Radar-based Self-localization for Autonomous Vehicles

SHAKER VERLAG

Ahmad Pishehvari

Berichte aus der Robotik

Ahmad Pishehvari

Radar-based Self-Localization for Autonomous Vehicles

Shaker Verlag
Düren 2021

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.: Genehmigte Dissertation der Bergischen Universität Wuppertal, 2020

Printed in Germany.

ISBN 978-3-8440-7874-9
ISSN 1434-8098

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

To my mother

Acknowledgment

Filled with the humbleness and gratefulness, I would like to acknowledge deeply to all those who have supported and encouraged me for pursuing my studies to accomplish the present work.

I wish to express my deepest gratitude to my mentor and immediate supervisor, Prof. Dr.-Ing. Bernd Tibken from Wuppertal university (BUW) for his support, continuous guidance, meticulous suggestions and constructive criticism during the practical phase and for his inexhaustible patience during the correction phase of this book. His insight and knowledge into the subject matter steered me in the right directions through this research while respecting my personal reasoning and ideation which has resulted in a productive collaboration. His enthusiasm and love for teaching is contagious and he is doubtless one of my best role models for a scientist, mentor, and teacher.

I wish to express my deepest gratitude to Prof. Dr.-Ing. Reinhard Möller for kindly accepting the peer review of this book. His comprehensive and prompt support helped me to complete this research work.

It gives me immense pleasure to thank my colleagues within the Faculty of automation technology/ control technology of BUW, Dr.-Ing. Robert Dehnert and Dr.-Ing. Roland Clauß, for their unconditional support throughout my intense academic years. I greatly appreciate the extensive personal and professional guidance through the collaborative work undertaken with them. Their ability to work collectively, to innovate and increase the motivation of the undergraduates keeps astonishing me.

I am also pleased to express my gratitude and recognition to Stephanie Leßmann for the thoughtful comments and recommendations on this book during the culmination of four years of my Ph.D. Her consistent willing and assisting enthusiastic is invaluable throughout this study. She has supported me not only by providing a research assistantship and guidance but also by insightful and stimulating discussions which guided me to rectify numerous aspects. Her wealth of knowledge in the field of mathematics and robotics in particular is inspiring and her passion for this field is contagious and motivational. Moreover, I would like to express my gratefulness to Dr.-Ing. Markus Stefer within the team of advance engineering of APTIV company for his significant contributions to this book. As a conscientious professional, he provided me with his

technical know-how accompanied with patience and his unique enthusiasm to educate. His performance commitment, integrity and cooperative spirit are beyond the imagination and his faithful support during the crucial stages of this Ph.D. is so appreciated.
I extend my sincere gratitude to Dr.-Ing Dennis Vollbracht for his creativity and power of expression with whom the conversations were vital in inspiring me to think from multiple perspectives to form a comprehensive and objective critique. He provided and intensified consistently vital stimulus to the further development of my personal and professional abilities. His insightful suggestions played a major role in polishing my research writing skills during the compilation of this book. Thank you for expressing your thoughts so eloquently and unapologetically, making you an ultimate role model.
I greatly appreciate the support received through the collaborative work undertaken with Dr-.Ing. Lutz Roese-Korner, Mathias Busch, Maryam Foroughi and Julian Lategahn from APTIV. Collaborative effort of Mathias Busch for the data collection and road tests made my access simpler to the research materials. The precious support and assisting enthusiastic of Dr.-Ing. Roese Koerner as an extremely knowledgeable expert strengthened my morale. His knowledge variety stimulated the emergence of abundant ideas during the compilation of this book. I admire his positive outlook and his patient personality despite the challenging situations creating a most pleasant working atmosphere. Without his intensity and excellent cooperation and willingness at all times to find solutions, the cornerstones of this research would not have been realized.
My appreciation also extends to Dr.-Ing. Jens Westerhoff for his unwavering support during the time of composing and editing of this book. His thoughtful comments, constructive critiques and recommendations greatly assisted and improved the research.
This 4-year Ph.D. journey would not have been possible without the financial support of APTIV Services Deutschland GmbH. I'm honored to be a part of the advances engineering team of this company and gratefully acknowledge the funding sources that made my Ph.D. work possible.
My deep appreciation goes to Maryam Safaei who has accompanied me through the years of hard work and stood beside me during the difficult days. Thank you for your

dedication and unwavering support, especially within the final phase of my Ph.D. for enabling me to finish what I started.
I would also like to express my sincere gratitude to my brother, Amin Pishehvari as the most professional designer I could ever imagine. Thank you for designing the cover of my book and for being there when I needed.
Last but not least, I would like to thank my family and friends for all their love and encouragement. Thank you, Mother, for your words of hope, thank you for raising me with love and for teaching me there is nothing that I could not do. What an infinite Love you are which never deserts me. An immortal and unrepeatable miracle that lights up every fraction of time. I feel so blessed and thankful for having you in my life.
Thank you.

Abstract

Autonomous driving is developing from an insurmountable aspiration into a more realistic vehicle's feature radically transforming the transportation system. The self-localization system implementation with a stable and accurate performance is a fundamental and substantial challenge for accomplishing this objective. This doctoral thesis focuses on the conceptual design and implementation of new radar-based solutions for self-localization in GNSS-restricted areas utilizing a priori environment model registration techniques and particle filtering as a sequential Monte-Carlo (SMC) method.
The first proposed algorithm is initialized with dead reckoning and aided with radar measurements and an OpenStreetMap data– composed of lines – as the a priori environment model. The registration problem is formulated to interpret and process the a priori model using mathematically described native lines for preventing its discretization which accelerates the registration procedure. Two new radar-relevant weighting procedures enhance the algorithm functionality in terms of the plausible robustness by taking the measurement density into account to identify noisy data.
As the preeminent contribution of this work, the registration execution is transferred from the radar measurement in Cartesian coordinates to the range-Doppler domain offering significant advantages. This domain transformation leads to the reduction of required data processing and transformations between measurement domains. Moreover, it excludes the angle estimation as a potential supplementary uncertainty source from the registration problem. Beside the observation dimension reduction, this methodology facilitates the application of single transmit/receive antenna for the self-localization application.
The absolute self-localization using SMC method is extended with new subsystems to optimize the algorithm's robustness and reliability. After performing a sample clustering, the first technique processes the main clusters as independent filters and monitors the filter convergence by entropy information and effective sample size. The second methodology tracks the main clusters by their Gaussian parameters to recover the filter in case of divergence by performing a systematic particle injection. The applicability of the proposed algorithms is evaluated comparatively by using experimental data.

Kurzfassung

Das atemberaubende Tempo des technologischen Fortschritts scheint die Verwirklichung von autonom fahrenden Fahrzeugen in greifbare Nähe zu rücken. Die Implementierung eines optimal funktionierenden Selbstlokalisierungssystems stellt die Grundvoraussetzung für die Entwicklung eines solchen Systems dar. Der Fokus dieses Buches liegt auf der Konzeptionierung und Implementierung neuer Radar-basierter Selbstlokalisierungssysteme mittels Registrierungsverfahren sowie Sequentieller Monte-Carlo (SMC) Methode. Die Radarbeobachtungen und OpenStreetMap als a-priori Umgebungsmodell werden in den entwickelten Registrierungsalgorithmus eingespeist. Die Hauptidee dieser Methodik besteht in der Formulierung des Verfahrens mittels mathematisch definierter nativer Linien ohne diese zu diskretisieren. Dies führt zur Beschleunigung und Genauigkeitserhöhung des Registrierungsprozesses. Darüber hinaus werden zwei auf Beobachtungsdichte basierende neue Gewichtungsverfahren implementiert, welche die Prozessrobustheit optimieren.

Als herausragenden Beitrag dieser Arbeit wird ein Konzept zur Übertragung der Registrierung zu einer den Rohdaten näherliegenden Sensordatenebene entwickelt. Durch die sogenannte Range-Doppler-Registrierung reduzieren sich die Datenverarbeitungsprozesse und die Anzahl der Transformationen zwischen den Beobachtungsdomänen. Darüber hinaus schließt diese Methodik die Winkelschätzung von der Registrierungsformulierung aus, welche zur Dimensionsreduktion des Problems und Verringerung der potenziellen Unsicherheiten führt. Weiterhin wird der Einsatz einer einzelnen Sende-/Empfangsantenne für die Selbstlokalisierung ermöglicht. Des Weiteren wird die globale Selbstlokalisierung mittels SMC durch neue Teilsysteme erweitert um ihre Robustheit zu erhöhen. Die erste Technik verarbeitet nach dem Clustering parallel die Hauptcluster über die SMC-Methode als unabhängige Filter. Die Filterkonvergenz wird durch die Entropie und effektive Stichprobengröße als Überwachungsparameter verifiziert. Die zweite Methodik verfolgt die Hauptcluster mittels ihrer Gaußschen Parameter und führt eine systematische Partikeleinspeisung im Falle einer Divergenz durch. Um die Umsetzbarkeit und Validität der entwickelten Algorithmen nachzuweisen, werden ausführliche Versuchsreihen durchgeführt.

Contents

Radar-based Self-localization for Autonomous Vehicles

Autonomous driving is developing from an insurmountable aspiration into a more realistic vehicle's feature radically transforming the transportation system. Implementing a self-localization system with a stable and accurate performance is a fundamental and substantial challenge for accomplishing this objective. Global navigation satellite systems are frequently implemented to register the absolute position and orientation of the vehicle. However, in the absence of satellite signals, an alternative is required to ensure the continuous and unimpaired functionality of the self-localization system. A widely applied method with a straightforward implementation is dead reckoning as a self-localization technique based on mechanical motion sensors. A major disadvantage of such a system is the self-localization inaccuracy due to the sensors' systematic and non-systematic errors propagating over time. Access to an environment map allows the application of registration techniques using the perception of the vehicle environment and its dynamic changes through appropriate sensing systems. In this book, the realization of the map registration algorithms is performed with radar sensors, as they perceive the environment regardless of weather and light conditions.
This book focuses on the conceptual design and implementation of new radar-based solutions for self-localization in GNSS-restricted areas utilizing registration of environment models and sequential Monte-Carlo method. A map registration algorithm is proposed utilizing radar observations and mathematically defined native lines of OpenStreetMap initialized with dead reckoning. Moreover, a particle filtering approach is implemented to realize absolute self-localization with divergence avoidance strategies. As the preeminent contribution of this book, the map registration of radar measurements is transferred from Cartesian coordinates to Range-Doppler coordinates offering significant advantages.

Ahmad Pishehvari has finished his academic master's degree in electrical engineering with a focus on control technology and automation engineering in 2016 at the Bergische Universität Wuppertal (BUW). He completed his Ph.D. in the field of autonomous driving with an emphasis on radar-based self-localization algorithms in 2020 at BUW in collaboration with APTIV Services Deutschland GmbH. During his doctoral studies, he published four scientific papers, one journal paper and seven patents in the field of radar-based self-localization.

ISBN 978-3-8440-7874-9

9 783844 078749

SHAKER VERLAG