

CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Electrical Engineering
Department of Measurement



Application of Magnetic Sensors for Navigation Systems

DOCTORAL THESIS

2007

Jan Včelák

Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Measurement



Application of Magnetic Sensors for Navigation Systems

DOCTORAL THESIS

Ph.D. Programme: Electrical Engineering and Information
Technology

Branch of study: Measurement and instrumentation

Supervisor: Doc. Ing. Petr Kašpar, CSc.

2007

Jan Včelák

Reports on Sensors and Instrumentation

Volume 2

Jan Včelák

**Application of Magnetic Sensors
for Navigation Systems**

Shaker Verlag
Aachen 2009

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Czech Technical University Prague, Diss., 2007

Copyright Shaker Verlag 2009

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8322-7738-3

ISSN 1868-5056

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

ACKNOWLEDGEMENT

I would like to express my acknowledgements to supervisor Petr Kašpar and to Pavel Ripka and Antonín Platil for their scientific guidance, valuable comments and patience during my studies.

I also want to thank to my colleagues Jan Kubík, Michal Malátek, Vojtěch Petrucha, Michal Janošek, Aleš Cerman, Michal Vopálenský, Pavel Mlejnek, Jiří Saneistr for their cooperation in „MagLab“ team, their long-lasting friendship and support even in bad times.

My thanks also belong to my parents Iva Včeláková, Jaroslav Včelák and sister Kateřina Včeláková for their patience, support and given possibility to study.

CONTENTS:

1	Introduction	1
2	State of the art	3
2.1	<i>Navigation systems used</i>	3
2.1.1	Radio navigation systems	4
2.1.1.1	Terrestrial radio navigation systems	4
2.1.1.1.1	Radio direction finders	5
2.1.1.1.2	Hyperbolic position estimation	6
2.1.1.2	Satellite radio navigation systems	7
2.1.1.2.1	US Department of Defense's NAVSTAR Global Positioning System (GPS)	9
2.1.1.2.2	Russian Federation's Global Positioning System (GLONASS)	11
2.1.2	Inertial navigation systems	11
2.1.2.1	Sensors used for strap down systems (accelerometers & gyroscopes)	12
2.2	<i>Electronic compasses</i>	17
2.2.1	Gyroscopic compass	17
2.2.2	Electronic magnetic compasses and magnetometer modules	19
2.2.3	Sensors for magnetic compasses	22
2.2.4	AMR sensors	22
2.2.5	Fluxgate sensors	27
2.2.6	Published calibration techniques for multi-sensor magnetometers and compasses.	31
3	Goals of doctoral thesis	32
4	Theoretical background	34
4.1	<i>Basic used coordinate frames for navigation</i>	34
4.1.1	True Inertial Frame	34
4.1.2	Earth-Centered Inertial Frame (ECI)	34
4.1.3	Earth-Centered Earth – Fixed (ECEF) Frame	35
4.1.4	Navigation Frame	35
4.1.5	Body Frame	35
4.1.6	Wander Azimuth Frame	35
4.2	<i>Coordinate frames transformations</i>	37
4.3	<i>Euler's Angles</i>	37
4.3.1	Rotation through roll angle φ	38
4.3.2	Rotation through pitch angle θ	39
4.3.3	Rotation through yaw angle ψ	40
4.3.4	Euler's angles transformation from inertial to body reference coordinate system	41
4.3.5	Direction Cosine Matrix	43

4.4	<i>Geomagnetic field of Earth</i>	44
4.4.1	Magnetic field vector	44
4.4.2	The Geodynamo	47
4.4.3	Field variation in long timescales	48
4.4.4	The Earth's Ionosphere and Diurnal-Field Variation	48
4.4.5	Earth's magnetosphere	49
4.4.6	Magnetic field on the test site	52
4.5	<i>The Earth's field of gravity</i>	53
4.6	<i>Estimation of basic parameters from measured results</i>	55
4.6.1	Noise processing	55
4.6.2	Effective number of bits and signal to noise ratio	56
5	Electronic compass design	57
5.1	<i>Electronic compass with dual axis sensor</i>	57
5.1.1	Error caused by sensors non-orthogonality	60
5.2	<i>Compass with three-axis magnetic sensor and tilt compensation</i>	64
5.2.1	Error caused by sensors non-orthogonality	65
5.2.2	Simplification of general deviation matrix A	68
6	Scalar calibration	70
6.1	<i>Presumptions for the Scalar Calibration</i>	70
6.1.1	Homogeneity of measured field	70
6.1.2	Measurement of field in the calibration area	71
6.1.3	Data Acquisition	71
6.2	<i>Iteration algorithm to process the data</i>	73
7	Misalignment of sensors axis with the compass case and with the second sensor triplet	77
7.1	<i>Consequences of sensors misalignments</i>	81
7.1.1	Influence of the sensor x misalignment	82
7.1.2	Influence of the sensor y misalignment	83
7.1.3	Influence of the sensor z misalignment	85
7.1.4	Consequences of misalignments to pitch, roll and azimuth calculation	87
7.2	<i>Calibration of misalignment angles</i>	90
7.2.1	Rotation of the compass case in roll	90
7.2.2	Estimation of accelerometer misalignment angle $\alpha_{\Phi-A}$	95
7.2.3	Rotation of the compass in azimuth	96
8	Developed and verified compass modules	99
8.1	<i>Developed compass with AMR sensors and accelerometers</i>	99
8.1.1	Hardware construction	100
8.1.2	Basic sensor parameters	104

8.1.3	Results of scalar calibration	108
8.1.4	Results of sensors misalignment calibration	111
8.2	<i>Developed compass with PCB fluxgate sensors and accelerometers</i>	119
8.2.1	Hardware construction	119
8.2.2	Mechanical construction and sensor placement	126
8.2.3	Compass with PCB fluxgate sensors and accelerometers – basic sensors parameters	127
8.2.4	Results of scalar calibration	134
8.2.5	Results of sensors misalignments calibration	141
8.2.6	Accuracy verification measurements	149
8.3	<i>Commercially produced magnetometer module Honeywell HMR2300</i>	152
8.3.1	Results of Scalar calibration for HMR2300 magnetometer	152
8.3.2	Results of misalignment angles calibration	155
9	Using the calibration procedures for fluxgate gradiometer	157
10	Conclusions	159
10.1	<i>Conclusion summary</i>	162
10.2	<i>Issues of further research and improvement</i>	163
11	Appendices	165
11.1	<i>PC software description</i>	165
11.2	<i>Technical designs</i>	166
11.2.1	PCB fluxgate compass case - technical drawing	166
11.2.2	Theodolite holder- Carl Zeiss THEO 080A	167
11.2.3	Theodolite holder bed – PERTINAX	168
11.2.4	Fork holder for PCB fluxgate compass prototype	169
11.2.5	Fork holder for AMR compass prototype	170
12	List of Abbreviations	171
13	Publications	172
14	References	174