC LabMate	4×4 ms 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 Grabble, 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 [º]	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: ±2% max. Resultion: 2º	analog		0º - 359º	[BENTHOS] BENTHOS, Inc.
Futaba model helicopter gyro FP-G154	Output: pulse-width modulated signal			Drift: >1°/s	20 ms	$150		[TOWER]
Gyration GyroEngine	RS232 interface			Drift: 9º/min		$300	Unlimited	[GYRATION] Gyration, Inc.
Murata Gyrostar ENV-05H	Analog interface	Piezoelectric triangular prism. Drift: 9º/sec (maximum rated by manufacturer. Actual drift is lower)		Measured drift: 3-15º/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°/s	100 Hz		Unlimited	Komoriya and Oyama [1994], [HITACHI]
Andrew Autogyro and Autogyro Navigator	RS232 interface	Quoted minimum detectable rotation rate: ±0.02º/s Actual minimum detectable rate limited by deadband after A/D conversion: 0.0625º/s		Drift: 0.005º/s	10 Hz	$1000	Unlimited	[ANDREW] Andrew Corporation
Complete inertial navigation system including ENV-O5S 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 5-15º/min. After compensation: drift 0.75º/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] Magelan 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 ±1.3 mm outdoor ±5 mm	Indoor and outdoor ±0.05°	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° 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°	Retroreflective targets of known dimensions	Angular accuracy is within ±0.05% with a resolution of 0.006° 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 standalone poles	Resolution is 120 mm (4-3/4 in) in range and 0.125° in bearing for full 360° coverage in a horizontal plane		1 Hz	Currently limited to single work area of 80×80 ft	24.4 m (80 ft)	[TRC]
LASERNAV	64180 microcomputer	Laser scanner	Retroreflective bar codes. Up to 32 can be distinguished.	±1 in moving at 2 ft/sec; ±0.5 in stationary	±0.03°.	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: ±1 mm Vertical: ±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 (±10° field of view in horizontal and vertical axes)	Infrared beacon transmitter (uniquely identifiable, 128 codes)		0.3° in the ±5° central area and ±1° 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: ±500 LN-20: ±20 LN-30: ±500 LN-40: ±20	LN-10: ±1° LN-20: ±0.1° LN-30: ±1° LN-40: ±0.1°	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^2 space	Measured standard dev. of path error of 40 mm		150 ms			[Kleeman, 1992]
Infrared beacons		One optical infrared scanner	Infrared beacons	25 m^2 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=0.07σ=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 [º]	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 σ= 0.8 Y: mean: 2 max: 5, std. 2	Repeatability mean: 0.3º max: 0.7º std. 0.4º	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	0.1º	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 Chaio Tung University
Omnidirectional vision navigation with beacon recognition		Vision camera with fish-eye lens	A light array (3x3)	40 mm	0.3º				[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%	5º		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 rangefinder, 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 [º]	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	<1º		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 20×20 ft room can be matched with 6 in displacement and 3º 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 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 1.2º 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 erronrous 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	0.20º 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: multisensor 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.

Name	Computer	Onboard Components	Maps and Features	Accuracy - position [mm]	Accuracy - orientation [º]	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 Grabble, 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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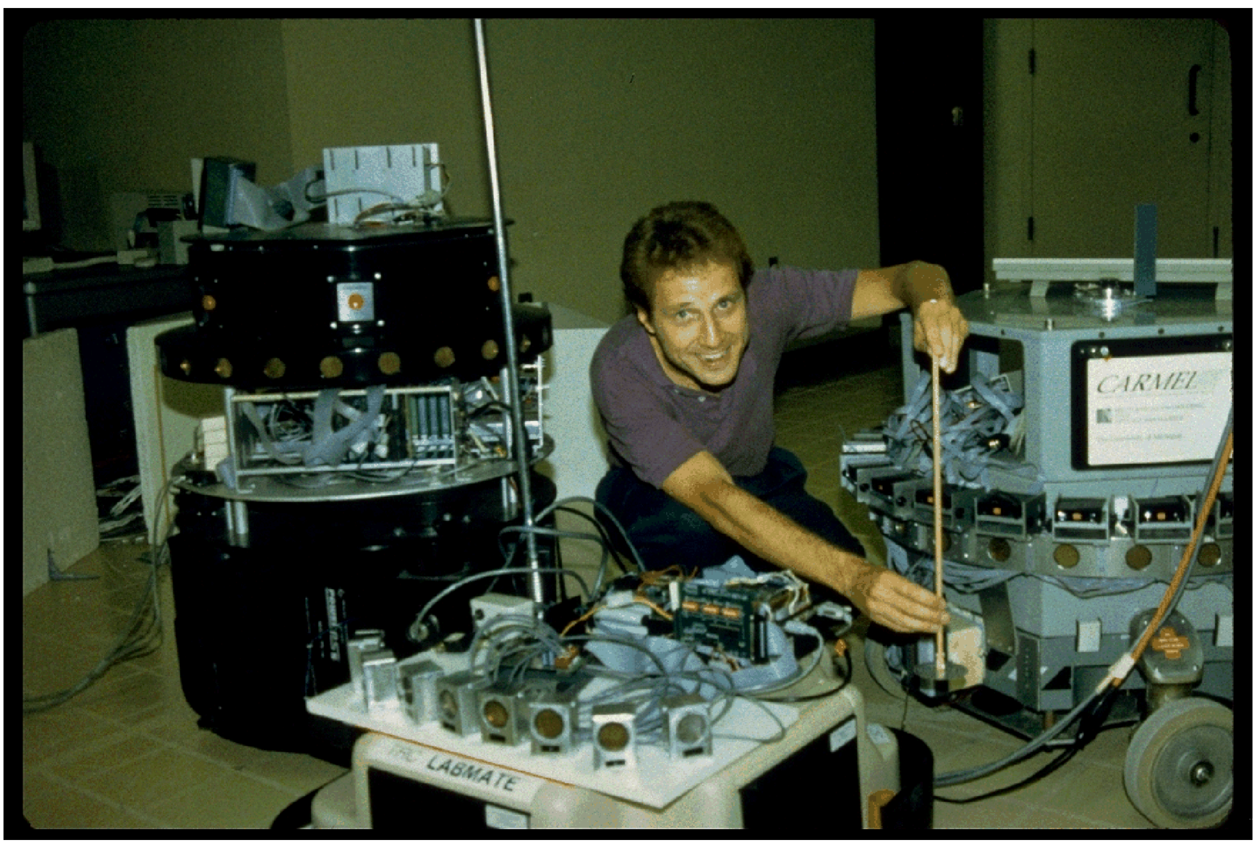

University of Michigan grad. student Ulrich Raschke verifies the proper alignment of ultrasonic sensors. All three robots in this picture use 15°-angular spacing between the sensors. Many researchers agree that 15° spacing assures complete coverage of the area around the robot.

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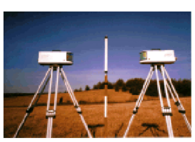
	Atomic Energy of Canada (AECL): "ARK" System Duration: 3:42 minutes 240x180 360x240		Transition Research Corporation (TRC): a. LightRanger rotating/nodding lidar b. Vision-based landmark detection Duration: 4:28 minutes 240x180 360x240
	The University of Michigan: Multi-Degree-of-Freedom vehicle with compliant linkage. Duration: 3:15 minutes 240x180 360x240		The University of Michigan: Internal Odometry Error Correction with the CLAPPER. Duration: 4:24 minutes 240x180 360x240
	Spatial Positioning Systems: Odyssey laser beacon positioning system Duration: 2:23 minutes 240x180 360x240		MTI: CONAC laser beacon positioning system, applied in Scooter experiment Duration: 3:27 minutes 240x180 360x240
	Windsor Industries and Denning Branch International Robotics: RoboScrub Duration: 2:00 minutes 240x180 360x240	 Learn about video	To learn some more about digital video and how the video clips on this CD-ROM were produced, click the "Learn about video" icon.

Index to Full-length Papers Included on This CD

The papers listed below are included on this CD in full length. To view a paper, click "Paper #." You will find that only papers with "Johann Borenstein" as either author or co-author are listed. The reason for not including papers by other authors is Copyright. When an author submits a paper to a journal or conference, he/she transfers copyright to the publisher and the paper may be reprinted only with permission by the publisher. We negotiated with IEEE to obtain the rights to re-print certain papers. The result: IEEE charges $25 per page for the permission to reprint papers that were originally published in IEEE journals or at IEEE conferences. This cost is inhibitive for our purposes. However, we are allowed to re-print at no cost papers that we authored ourselves.

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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.

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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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