

# A Neural Network Approach to Fluid Quantity Measurement in Dynamic Environments

Edin Terzic · Jenny Terzic  
Romesh Nagarajah · Muhammad Alamgir

# A Neural Network Approach to Fluid Quantity Measurement in Dynamic Environments

Edin Terzic  
Delphi Automotive Systems  
Regent Court 20  
Sandringham, VIC 3191  
Australia

Romesh Nagarajah  
Swinburne University of Technology  
Orchard Gve 89  
Blackburn South, VIC 3130  
Australia

Jenny Terzic  
Iveco Trucks Australia (Fiat Group)  
Regent Court 20  
Sandringham, VIC 3191  
Australia

Muhammad Alamgir  
Vipac Australia  
Eldridge Road 4  
Wyndham Vale, VIC 3024  
Australia

ISBN 978-1-4471-4059-7  
DOI 10.1007/978-1-4471-4060-3  
Springer London Heidelberg New York Dordrecht

ISBN 978-1-4471-4060-3 (eBook)

British Library Cataloguing in Publication Data  
A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2012936111

© Springer-Verlag London 2012

MATLAB and Simulink are registered trademarks of The MathWorks, Inc. See [www.mathworks.com/trademarks](http://www.mathworks.com/trademarks) for a list of additional trademarks. Other product or brand names may be trademarks or registered trademarks of their respective holders.

LabVIEW™ is a trademark of National Instruments. National Instruments Corporation, 11500 N Mopac Expwy, Austin, TX 78759-3504, U.S.A. <http://www.ni.com>.

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Overview	1
1.2	Background	1
1.3	Aims and Objectives	6
1.4	Methodology and Approach	7
1.5	Outline of the Thesis	7
	References	8
<b>2</b>	<b>Capacitive Sensing Technology</b>	<b>11</b>
2.1	Overview	11
2.2	Characteristics of Capacitors	11
2.2.1	Overview	11
2.2.2	A Capacitor	11
2.2.3	Capacitance	12
2.2.4	Capacitance in Parallel and Series Circuits	14
2.2.5	Dielectric Constant	15
2.2.6	Dielectric Strength	15
2.3	Capacitive Sensor Applications	16
2.3.1	Overview	16
2.3.2	Proximity Sensing	17
2.3.3	Position Sensing	18
2.3.4	Humidity Sensing	19
2.3.5	Tilt Sensing	19
2.4	Capacitors in Level Sensing	19
2.4.1	Overview	19
2.4.2	Sensing Electrodes	20
2.4.3	Conducting and Non-Conducting Liquids	24
2.5	Effects of Dynamic Environment	25

2.5.1	Overview . . . . .	25
2.5.2	Effects of Temperature Variations . . . . .	25
2.5.3	Effects of Contamination . . . . .	26
2.5.4	Influence of Other Factors . . . . .	28
2.6	Effects of Liquid Sloshing . . . . .	29
2.6.1	Overview . . . . .	29
2.6.2	Slosh Compensation by Dampening Methods . . . . .	29
2.6.3	Tilt Sensor . . . . .	30
2.6.4	Averaging Methods . . . . .	32
2.7	Summary . . . . .	34
	References . . . . .	35
<b>3</b>	<b>Fluid Level Sensing Using Artificial Neural Networks . . . . .</b>	<b>39</b>
3.1	Overview . . . . .	39
3.2	Signal Processing and Classification . . . . .	39
3.2.1	Overview . . . . .	39
3.2.2	Data Collection . . . . .	39
3.2.3	Signal Filtration . . . . .	40
3.2.4	Feature Extraction . . . . .	41
3.2.5	Signal Classification . . . . .	44
3.3	Artificial Neural Networks . . . . .	45
3.3.1	Neuron Model . . . . .	45
3.3.2	Transfer Function . . . . .	47
3.3.3	Perceptron . . . . .	48
3.4	Neural Network Architectures . . . . .	49
3.4.1	Overview . . . . .	49
3.4.2	Network Layers . . . . .	49
3.4.3	Network Topologies . . . . .	49
3.5	Training Principles . . . . .	52
3.5.1	Overview . . . . .	52
3.5.2	Supervised Learning . . . . .	52
3.5.3	Unsupervised Learning . . . . .	53
3.6	Neural Networks in Dynamic Environments . . . . .	53
3.6.1	Overview . . . . .	53
3.7	Temperature Compensation with Neural Networks . . . . .	53
	References . . . . .	54
<b>4</b>	<b>Methodology . . . . .</b>	<b>57</b>
4.1	Overview . . . . .	57
4.2	Capacitive Sensor-Based Level Sensing . . . . .	57
4.2.1	Capacitive Sensor Signal . . . . .	57
4.2.2	Sensor Response Under Slosh Conditions . . . . .	58
4.3	Design of Methodology . . . . .	59
4.4	Feature Selection and Reduction . . . . .	61

4.5	Signal Filtration . . . . .	63
4.6	Influential Factors Analysis . . . . .	66
	References . . . . .	67
<b>5</b>	<b>Experimentation . . . . .</b>	<b>69</b>
5.1	Overview . . . . .	69
5.2	Methodology . . . . .	69
5.3	Data Collection and Processing Methodology . . . . .	72
5.4	Apparatus and Equipment used in Experimental Programs . . . . .	73
5.4.1	Capacitive Level Sensor . . . . .	73
5.4.2	Fuel Tank . . . . .	75
5.4.3	Linear Actuator. . . . .	75
5.4.4	Heater . . . . .	76
5.4.5	Arizona Dust . . . . .	76
5.4.6	Signal Acquisition Card. . . . .	78
5.5	Experiment Set A: Study of the Influential Factors . . . . .	78
5.5.1	Overview . . . . .	78
5.5.2	Factorial Design . . . . .	79
5.5.3	Experimental Setup . . . . .	80
5.6	Experiment Set B: Performance Estimation of Static and Dynamic Neural Networks . . . . .	81
5.6.1	Overview . . . . .	81
5.6.2	Experimental Setup . . . . .	81
5.6.3	BP Network Architecture . . . . .	82
5.6.4	Distributed Time-Delay Network Architecture . . . . .	84
5.6.5	NARX Network Architecture . . . . .	85
5.7	Experiment Set C: Performance Estimation Using Signal Enhancement. . . . .	86
5.7.1	Overview . . . . .	86
5.7.2	Backpropagation Network Architecture . . . . .	87
5.7.3	Experimental Setup . . . . .	88
5.8	Neural Network Data Processing . . . . .	90
5.8.1	Network Initialization . . . . .	92
5.8.2	Raw Signal Data . . . . .	92
5.8.3	Filtration . . . . .	92
5.8.4	Feature Extraction . . . . .	93
5.8.5	Network Training . . . . .	93
5.8.6	Network Validation . . . . .	93
	References . . . . .	94
<b>6</b>	<b>Results. . . . .</b>	<b>95</b>
6.1	Overview . . . . .	95
6.2	Experiment Set A . . . . .	95

6.2.1	Main Effects Plot . . . . .	95
6.2.2	Interaction Plots . . . . .	96
6.2.3	Summary . . . . .	97
6.3	Experiment Set B . . . . .	98
6.3.1	Frequency Coefficients . . . . .	99
6.3.2	Backpropagation Network . . . . .	99
6.3.3	Distributed Time-Delay Network . . . . .	99
6.3.4	NARX Neural Network . . . . .	99
6.3.5	Summary . . . . .	100
6.4	Experiment Set C . . . . .	102
6.4.1	Raw Capacitive Sensor Signals . . . . .	102
6.4.2	Selection of Optimal Preprocessing Parameters (Experiment Set C1) . . . . .	103
6.4.3	Selection of Optimal Signal Smoothing Parameters (Experiment Set C2) . . . . .	108
6.4.4	Final Validation Results (Experiment Set C3) . . . . .	111
6.4.5	Frequency Coefficients . . . . .	112
6.4.6	Network Weights . . . . .	114
6.4.7	Validation Results . . . . .	115
6.4.8	Validation Error . . . . .	118
6.4.9	Summary . . . . .	118
7	<b>Discussion . . . . .</b>	121
7.1	Overview . . . . .	121
7.2	Backpropagation Network Configurations . . . . .	121
7.3	Selection of Signal Preprocessing Parameters . . . . .	122
7.4	Selection of Signal Smoothing Parameters . . . . .	124
8	<b>Conclusions and Future Work . . . . .</b>	129
8.1	Conclusion . . . . .	129
8.2	Future Work . . . . .	131
	<b>Appendices . . . . .</b>	133
	<b>About the Authors . . . . .</b>	135
	<b>Index . . . . .</b>	137

# Acronyms

ANN	Artificial Neural Network
BP	Backpropagation Neural Network
DAQ	Data Acquisition
dB	Decibel (logarithmic unit)
DCT	Discrete Cosine Transform
DFT	Discrete Fourier Transform
DOE	Design of Experiments
DSP	Digital Signal Processing
DST	Discrete Sine Transform
DWT	Discrete Wavelet Transform
FFT	Fast Fourier Transform
FS	Fourier Series
FT	Fourier Transform
FTDNN	Focused Time-Delay Neural Network
FWT	Fast Wavelet Transform
IDCT	Inverse Discrete Cosine Transform
IFFT	Inverse Fast Fourier Transform
NARX	Nonlinear Autoregressive Network with Exogenous Inputs
NN	Neural Network
OEL	Occupational Exposure Limit
PCMCIA	Personal Computer Memory Card International Association
PLC	Programmable Logic Controller
RBF	Radial Basis Function
TDNN	Distributed Time-Delay Neural Network
WT	Wavelet Transform



# **Abstract**

This book describes the research and development of a fluid level measurement system for dynamic environments. The measurement system is based on a single tube capacitive sensor. An Artificial Neural Network (ANN)-based signal characterization and processing system has been developed and used to compensate for the effects of sloshing, temperature variation, and the influence of contamination in fluid level measurement systems operating in dynamic environments, particularly automotive applications. It has been demonstrated that a simple backpropagation neural network coupled with a Moving Median filter could be used to achieve the high levels of accuracy required, for fluid level measurement in dynamic environments including those relating to automotive applications.