Beiträge aus der Elektrotechnik

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Design and Analysis of an Integrated Impulse Radio Ultra-Wideband Primary Radar System

VOGT

Dresden 2023

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.dnb.de abrufbar.

Bibliographic Information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Zugl.: Dresden, Techn. Univ., Diss., 2022

Die vorliegende Arbeit stimmt mit dem Original der Dissertation „Design and Analysis of an Integrated Impulse Radio Ultra-Wideband Primary Radar System“ von Xin An überein.

Gesetzt vom Autor

ISBN 978-3-95947-060-5

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Niederwaldstr. 36
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Internet :   www.vogtverlag.de

Technische Universität Dresden

Design and Analysis of an Integrated Impulse Radio Ultra-Wideband Primary Radar System

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der Fakultät Elektrotechnik und Informationstechnik
der Technischen Universität Dresden
zur Erlangung des akademischen Grades

Doktoringenieur
(Dr.-Ing.)

genehmigte Dissertation

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Gutachter:	Prof. Dr. sc. techn. Frank Ellinger
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Tag der Einreichung:	17. Mai 2022
Tag der Verteidigung:	02. Dezember 2022

Acknowledgement

I would like to take this opportunity to thank all the people who have supported this work over the past few years. My thanks go in particular to Professor Frank Ellinger for his motivation and inspiration in the field of radio frequency integrated circuits design. His support and encouragement enabled me to complete my dissertation at his chair.

I have also had the immense pleasure to work with Jens Wagner. Thanks for sharing his many experiences and many professional discussions, as well as his excellent organization. Of course, I am grateful to my great colleagues for the creative and pleasant atmosphere, as well as for the many concrete helpings in the profession and in the lab.

I would like to give special thanks to my family, my wife and daughter, who was born during this work. Their love and support have provided my strong spiritual base and gave me motivation. Finally, please allow me to thank my parents in a language that they can understand. 最后，我要感谢父母的爱和培养。这是我成为今天的我的原因，也是我今后继续前进的动力。

Zusammenfassung

In dieser Arbeit wird der Entwurf eines primären impulsradio (*Impulse Radio, IR*)-Radarsystems untersucht, das im Ultrabreitband (*Ultra Wideband, UWB*) Frequenzband von 3,1 GHz bis 10,6 GHz arbeitet. Es wurde erforscht, um die Latenz von Ortungssystemen in einem komplexen Umfeld mit kurzer Reichweite zu reduzieren.

Stand-der-Technik Radararbeiten konzentrieren sich hauptsächlich auf die Erhöhung der Auflösung und der Reichweite. Allerdings ist die Latenz auch ein wichtiger Aspekt. Eine niedrige Latenz ist für viele Anwendungen von entscheidender Bedeutung, zum Beispiel für ein intelligentes Verkehrssystem (*Intelligent Traffic System, ITS*). Diese Arbeit zielt darauf ab, diese Latenz durch latenzorientiertes Systemdesign und Optimierung von verschiedenen Aspekten deutlich zu reduzieren. Die Theorie von frequenzmodulierten Dauerstrichradaren (*Frequency-Modulated Continuous-Wave radars, FMCW radars*) und Impulsradaren wird untersucht und verglichen, bevor die Impulsradio-Ultrabreitband (*Impulse-Radio-Ultra-Wideband, IR-UWB*)-Topologie ausgewählt wird. IR-UWB-Radare weisen intrinsisch eine hohe Entfernungsauflösung und eine starke Immunität gegen dem Mehrwegeffekt auf, die für kurze Reichweiten und ein komplexes Umfeld gut geeignet sind.

Um die Latenz zu reduzieren, wurden auch Aspekte des Schaltungsdesigns optimiert. Der Sender enthält einen UWB-Impulsgenerator und einen Verstärker mit automatischer Ein-/Ausschalten-Funktion. Im Empfängerteil wurde ein UWB-Verstärker mit einer Verstärkung von 50 dB unter Verwendung einer positiven Rückkopplung für eine erhöhte Bandbreite entworfen. Dieser liefert verstärkte Echosignale, die direkt von einem 1-Bit-Echtzeit-Sampler abgetastet werden können. Der Sampler-Ausgangsdatenstrom wird einer vor Ort programmierbare Logikgatter-Anordnung (*Field-Programmable Gate Array, FPGA*) zugeführt, wo Datenverarbeitung und Warnbeurteilung durchgeführt werden. Die Schaltungsblöcke wurden einzeln hergestellt und gemessen. Dann wurden sie als integrierter Schaltkreis entworfen und gefertigt. Darauf basierend wurde das IR-UWB-Radarsystem entworfen und auf einer Leiterplatte realisiert, das hauptsächlich die Antennen, das Systemboard und das FPGA-Modul umfasst, um die Funktionsfähigkeit des vorgeschlagenen Konzeptes zu zeigen.

Messungen zeigen, dass das Radar eine maximale Reichweite von 15 m abdeckt. Die Entfernungsauflösung beträgt bis zu 3 cm. Darüber hinaus kann ein Ziel von Interesse mit einer Latenzzeit von nur 16 μs gewarnt werden, indem die 1-

Bit Echtzeit-Abtastung mit einer Abtastrate von 10 GS/s verwendet wird. Der ASIC verbraucht nur 135 mW und belegt 1,9 mm^2 unter Verwendung einer 45-nm Silizium-auf-Isolator (*Silicon-on-Insulator, SOI*) Technologie.

Abstract

In this work, the design of a primary Impulse Radio (IR) radar system working in the Ultra-Wideband (UWB) frequency band from 3.1 GHz to 10.6 GHz is presented. It is researched to reduce the latency of positioning systems in a short-range complex environment.

State-of-the-Art (SotA) radar works focus mainly on increasing the resolution and the detection range. However, latency is also a relevant aspect. Low latency is critical for many applications, for example, for an Intelligent Traffic System (ITS). This work aims to reduce this latency significantly through latency-orientated system design and optimization in various aspects. The theory of Frequency-Modulated Continuous-Wave (FMCW) and pulse radars is analyzed and compared before the Impulse-Radio Ultra-Wideband (IR-UWB) topology is selected, which has intrinsically high range-resolution and strong immunity against the multi-path effect that is well suited for a short-range complex environment.

To reduce the latency, optimization was also performt in aspects of circuit design. The transmitter contains a UWB pulse generator and an amplifier with automatic on-off function. In the receiver part, a 50-dB-gain UWB amplifier using positive feedback for increased bandwidth was carried out. This provides amplified echo signals that can be directly sampled by a 1-bit real-time sampler. The sampler output data stream is fed to a Field-Programmable Gate Array (FPGA), where data processing and warning judgement are performed. The circuit blocks were fabricated and tested individually. Then, a Radio-Frequency (RF) Application Specific Integrated Circuit (ASIC) was designed and taped out. Based on this, the IR-UWB radar system was designed and realized in hardware on a Printed Circuit Board (PCB) mainly including the antennas, the system board and the FPGA module to demonstrate the functionality of the proposed concept.

Measurements show that the radar covers a maximum detection range of 15 m. The range resolution is measured down to 3 cm. Furthermore, a target of interest can be warned with a latency as fast as 16 μs by using the 1-bit real-time sampling with a sampling rate of 10 GS/s. The ASIC consumes only 135 mW and occupies 1.9 mm^2 using a 45-nm Silicon-on-Insulator (SOI) technology.

Note On the Use of Own Published Materials

Party of the contents of this dissertation are based on published works, of which I have been the first author. These publications were carried out, when I was working as doctoral candidate in the Chair for Circuit Design and Network Theory at the Technische Universität Dresden. All the in IEEE published papers have been referenced in accordance to the IEEE copyright policy and are included in the list of own publications at the end of this dissertation. Additionally, a footnote is used at the beginning of the related chapters and sections to clarify the reuse of the materials in related sections. Furthermore, the citations for these self-authored articles are marked with an asterisk sign, for example [AWE22*], to differentiate them from other citations.

Contents

1. Introduction

1.1. Background and Motivation

The progress of human civilization is always accompanied by development of the means to explore the unknown world. For a long time, eyes have been the only tool for people to observe and explore the world. Since the growth of modern times, however, people have no longer been satisfied to perceive the world only through their eyes. After the Italian polymath Galileo Galilei first aimed his self-made telescope at the moon in the year 1609, the history of mankind's use of tools to expand its horizons has evolved. Since then, optical telescopes with farther and clearer fields of view have been continuously manufactured.

As time passed, people became no longer satisfied with those telescopes and realized that electromagnetic waves, to which visible light also belong, can be used to detect objects, and this greatly expanded the horizons of mankind. In 1886, German physicist Heinrich Hertz experimentally proved that metallic objects reflect electromagnetic waves. Based on this, radar was invented, which was used originally as an abbreviation for *radio detection and ranging*. In 1904, the German inventor Christian Hülsmeyer demonstrated the detection of a ship in dense fog, and this was the first use of radio waves to detect distant objects [Rad07]. From the first half of the last century, radar technology developed by leaps and bounds. Radar helped people realize the dream of having clairvoyance.

Let us move the progress bar forward to the last few decades. Thanks to the advancement of electronic technology, developments to radar have overcome people's perceptions that radars are cumbersome and huge, and it is also more and more affordable for civilian applications, e.g., automotive applications. Therefore, radar is appearing more and more in our lives for detection and localization.

Localization is one of the most imperative cornerstones of the current wave of an all-round "smartification" of our life. With Intelligent Traffic System (ITS), the digital horizon of cars can be extended by deploying sensors at critical points in the infrastructure. The authors of [GT07, RFM03] have studied and indicated that measures to increase visibility and conspicuity of pedestrians are one of three important countermeasures of infrastructure enhancements to reduce pedestrian-related accidents. For example, a sensor-equipped Roadside Unit (RSU) could be installed at a crossing, a curve or anywhere that the sight of a driver or an autonomous vehicle could be blocked. It detects Vulnerable Road Users (VRU), such as pedestrians and cyclists as well as persons with limited mobility, and warns approaching vehicles from the potential danger. There are many solutions for these scenes, which can be mainly divided into three categories according to the method of obtaining data, namely using conventional sensors, cameras, or radars.

Conventional sensors, such as infrared motion sensor, light barrier sensor, and so on, are low-cost and uncomplicated. They have already been widely used in, for example, automatic door and automatic turnstile gates. However, they may not be competent for open spaces like traffic infrastructures, and these sensors can only provide a small amount of inaccurate information. Camera- or vision-based pedestrian detection is a popular research field, for instance, [DWSP12, EG09], and can be combined with Artificial Intelligence (AI) techniques that are very promising. However, vision-based applications in dim light and all-weather conditions are still very challenging, especially when high reliability is required, e.g., in ITS. What's more, cameras provide a lot of redundant information that thirst for high and reliable computing power and may cause privacy issues. Compared with the previous two alternatives, radars can work in all-weather conditions and also provide sufficient details for pedestrian detection [DT14]. Radars can also be combined with cameras and other sensors that make good use of all their advantages [CGA16].

However, the existing radar system also has deficiencies. For ITS, latency is a critical parameter. According to an evaluation in [ASHL18], autonomous driving requires a Vehicle-to-Everything (V2X) communication latency shorter than 10 ms. However, current radar systems are not specifically developed for short-range low-latency scenarios, and will take several tens to hundreds of milliseconds only for the target detection, which is far too long [Fas16]. In order to reserve enough time for the back-end radar signal processing and the V2X communication, the radar detection time has to be reduced.

This thesis presents the analysis and design of a primary Impulse-Radio Ultra-Wideband (IR-UWB) radar system with low-latency for real-time short-range human detection in a complex environment. The challenging latency requirement can only be met using primary radar systems, since primary radars do not require the target to be equipped with special devices. A new topology is proposed and demonstrated, which eliminates the use of mixers and Analog-to-Digital Converter (ADC). It further reduces the detection time of a primary impulse radar. The IR-UWB radar is suitable for short-range complex environments and allows for high-range resolution. Meanwhile, it keeps low power consumption to allow for large-scale application.

The bigger part of this work was carried out in the context of the project entitled *fast-traffic*, within the cluster project *fast actuators sensors and transceivers* and the acronym *fast*. The cluster project was founded by the Bundesministerium für Bildung und Forschung (BMBF), the German Federal Ministry of Education and Research, within the program “Zwanzig20 — Partnerschaft für Innovation”.

Fast-traffic aimed to realize real-time wireless communications between vehicles and infrastructure.

The work was also supported in part by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) as part of Germany's Excellence Strategy: Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop (CeTI)" of Technische Universität Dresden.

1.2. Objectives and Structure

The goal of this work was to present a structured design approach of an integrated IR-UWB primary radar system with low-latency for short-range detection. First, the application scenario was analyzed. The corresponding radar design was proposed based on the research of different radar principles. Then, the proposed radar design was modeled. The various modules of the radar system were characterized. Using these, the modules were designed and taped out firstly for separate tests. Last but not least, the Application Specific Integrated Circuit (ASIC) was carried out. The radar system was realized in hardware, and a suited algorithm to prove the concept was designed.

The focus of this work is on circuit and system design. The algorithm was designed due to the need of test on the Field-Programmable Gate Array (FPGA). Therefore, it is not going to provide a comprehensive discussion on radar signal processing algorithms. However, efforts have still been put into high-speed data receiving and simple processing. Further processing is always possible and beneficial. Indeed, a deeper algorithm could also take full advantage of the large data throughput of this design.

The thesis begins with an introduction of the motivation of this work and the application background in chapter 1, and the principles of Frequency-Modulated Continuous-Wave (FMCW) and IR-UWB radar are analyzed and compared in chapter 2. Based on this, the suited radar type is selected in consideration of the application scenario, as shown in chapter 3. The radar, including the transmitting channel, is also modeled in chapter 4.

The thesis is pushed forward to the design of the radar system in chapter 5 and chapter 6. Chapter 5 studies the design of the Analog Front-End (AFE) of the radar, and the final ASIC. The algorithm to recover the received pulsed and to detect the pedestrians is discussed in chapter 6.

Finally, the radar system is assembled and tested that is illustrated in chapter 7. The thesis is summarized by a conclusion and an outlook to future work and the improvement of the radar system in chapter 8.