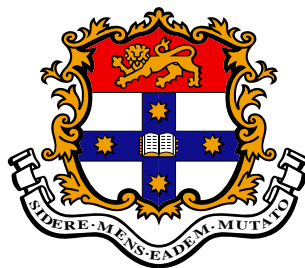


Radio-Frequency Signal Strength Based Localisation in Unstructured Outdoor Environments

Gerold Kloos

A thesis submitted in fulfillment
of the requirements for the degree of
Doctor of Philosophy



Australian Centre for Field Robotics
Department of Aerospace, Mechanical and Mechatronic Engineering
The University of Sydney

August 2007

Declaration

This thesis is submitted to the University of Sydney in fulfillment of the requirements for the degree of Doctor of Philosophy. This thesis is entirely my own work, and except where otherwise stated, describes my own research.

Gerold Kloos

31st August, 2007

Reprinted with corrections and emendations 18th February, 2008

Abstract

Gerold Kloos
The University of Sydney

Doctor of Philosophy
August 2007

Radio-Frequency Signal Strength Based Localisation in Unstructured Outdoor Environments

This thesis addresses the issues arising in range-only localisation and tracking using Radio Frequency Received Signal Strength Indicator measurements.

One of the key issues in Radio Frequency (RF) based localisation and tracking applications is to obtain an accurate sensor representation. Such a sensor model is one of the prerequisites to achieve high accuracy and precision in the localisation and tracking task. The sensor models used at present for this task are very simplistic, and as a consequence are unable to achieve highly accurate and precise localisation. While such an accurate sensor description is desirable it has not been presented for RF sensors.

This thesis addresses the task of obtaining an accurate sensor model for RF sensors. The major drawbacks of the most commonly used model, the n th power model, are demonstrated. A new model to satisfy the necessary requirements for high accuracy localisation is developed. This model is based on theoretical considerations and experimental data. It depicts the real occurring behaviour of RF sensors more closely than the models used so far for RF based range-only localisation. The use of this better sensor representation offers the possibility of achieving more accurate localisation.

The expected performance of the alternative sensor model is compared to the commonly used n th power model. Furthermore, the inherent properties of the new sensor model are presented and their ramifications with regards to the goal of achieving highly accurate localisation are discussed.

In addition to the sensor model development, the well-known probabilistic filtering techniques Kalman Filter, Particle Filter and Histogram Filter are compared and used to implement 1-dimensional and 2-dimensional range-only trackers. The filtering techniques are evaluated with respect to their suitability for appropriately handling the new multi-modal sensor model and the resulting multi-modal state distributions, and to provide correct and conclusive localisation and tracking results.

Results from experiments using real data obtained in outdoor environments with a prototype RF localisation system as well as results obtained from simulations are presented in this thesis to validate the theoretical findings and the newly developed sensor model.

Acknowledgements

I want to thank all the people that helped and supported me in any way during the four years of my research at the ACFR.

There are firstly my supervisors Eduardo Nebot and José Guivant. Eduardo, I want to thank you for giving me the opportunity to do my PhD at the ACFR, for supporting me in any possible way to achieve this goal and for the critical feedback you provided. Thank you José for all the discussions we had, related to my studies or not, for helping me out with the occasional SW issue, and for being my friend.

A big thank you goes to Stewart for keeping my spirits high, but also for helping me with the outdoor experiments. Juan, you helped me a lot with the hardware and were available for a discussion or just a chat. Gracias mi amigo. Tim, you introduced to me the concept of particle filtering in a private lesson, so that even I could understand it. Thank you for this and all the discussions we had. Also, thank you Graham for the help with the antenna pattern logging.

My thanks go to the technical staff, to Chris, Vijay, Allan and Jeremy for the hardware support they provided to me, but also to the Argentinean gang (all the Favios, Pedros and Juans) that developed the CPS hardware for my experiments. Special thanks to Favio Masson for his support and valuable feedback. Thanks also to the admin staff Christy and Ruth.

I would like to express my thanks to the CRC Mining for the financial support they provided to me.

Also a big thank you to my *social life*. You guys brought welcome distraction from work (too often according to the supervisors). Stewart, Marianne, Juan, Marina, José, Jürgen, Ute, Aléjandra, Connie, Ollie, Roman, Fabio, Andrew, Sharon, Piglet Lee and all the others, thank you, too.

To my best friend Peter, his wife Claudi and their kids Emily and Mia. Thank you for keeping in touch with us. Our weekly Skype session is always a highlight.

Most importantly I want to thank my family in Germany. Mum, Dad, Chris, Anita, Lea, Anne, Horst, Uschi and all the others. Thank you for all the encouragement and the support. I miss you all.

My biggest thanks go to my wife Cathérine for all the love she gives to me, for being my partner on the journey through life and for soon making us three in our home. You are the brightest star in my life.

To Cathérine & Amélie

Contents

Abstract	ii
Acknowledgements	iii
Contents	v
List of Figures	ix
List of Tables	xiii
List of Acronyms and Abbreviations	xiv
Notation	xvi
1 Introduction	1
1.1 Context	1
1.2 State of the art	2
1.3 Research hypothesis	5
1.4 Contributions	5
1.5 Structure of the thesis	6
2 Safety in Mining	8
2.1 Introduction	8
2.2 Causes for mining haul truck related accidents	9
2.3 Requirements for a Close Proximity System	15
2.4 Types of protection systems currently available	17
2.4.1 Global Positioning System based systems	17
2.4.2 Vision based systems	18
2.4.3 Radar based systems	18
2.4.4 Laser based systems	19
2.4.5 Ultrasonic based systems	19
2.4.6 Magnetic field based systems	19

2.4.7	Radio Frequency based systems	20
2.5	Future of Close Proximity Systems	22
2.6	Hardware used in the experiments	23
2.6.1	System design	23
2.6.2	Hardware components	26
2.6.3	Note on the inclusion of Global Positioning System in the presented Close Proximity System	30
2.7	Summary	30
3	Radio Frequency Sensor Modelling	32
3.1	Introduction	32
3.2	Radio Frequency propagation mechanisms	33
3.3	Antennas	36
3.3.1	Radiation patterns	36
3.3.2	Geometric considerations - the effect of mounting height	39
3.4	Models describing Radio Frequency propagation	39
3.4.1	n th-power law model - free space propagation model	41
3.4.2	Multiple-ray and two-ray model	42
3.4.3	Communication models	46
3.4.4	Robotics models	48
3.5	Summary	51
4	Tracking and Localisation Using Radio Frequency	52
4.1	Introduction	52
4.2	Probabilistic filtering algorithms	53
4.2.1	Recursive Bayesian Estimation	53
4.2.2	Kalman Filter	54
4.2.3	Particle Filter	55
4.2.4	Histogram Filter	57
4.3	Process models for a person's motion	58
4.3.1	Constant Velocity Model	59
4.3.2	Gaussian Kernel Convolution	59
4.4	Observation models	60
4.4.1	On the importance of a correct observation model	60
4.4.2	Multi-modal observations	62
4.4.3	Bias of observation models	68
4.5	Summary	74

5	An Accurate Sensor Model Representation for Radio Frequency Sensors	75
5.1	Introduction	75
5.2	A more accurate sensor model representation for Radio Frequency sensors	76
5.2.1	Alternative Radio Frequency sensor model	76
5.2.2	Comparison of the new Radio Frequency sensor model with the n th power law	90
5.3	Multi-sensor localisation	93
5.3.1	Range-only localisation in 2D	94
5.3.2	Data association	94
5.3.3	Data fusion	98
5.3.4	The effect of ranging errors and the baseline	100
5.3.5	Using external information	105
5.4	Bayesian Decision Theory for model selection	109
5.4.1	Bayesian decision theory for two and multiple sensor models	110
5.4.2	Decision regions and decision boundaries for two and multiple sensor models	111
5.4.3	On-line sensor-model selection — examples	114
5.4.4	Decision theory with variable switching threshold and minimum posterior threshold	117
5.5	Summary	123
6	Experimental Results	124
6.1	Introduction	124
6.2	Sensor modelling results	125
6.2.1	Example of a sensor model using real data	125
6.2.2	Compression	125
6.2.3	The influence of antenna mounting height	128
6.3	1-dimensional tracking results	130
6.3.1	Kalman Filter tracking	132
6.3.2	Particle Filter tracking	138
6.3.3	Histogram Filter tracking	146
6.4	2-dimensional tracking results	150
6.4.1	Simulation	151
6.4.2	Experimental results	156
6.5	Summary	166
7	Conclusions	167
7.1	Summary of contributions	167
7.1.1	Demonstration that the n th power model is not sufficient for accurate range based localisation	168

7.1.2	Development of an accurate Radio Frequency sensor model	168
7.1.3	Development of probabilistic tracking techniques to be used with the new sensor model	168
7.1.4	Evaluation of single-sensor versus multi-sensor localisation systems for Radio Frequency-Received Signal Strength Indicator based range-only localisation	169
7.1.5	Experiments	169
7.2	Future research	169
7.2.1	Pre-calculation of the signal mean function	170
7.2.2	Compensation mechanisms for the sensor bias	170
7.2.3	Sensor fusion to enhance the system capabilities	170
7.2.4	Deployment of the system in a real environment and Real-time implementation	171
7.3	Summary	171
A	Probability Distributions and Bayes Theorem	172
A.1	Probability distributions	172
A.2	Bayes Theorem	173
B	Fourier Series	175
B.1	Fourier Series - real notation	175
B.2	Fourier Series - complex notation	176
B.3	Discrete Fourier Transform	176
B.4	Nyquist theorem	177
	Bibliography	180

List of Figures

2.1	Machine - personnel interaction in a mine	9
2.2	Bad weather conditions in a mine	11
2.3	Complex machine interactions in a mine	12
2.4	Blind spots for a Komatsu 730E truck	13
2.5	Personnel operating in a blind spot	14
2.6	Accident in a mine (1 st example)	14
2.7	Accident in a mine (2 nd example)	15
2.8	Radio Frequency Identification hardware — active and passive tags	22
2.9	Close Proximity System system setup	24
2.10	Close Proximity System area coverage	25
2.11	Haul truck node Close Proximity System with Global Positioning System	27
2.12	Light vehicle node Close Proximity System with Global Positioning System	28
2.13	Light vehicle operator interface Close Proximity System	28
2.14	Processor board Close Proximity System	29
2.15	Personnel node Close Proximity System	29
3.1	Wireless communication link	33
3.2	Reflection from the ground	35
3.3	Antenna radiation patterns in 2D	37
3.4	Antenna radiation patterns in 3D	38
3.5	Schematic of the antenna influence	40
3.6	Relative path gain versus distance for the n th power model	42
3.7	Relative path gain versus distance for the two ray-model	44
3.8	Relative path gain versus distance for the two ray model with antenna influence	45
3.9	Relative path gain versus distance for 434 MHz and 900 MHz	46
3.10	Binary and Distance-bound sensor models	49
3.11	Discrete Equal Likelihood Areas Model	50
3.12	Signal strength map	50
4.1	Gaussian kernel	60
4.2	Histogram filter representation	61

4.3	Need for correct sensor model	62
4.4	Sensor models used for Kalman Filter measurement approximation.	63
4.5	Approximating a multi-modal distribution with a Gaussian	64
4.6	Gaussian approximation of a multi-modal distribution	65
4.7	Gaussian approximation of two multi-modal distributions	66
4.8	Observation with Particle Filter	67
4.9	Observation with Histogram Filter	68
4.10	Signal variance as a function of the signal mean.	70
4.11	Sensor bias	71
4.12	Sensor bias for multi-modal functions	73
5.1	Radio Frequency sensor modelling diagram	77
5.2	Relative path gain versus distance with antenna influence — approximation	78
5.3	Residual components	79
5.4	Static signal distribution	80
5.5	Simulation data for rotating receiver	83
5.6	Approximation of the two-ray model	83
5.7	Sensor Likelihood Function (theoretical)	85
5.8	Sensor Likelihood Function (Conditional Probabilities)	86
5.9	Conditional likelihood for a measurement considering distance and azimuth angle	87
5.10	Sensor Likelihood Function (Conditional Likelihoods)	88
5.11	n th power model vs. new developed model — Inferring shorter distances	91
5.12	n th power model vs. new developed model — Inferring larger distances	91
5.13	n th power model vs. new developed model (Model differences)	92
5.14	n th power model vs. new developed model (Model differences)	93
5.15	Uni-modal range-only sensor likelihood-function	95
5.16	Uni-modal range-only sensors	96
5.17	Uni-modal range-only sensors fused	97
5.18	Fully centralised sensor fusion system	99
5.19	Range-only localisation with perpendicular sensor arrangement and correct measurements	101
5.20	Range-only localisation with perpendicular sensor arrangement and one sensor observing a wrong range (large baseline)	102
5.21	Range-only localisation with perpendicular sensor arrangement and one sensor observing a wrong range (small baseline)	102
5.22	Range-only localisation with co-linear sensor arrangement and correct measurements	103
5.23	Range-only localisation with co-linear sensor arrangement and wrong measurements (hypothesis split)	103

5.24	Range-only localisation with co-linear sensor arrangement and wrong measurements (hypothesis weakening)	104
5.25	External observer	106
5.26	Transforming an external measurement	107
5.27	External observation	108
5.28	External observation with decreased position accuracy	109
5.29	Sensor models for two different conditions	110
5.30	Decision regions and boundaries for three sensor model candidates	112
5.31	Decision boundaries for two sensor models obtained with real data	113
5.32	Decision boundaries for two sensor models obtained with real data (zoom)	113
5.33	Sensor models for model identification	115
5.34	Choice of models (uninformative prior)	116
5.35	Choice of models (keeping posterior estimates)	118
5.36	Choice of models (minimum posterior threshold)	121
5.37	Choice of models (modified switching threshold)	122
6.1	Sensor model example with real data (individual components)	126
6.2	Sensor model example with real data (final model)	127
6.3	Model compression (uncompressed model)	129
6.4	Model compression (compressed model)	129
6.5	Sensor models for three different receiver heights	131
6.6	Experimental tracking with Radio Frequency sensors — multi-sensor case (experimental setup)	132
6.7	Tracking with the Kalman Filter and the n th power model — simulation with one sensor	133
6.8	Tracking with the Kalman Filter and calculating the mean and variance of the multi-modal observation distribution — simulation with one sensor	134
6.9	Tracking with the Kalman Filter and the n th power model — simulation with multiple sensors	134
6.10	Tracking with the Kalman Filter and calculating the mean and variance of the multi-modal observation distribution — simulation with multiple sensors	135
6.11	Experimental tracking with Radio Frequency sensors — multi-sensor case for the Kalman Filter (experimental result)	136
6.12	Experimental tracking with Radio Frequency sensors — multi-sensor case for the Kalman Filter (experimental result - estimated track)	137
6.13	Experimental tracking with Radio Frequency sensors — multi-sensor observations for the Kalman Filter (large distances)	137
6.14	Experimental tracking with Radio Frequency sensors — multi-sensor observations for the Kalman Filter (small distances)	138
6.15	Tracking with the Particle Filter — multi-sensor tracking (simulation)	139
6.16	Particle Filter multi-sensor tracking (simulation — situation 1)	141

6.17	Particle Filter multi-sensor tracking (simulation — situation 2)	141
6.18	Particle Filter multi-sensor tracking (simulation — situation 3)	142
6.19	Experimental tracking with Radio Frequency sensors — multi-sensor case for the Particle Filter (experimental result)	143
6.20	Experimental tracking with Radio Frequency sensors — multi-sensor case for the Particle Filter (experimental result - estimated track)	143
6.21	Experimental tracking with Radio Frequency sensors — multi-sensor case for the Particle Filter (analysed locations)	144
6.22	Particle Filter multi-sensor tracking (experiment — situation 1)	145
6.23	Particle Filter multi-sensor tracking (experiment — situation 2)	145
6.24	Tracking with the Histogram Filter — multi-sensor tracking (simulation)	146
6.25	Histogram Filter multi-sensor tracking (simulation — convolution of the state Probability Density Function)	147
6.26	Histogram Filter multi-sensor tracking (simulation — observation likelihoods)	148
6.27	Histogram Filter multi-sensor tracking (simulation — state Probability Density Function)	149
6.28	Tracking with the Histogram Filter — multi-sensor tracking (experiment)	150
6.29	2D simulation setup	151
6.30	2D simulation results (track)	152
6.31	2D simulation results (deviations)	153
6.32	Startup — one sensor observing	154
6.33	Startup — two sensors observing	155
6.34	Startup — three sensors observing	155
6.35	Multiple hypotheses	156
6.36	Ranging error	157
6.37	2D experimental setup (1 st example)	158
6.38	2D experimental results (1 st example — track)	159
6.39	2D experimental results (1 st example — deviations)	159
6.40	2D experimental results (1 st example — situation one at close distance)	160
6.41	2D experimental results (1 st example — situation two at close distance)	161
6.42	2D experimental results (1 st example — situation at medium distance)	161
6.43	2D experimental results (1 st example — wrong observation)	162
6.44	2D experimental results (1 st example — situation at far distance)	163
6.45	2D experimental results (1 st example — situation at very far distance)	164
6.46	2D experimental results (2 nd example)	165
B.1	Saw-tooth signal	178
B.2	Magnitude of the Fourier coefficients of the saw-tooth signal	178
B.3	Reconstruction of the sawtooth signal	179

List of Tables

2.1	Number of accidents and fatalities in United States of America mines	9
2.2	Technical data of Close Proximity System nodes	30

List of Acronyms and Abbreviations

APS	Acoustic Parking System
BDT	Bayesian Decision Theory
CDF	Cumulative Distribution Function
CPS	Close Proximity System
CRC	Cooperative Research Council
DOL	Department of Labor
EEG	Electroencephalogram
GPS	Global Positioning System
KF	Kalman Filter
EKF	Extended Kalman Filter
FFT	Fast Fourier Transformation
GMM	Gaussian Mixture Model
GPS	Global Positioning System
HF	Histogram Filter
IP	Internet Protocol
IR	Infrared
ISM	Industrial, Scientific, and Medical
KL	Kullback-Leibler
LCD	Liquid Crystal Display
LOS	Line-of-Sight
MAP	Maximum A Posteriori

- MCMC** Monte Carlo Markov Chain
- MHz** Megahertz
- ML** Maximum Likelihood
- MSHA** Mine Safety and Health Administration
- MMWR** Millimeter Wavelength Radar
- NIOSH** National Institute for Occupational Safety and Health
- OG** Occupancy Grid
- PDF** Probability Density Function
- PF** Particle Filter
- PTP** Peer-To-Peer
- RF** Radio Frequency
- RFID** Radio Frequency Identification
- RI** Report of Investigations
- RSSI** Received Signal Strength Indicator
- RTK** Real Time Kinematic
- SLAM** Simultaneous Localisation and Mapping
- SOG** Sum of Gaussians
- TCAS** Traffic alert and Collision Avoidance System
- TCP/IP** Transmission Control Protocol/Internet Protocol
- TDOA** Time-Difference-of-Arrival
- TOF** Time-of-Flight
- UDP** User Datagram Protocol
- UNS** Universidad Nacional del Sur
- U.S.A.** United States of America
- VW** Volkswagen
- WAF** Wall Attenuation Factor

Notation

\mathbf{x}	state vector
z	a single measurement
\mathbf{Z}_k	measurements up to timestep k
$k \in \{1, 2, \dots\}$	discrete time step or index
t	continuous time
\mathcal{U}	Uniform distribution
$\lambda(\cdot)$	likelihood function
w	weight
$\mathcal{P}(\cdot)$	Probability mass
$p(\cdot)$	Probability distribution of a variable
P	Covariance
μ	mean of a distribution
σ	standard deviation of a distribution
\mathcal{E}	Expectation operator
$g(x; \mu, \sigma)$	Gaussian distribution as a function of x with mean μ and variance σ
$k(x, y, \sigma)$	symmetrical Gaussian kernel as a function of x, y , and standard deviation σ
I	Intensity
E	Electric field
P	Power
G	Gain
PL	Path loss
λ	wavelength
ω	angular frequency
f	frequency
T	period duration
ϕ	azimuth angle
θ	elevation angle

i	imaginary unit
$\delta(\cdot)$	delta function
$*$	convolution operator
\mathbf{x}^T	an arbitrary vector \mathbf{x} transposed
\mathcal{X}	an arbitrary set
ε	an arbitrary threshold