



# **HIGH ACCURACY GPS-FREE VEHICLE LOCALIZATION FRAMEWORK VIA A SINGLE RSU**

By

Ahmed Abdel Wahab Mohamed El Marady

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
Electronics and Communications Engineering

FACULTY OF ENGINEERING , CAIRO UNIVERSITY  
GIZA, EGYPT  
2015

# **HIGH ACCURACY GPS-FREE VEHICLE LOCALIZATION FRAMEWORK VIA A SINGLE RSU**

By

Ahmed Abdel Wahab Mohamed El Marady

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
MASTER OF SCIENCE  
in  
Electronics and Communications Engineering

Under the Supervision of

Dr. Yasmine Aly Hassan Fahmy

Associate Professor

Electronics and Communications Engineering Department

Faculty of Engineering , Cairo University

Dr. Ahmed Khattab Fathi Khattab

Assistant Professor

Electronics and Communications department

Faculty of Engineering , Cairo University

FACULTY OF ENGINEERING , CAIRO UNIVERSITY

GIZA, EGYPT

2015

# **HIGH ACCURACY GPS-FREE VEHICLE LOCALIZATION FRAMEWORK VIA A SINGLE RSU**

By

Ahmed Abdel Wahab Mohamed El Marady

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
MASTER OF SCIENCE  
in  
Electronics and Communications Engineering

Approved by the Examining Committee:

---

Dr. Yasmine Aly Hassan Fahmy , Thesis Main Advisor

---

Prof. Hebat-Allah Mostafa Mourad, Internal Examiner

---

Dr. Ahmed Hasan Kamel Aly Madian, External Examiner

(Associate Professor at German University in Cairo)

FACULTY OF ENGINEERING , CAIRO UNIVERSITY  
GIZA, EGYPT  
2015

**Engineer's Name:** Ahmed Abdel Wahab Mohamed El Marady  
**Date of Birth:** 25/5/1985  
**Nationality:** Egyptian  
**E-mail:** ahmed.abdel-wahab@civilaviation.com.eg,  
ahmedabdelwahab02@yahoo.com  
**Phone:** +2 01144007328  
**Address:** Shoubra El-Khima, Qalyubia  
**Registration Date:** 1/10/2011  
**Awarding Date:** 00/00/2015  
**Degree:** Master of Science  
**Department:** Electronics and Communications Engineering



**Supervisors:**

Dr. Yasmine Aly Hassan Fahmy  
Dr. Ahmed Khattab Fathi Khattab

**Examiners:**

Dr. Yasmine Aly Hassan Fahmy	(Thesis main advisor)
Prof. Hebat-Allah Mostafa Mourad	(Internal examiner)
Dr. Ahmed Hasan Kamel Aly Madian	(External examiner)
(Associate Professor at German University in Cairo)	

**Title of Thesis:**

High Accuracy GPS-Free Vehicle Localization Framework via a Single RSU

**Key Words:**

Roadside unit; Dead reckoning; Inertial navigation system; Dedicated short-range communication (DSRC); Vehicular ad-hoc network (VANET); Kalman filter.

**Summary:**

This thesis presents a high accuracy GPS-free vehicle localization framework to be used in collision avoidance applications. In contrast to the error-prone existing localization techniques, the approach proposed in this thesis determines the vehicle location, up to lane-level accuracy via a single Road Side Unit (RSU). By using one RSU, the cost of the localization system installation is reduced. The suggested framework integrates the information from the local Inertial Navigation System (INS) and a single RSU via Kalman and extended Kalman filters.

# Acknowledgements

Firstly, I thank God for guiding me to finish this work.

Secondly, I would like to express my gratitude to my supervisors Dr. Ahmed Khattab and Dr. Yasmine Fahmy for the useful guidance, comments, remarks and engagement through the learning duration of this master thesis.

Finally, I would like to thank my superiors at work Eng. Said Jouban and Mr. Hesham El Gammal for motivating and helping me through their working time.

# Dedication

To my mother, my father and my wife.

# Table of Contents

<b>List of Tables</b>	<b>iii</b>
<b>List of Figures</b>	<b>iv</b>
<b>List of Abbreviations and Symbols</b>	<b>vi</b>
<b>Acknowledgements</b>	<b>x</b>
<b>Dedication</b>	<b>xi</b>
<b>Abstract</b>	<b>xii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Research Motivation . . . . .	1
1.2 Thesis Contributions . . . . .	2
1.3 Thesis Outline . . . . .	3
<b>2 Background</b>	<b>5</b>
2.1 Characteristics of VANET . . . . .	5
2.2 Applications of VANET . . . . .	5
2.3 Challenges and Open-Research Areas in VANET . . . . .	8
2.4 Basics of DSRC . . . . .	9
2.5 IEEE 802.11 MAC . . . . .	11
2.5.1 Basics of IEEE 802.11 MAC . . . . .	12
2.5.2 RTS / CTS handshake . . . . .	14
2.5.3 Network Allocation Vector: Virtual Carrier Sense . . . . .	16
<b>3 Literature Review</b>	<b>17</b>
3.1 Absolute Positioning Techniques . . . . .	17
3.1.1 GPS-based Absolute Positioning Techniques . . . . .	17
3.1.2 GPS-Free Absolute Positioning Techniques . . . . .	21
3.2 Relative Positioning Techniques . . . . .	22
3.2.1 GPS-Based Relative Positioning Techniques . . . . .	22
3.2.2 GPS-Free Relative Positioning Techniques . . . . .	24
3.3 Lane-Level Positioning Techniques . . . . .	24
3.3.1 Vision-Based Lane-Level Positioning Techniques . . . . .	24
3.3.2 Vision-Free Lane-Level Positioning Techniques . . . . .	24
3.4 Chapter Summary . . . . .	25
<b>4 One-RSU-Based Framework for GPS-Free Vehicle Localization</b>	<b>26</b>
4.1 Introduction . . . . .	26
4.2 System Model . . . . .	27
4.3 The Proposed One-RSU-Localization Framework . . . . .	27
4.3.1 Determining the Vehicle Driving Direction . . . . .	27

4.3.2	Vehicle Localization . . . . .	30
4.3.2.1	Localization via V2R Communication for Distant Vehicles . . . . .	35
4.3.2.2	Localization via Dead Reckoning for Nearby Vehicles . . . . .	36
4.4	Simulation . . . . .	40
4.4.1	Simulations Environment . . . . .	40
4.4.2	Modified Random Waypoint Mobility Pattern Generator . . . . .	40
4.4.3	Metrics used . . . . .	41
4.4.4	Results . . . . .	41
4.4.4.1	Localization Accuracy . . . . .	42
4.4.4.2	Performance Under Different Mobility Patterns . . . . .	44
4.5	Summary . . . . .	44
<b>5</b>	<b>INS-Assisted Single RSU Framework for GPS-Free Vehicle Localization</b>	<b>46</b>
5.1	Introduction . . . . .	46
5.2	System Model . . . . .	47
5.3	RSU/INS Integration for Vehicle Localization . . . . .	49
5.3.1	Kalman and Extended Kalman Filters Preliminaries . . . . .	50
5.3.2	One-Dimensional Kalman Filter for Locating Distant Vehicles . . . . .	52
5.3.3	Two-Dimensional Extended Kalman Filter for Locating Nearby Vehicles . . . . .	56
5.4	Road/Lane Boundary Adjustment Stage . . . . .	58
5.5	Framework Integration . . . . .	61
5.6	Summary . . . . .	62
<b>6</b>	<b>Simulations</b>	<b>63</b>
6.1	Simulations Environment . . . . .	63
6.2	Metrics used . . . . .	63
6.3	Results . . . . .	64
6.3.1	Localization Accuracy . . . . .	64
6.3.1.1	Localization Accuracy along the Road Length . . . . .	65
6.3.1.2	Localization Accuracy along both Road Dimensions . . . . .	66
6.3.2	Impact of Measurement Errors . . . . .	67
6.3.3	Performance Under Different Mobility Patterns . . . . .	68
6.3.4	Impact of Traffic Density . . . . .	73
<b>7</b>	<b>Conclusion and Future Research Directions</b>	<b>74</b>
7.1	Conclusion . . . . .	74
7.2	Contributions . . . . .	74
7.3	Future Research Directions . . . . .	75
	<b>References</b>	<b>77</b>
	<b>Appendix A Examples of VANET Projects</b>	<b>81</b>
	<b>Appendix B Derivations of the Kalman Filter Equations</b>	<b>82</b>



# List of Tables

2.1	Summary and classifications of some important applications of VANET. .	7
2.2	Summary of the main differences between the two US DSRC generations [1]. . . . .	11
2.3	Comparison between different DSRCs standards for US, Europe and Japan [1]. . . . .	11
4.1	Summary of simulation parameters . . . . .	42
6.1	Simulation parameters . . . . .	64
A.1	Examples of VANET projects . . . . .	81

# List of Figures

2.1	Illustration of VANET architecture. . . . .	10
2.2	The frequencies of various channels in DSRC [1]. . . . .	10
2.3	The increment of contention window ( $CW$ ) with retires. . . . .	13
2.4	Hidden station problem. . . . .	13
2.5	Exposed station problem. . . . .	14
2.6	RTS/CTS/Data/ACK timeline. . . . .	15
2.7	Virtual channel sensing using CSMA/CA. . . . .	16
3.1	Illustration of various positioning techniques. . . . .	18
3.2	Illustration of RF-GPS technique. . . . .	19
3.3	The architecture of GPS/SBAS. . . . .	20
3.4	The concept of Assisted-GPS technique. . . . .	21
3.5	Illustration of RSU-based localization technique. . . . .	22
3.6	System overview of DSRC/radar sensors localization technique. . . . .	23
4.1	Illustration of the system model. . . . .	28
4.2	The proposed One-RSU-Based localization framework. . . . .	29
4.3	Illustration of vehicle driving direction determination technique. . . . .	31
4.4	Illustration of the concept of range-based localization technique. . . . .	32
4.5	Illustration of the threshold area . . . . .	33
4.6	Illustration of scenario where three vehicle travelling one in each lane of three lanes single carriageway road without changing lane. . . . .	34
4.7	The impact of curvature error. . . . .	35
4.8	The timeline of the proposed two-way TOA packet handshake. . . . .	37
4.9	Range estimation using two-way TOA. . . . .	37
4.10	Dead Reckoning vehicle kinematics. . . . .	38
4.11	Flow chart of the localization stage. . . . .	39
4.12	Accuracy of $y$ -location $\bar{y}_k$ of our framework. . . . .	42
4.13	The vehicle localization accuracy of vehicle moving in the first, second and third lane. . . . .	43
5.1	The proposed GPS-free integrated framework for vehicle localization using a single RSU and INS information. . . . .	48
5.2	Illustration of the system model assumed in the proposed INS-Assisted Single RSU framework. . . . .	49
5.3	An illustration of the various fusion techniques used along the road. Vehicles $V_1$ and $V_2$ are inside and outside the threshold area, respectively. . . . .	51
5.4	INS vehicle Kinematics. . . . .	52
5.5	The impact of curvature error. . . . .	54
5.6	The one-dimensional discrete Kalman Filter cycle. . . . .	55
5.7	The two-dimensional discrete extended Kalman Filter cycle. . . . .	57
5.8	Illustration of Road/Lane boundaries for single carriageway road with three lanes. . . . .	59

6.1	Accuracy of $y$ -location $\hat{y}_k$ of our framework. . . . .	65
6.2	Accuracy of vehicle-location in both $x$ and $y$ dimensions. . . . .	66
6.3	The impact of the range measurement error on $\hat{y}_k$ , $\tilde{\varphi}_k$ , and $\tilde{x}_k$ . . . . .	67
6.4	The vehicle localization accuracy of vehicle moving in the first lane ( $x=1.5$ m). . . . .	69
6.5	The vehicle localization accuracy of vehicle moving in the third lane ( $x=7.5$ m). . . . .	70
6.6	The vehicle localization accuracy of vehicle moving in the second lane ( $x=4.5$ m). . . . .	71
6.7	The vehicle localization accuracy of a vehicle moving in a random pattern. . . . .	72
6.8	The impact of traffic density. . . . .	73

# List of Abbreviations and Symbols

## List of Abbreviations

ACC	Adaptive Cruise Control
ACK	Acknowledge
A-GPS	Assisted–Global Positioning System
AIFS	Arbitration Inter-frame Space
AoA	Angle of Arrival
AP	Access Point
ARIB	Association of Radio Industries and Businesses
ASTM	American Society for Testing and Materials
CWS	Collision Warning Systems
CCW	Cooperative collision warning
CCH	Control Channel
CEN	European Committee for Standardization
CW	Contention Window
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
CTS	Clear–to–Send
DCF	Distributed Coordination Function
D-GPS	Differential–Global Positioning System
DIFS	DCF Inter Frame Space
DR	Dead Reckoning
DSRC	Dedicated Short–Range Communication
EDCA	Enhanced Distributed Channel Access Function
EKF	Extended Kalman Filter
EIFS	Extended IFS
ETC	Electronic Toll Collection
FCC	Federal Communications Commission
GBAS	Ground–Based Augmentation System
GOT	Grid-based On-road localization
GEO	Geostationary
GPS	Global Positioning System
HCCA	Hybrid Controlled Channel Access
IFS	Interframe Space
INS	Inertial Navigation System
IVCAL	Inter–Vehicle–Communication–Assisted Localization
ITS	Intelligent Transportation Systems
KF	Kalman Filter
LOS	Line of Sight
MAC	Media Access Control
MANET	Mobile Ad-Hoc Networks

MCC	Mission Control Centers
MSC	Mobile Switching Center
NAV	Network Allocation Vector
NHTSA	National Highway Traffic Safety Administration
NLOS	Non Line of Sight
NLES	Navigation Land Earth Stations
OBU	Onboard Unit
PCF	Point Coordination Function
PHY	Physical
QoS	Quality of Service
RIMS	Ranging and Integrity Monitoring Stations
RFID	Radio Frequency Identification
RF-GPS	Radio-Frequency-GPS
RMSE	Root-Mean-Square Error
RSU	Roadside Unit
RTS	Request-to-Send
RSS	Received Signal Strength
RTT	Round-Trip Time
SBAS	Satellite-Based Augmentation System
SCH	Service Channel
SIFS	Short Inter-Frame Space
TDOA	Time Difference of Arrival
TOA	Time of Arrival
TTFF	Time-To-First Fix
VANET	Vehicular Ad-hoc Networks
V2V	Vehicle-to-Vehicle
V2R	Vehicle-to-Roadside
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

## List of Symbols

$A, B$	Control matrices
$C$	Speed of light $=3 \times 10^8$
$CLT$	Change-lane-threshold
$CW_{min}$	Minimum contention window
$CW_{max}$	Maximum contention window
$EMA_K$	Exponential weighted moving average
$\varepsilon_k$	Curvature noise which reflects the lane-level ambiguity
$g_k$	Kalman gain used in one-dimensional Kalman filter
$\underline{g}_k$	2x1 Kalman gain used in two-dimensional extended Kalman filter
$h(\cdot)$	Non-linear function used to compute the predicted single-value measurement, $R_{V,RSU}$
$\underline{h}_k$	1x2 Jacobian vector of the partial derivatives of $h(\varphi)$
$I$	2x2 unit matrix
$L$	Length of the road
$L_{RSU}$	y-coordinate of the RSU
$L_i$ and $L_{i-1}$	The boundaries of lane $i$
$MA_K$	Moving average
$M$	Number of prior observations of $\tilde{x}_k$
$N$	North road driving direction
$n_r$	Noise comes from range estimation, $R_{V,RSU}$
$\theta$	Drift angle
$p_k$	Posteriori estimate error variance
$\bar{p}_k$	Priori estimate error variance
$P_k$	2x2 posteriori estimate error covariance matrix
$\bar{P}_k$	2x2 priori estimate error covariance matrix
$Q$	2x2 covariance matrix of the process noise
$R_{V,RSU}$	Estimated range between vehicle and RSU at time $t_2$
$R'_{V,RSU}$	Estimated range between vehicle and RSU at time $t_1$
$RMS E_x$	Root-mean-square error of vehicle location in x dimension
$RMS E_y$	Root-mean-square error of vehicle location in y dimension
$S$	South road driving direction
$T$	Time interval
$\tau$	Time delay experienced at the RSU
$\underline{u}_k$	2x1 vector that represent vehicle velocity components in the $x$ and $y$ directions
$v$	Vehicle speed
$v_{min}$	Minimum vehicle speed

$v_{max}$	Maximum vehicle speed
$W$	Width of the road
$\underline{w}_k$	Process noise comes from using INS
$\bar{y}_k$	Estimated vehicle location using our One-RSU-based approach at time $t_k$
$\hat{y}_k$	Posteriori state estimate of the vehicle location in y-dimension
$\hat{y}_k^-$	Priori state estimate of the vehicle location y-dimension
$\sigma_r^2$	Variance
$z_k$	Measurement
$(x_{actual.i}, y_{actual.i})$	Real vehicle location at time instant $i$
$\zeta_k$	Measurement noise
$\alpha$	Weighting factor
$\hat{\underline{\varphi}}_k^-$	2x1 priori state estimate of the vehicle location
$\hat{\underline{\varphi}}_k$	2x1 posteriori state estimate of the vehicle location