MICROWAVE
NONCONTACT
MOTION SENSING
AND ANALYSIS
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MICROWAVE NONCONTACT MOTION SENSING AND ANALYSIS

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WILEY
To our families who have been patient with us, and our colleagues who have been working with us on this interesting research subject.
CONTENTS

Preface xi

1 Introduction 1
   1.1 Background, 1
   1.2 Recent Progress on Microwave Noncontact Motion Sensors, 2
      1.2.1 Microwave/Millimeter-Wave Interferometer and Vibrometer, 2
      1.2.2 Noncontact Vital Sign Detection, 3
   1.3 About This Book, 4

2 Theory of Microwave Noncontact Motion Sensors 7
   2.1 Introduction to Radar, 7
      2.1.1 Antennas, 8
      2.1.2 Propagation and Antenna Gain, 10
      2.1.3 Radio System Link and Friis Equation, 13
      2.1.4 Radar Cross Section and Radar Equation, 15
      2.1.5 Radar Signal-To-Noise Ratio, 16
      2.1.6 Signal-Processing Basics, 17
CONTENTS

2.2 Mechanism of Motion Sensing Radar, 18
  2.2.1 Doppler Frequency Shift, 18
  2.2.2 Doppler Nonlinear Phase Modulation, 19
  2.2.3 Pulse Radar, 26
  2.2.4 FMCW Radar, 27
  2.2.5 Comparison of Different Detection Mechanisms, 29

2.3 Key Theory and Techniques of Motion Sensing Radar, 31
  2.3.1 Null and Optimal Detection Point, 31
  2.3.2 Complex Signal Demodulation, 33
  2.3.3 Arctangent Demodulation, 34
  2.3.4 Double-Sideband Transmission, 36
  2.3.5 Optimal Carrier Frequency, 43
  2.3.6 Sensitivity: Gain and Noise Budget, 49

3 Hardware Development of Microwave Motion Sensors
  3.1 Radar Transceiver, 53
    3.1.1 Bench-Top Radar Systems, 53
    3.1.2 Board Level Radar System Integration, 61
    3.1.3 Motion Sensing Radar-On-Chip Integration, 63
    3.1.4 Pulse-Doppler Radar and Ultra-Wideband Technologies, 85
    3.1.5 FMCW Radar, 89
  3.2 Radar Transponders, 92
    3.2.1 Passive Harmonic Tag, 93
    3.2.2 Active Transponder for Displacement Monitoring, 95
  3.3 Antenna Systems, 99
    3.3.1 Phased Array Systems, 99
    3.3.2 Broadband Antenna, 100
    3.3.3 Helical Antenna, 103

4 Advances in Detection and Analysis Techniques
  4.1 System Design and Optimization, 107
    4.1.1 Shaking Noise Cancellation Using Sensor Node Technique, 107
    4.1.2 DC-Coupled Displacement Radar, 111
CONTENTS

4.1.3 Random Body Movement Cancellation Technique, 116
4.1.4 Nonlinear Detection of Complex Vibration Patterns, 124
4.1.5 Motion Sensing Based on Self-Injection-Locked Oscillators, 131
4.2 Numerical Methods: Ray-Tracing Model, 136
4.3 Signal Processing, 141
4.3.1 MIMO, MISO, SIMO Techniques, 141
4.3.2 Spectral Estimation Algorithms, 142
4.3.3 Joint Time–Frequency Signal Analysis, 153

5 Applications and Future Trends 157
5.1 Application Case Studies, 158
5.1.1 Assisted Living and Smart Homes, 158
5.1.2 Sleep Apnea Diagnosis, 164
5.1.3 Wireless Infant Monitor, 169
5.1.4 Measurement of Rotational Movement, 173
5.1.5 Battlefield Triage and Enemy Detection, 178
5.1.6 Earthquake and Fire Emergency Search and Rescue, 179
5.1.7 Tumor Tracking in Radiation Therapy, 180
5.1.8 Structural Health Monitoring, 185
5.2 Development of Standards and State of Acceptance, 194
5.3 Future Development Trends, 196
5.4 Microwave Industry Outlook, 202

References 203
Index 215
PREFACE

By sending a microwave signal toward a target and analyzing the reflected echo, microwave radar sensors may be used for noncontact motion sensing in many applications. Typical applications range from long distance detection, such as weather radar and automobile speed radar, to short distance monitoring, such as human vital sign detection and mobile tumor tracking. While some speed detection and navigation devices are well known and have been used in the field for decades, other applications based on recent advancements in microwave sensing technologies show great promise and attract interest from practitioners. For example, the principle of detecting motion based on phase shift in a reflected radar signal can be used to sense tiny physiological movements induced by breathing and heartbeat, without any sensor attached to the body. This remote vital sign detection method leads to several potential applications, such as searching for survivors after earthquakes, and monitoring sleeping infants or adults to detect abnormal breathing conditions. Another recent advance in the microwave motion sensing technology is the extension from detecting one-dimensional to two-dimensional rotational movement, which can be used to monitor the spin speed of motors and servos in macroscale.
machineries and microscale microelectromechanical system (MEMS) devices.

These emerging technologies for health care and industrial sensing provide the advantage of neither confining nor inhibiting the target, as other contact-based technologies do. They enable fast remote identification of hidden target signatures, indicating promising applications in remote diagnosis, search, monitoring, and surveillance. Sensors may be used for the monitoring and treatment of sleep apnea and sudden infant death syndrome. They can outperform other technologies in motion-adaptive tumor tracking during cancer radiotherapy in many anatomic sites. When configured as a nonlinear vibrometer, the radar will also advance approaches to monitoring rotating and reciprocating machinery in the transportation and manufacturing industries. This may positively impact our society through dynamic structural health monitoring, as many buildings worldwide are structurally deficient or functionally obsolete.

While the emerging microwave motion sensing technologies predict attractive ways to replace traditional devices, they generally involve sophisticated hardware and signal analysis that leverage modern design, fabrication, and signal processing methods. Some of the technologies are positioned at the crossroads of electrical engineering, health care and life science, civil engineering, and micro fabrication. With growing interest in multidisciplinary development in the engineering community, researchers and engineers have created various microwave motion sensor front-end architectures and baseband methods.

Although researchers are working on microwave motion sensing technology, and a large number of articles have been published in recent years on state-of-the-art applications, there are not many books that review this technology and unveil the trends of future development. This book aims to review the fundamentals of microwave radar, discusses the state-of-the-art developments, and illustrates future trends.

This book is organized as follows. Chapter 1 introduces the background and recent progress on microwave noncontact motion sensors. Chapter 2 reviews theory and fundamentals of microwave motion sensors. It presents general information about antennas, electromagnetic propagation, link budget, and signal processing. Then it covers typical types of motion sensing radar including Doppler radar, pulse radar,
and frequency modulated continuous wave (FMCW) radar. Chapter 2 also discusses the key theory and techniques of motion sensing radar. The recent hardware developments of microwave motion sensor are discussed in Chapter 3, including radar transceiver architectures, antenna systems, and special building blocks. In Chapter 4, advances in detection and analysis techniques are discussed, covering system considerations, modeling, simulation, and signal processing. Several application case studies are provided in the first part of Chapter 5, followed by discussion on development of standards and state of acceptance. Finally, future development trends and microwave industry outlook are presented in Chapter 5.

The authors have years of experience working together on microwave noncontact motion sensing technologies from bench-top modules to CMOS integrated microchips, covering a frequency range of over 30 GHz. Besides presenting the history, theory, and technical details of related technologies, the authors provide plenty of application-oriented case studies. Furthermore, the authors exemplify the tight connections of this technology to healthcare, industrial, and military services. Potential research booms are also illustrated to scientists from microwave, electronic circuit, signal processing, and healthcare perspectives.

The authors give their respects to Prof. James Lin at the University of Illinois at Chicago, who pioneered the research of radar noncontact vital sign detection. The authors would like to acknowledge Drs. Arye Rosen, Aly Fathy, and Hao Ling for providing valuable review to the book proposal. Their valuable comments are very much appreciated. The authors would also like to thank their colleagues T.-S. Jason Horng, Olga Boric-Lubecke, Victor Lubecke, Lixin Ran, Jian Li, Wenhsing Wu, Michael Weiss, and Xiaolin “Andy” Li for their valuable discussions and collaborations in the past decade. In addition, the valuable contributions from students who worked diligently on radar motion sensing projects at the University of Florida and Texas Tech University: Yanming Xiao, Changzhan Gu, Te-Yu Jason Kao, Yan Yan, Xiaogang Yu, Gabriel Reyes, Julie Cummings, Jeffrey Lam, and Eric Graves are greatly acknowledged. Last but not least, the authors would also like to thank Tien-Yu Huang, Bozorgmehr Vosooghi, and Yiran Li for assistance in preparing figures, indexing, and proofreading the manuscript.
The intended audience of this book includes microwave engineers and researchers, microwave application engineers, researchers in healthcare institutes, developers of military and security equipment, and biomedical engineers.

**Changzhi Li and Jianshan Lin**
INTRODUCTION

1.1 BACKGROUND

Microwave radar has been used for remote sensing applications for many years. Most common applications include displacement and low velocity measurement (Kim and Nguyen, 2003; Kim and Nguyen, 2004; Benlarbi et al., 1990; Rasshofer and Biebl, 1999), distance and position sensing (Stezer et al., 1999), automobile speed sensing (Meinel, 1995), and vital sign detection (Lin, 1992). Traditionally, microwave radar can be divided into two categories: the pulse radar and the Doppler radar. The pulse radar determines the target range by measuring the round-trip time of a pulsed microwave signal. It does not directly measure the velocity of a target but the velocity can be calculated. The Doppler radar, on the other hand, measures the velocity of a target directly. If the target has a velocity component, the returned signal will be shifted in frequency, due to the Doppler effect.

On the hardware side, the pulse radar uses powerful magnetrons to generate microwave signals with very short pulses of applied voltage. In order to overcome the pulse radar’s disadvantage of high cost due to the expensive magnetron, the frequency modulated continuous wave
(FMCW) radar was invented in recent years. Compared with the pulse radar, the FMCW radar can be integrated with solid-state technology, and has the advantages of superior target definition, low power, and better clutter rejection. However, the FMCW radar requires accurate control (modulation) of both the frequency and amplitude of the transmitted signal, and is mainly used for range detection. To measure both the displacement and the velocity, a system using millimeter-wave interferometry (Kim and Nguyen, 2003) was reported. It used a quadrature mixer to realize the coherent phase-detection process effectively. It has a very high detection resolution, but has a limit on the minimum measurable speed (Kim and Nguyen, 2004).

1.2 RECENT PROGRESS ON MICROWAVE NONCONTACT MOTION SENSORS

With contributions from many researchers in this field, new detection methods and system architectures have been proposed to improve the detection accuracy and robustness. The advantage of noncontact/covert detection has drawn interest on various applications. While many of the reported systems are bench-top prototypes for concept demonstration, several portable systems and integrated radar chips have been demonstrated.

1.2.1 Microwave/Millimeter-Wave Interferometer and Vibrometer

The development of various instrumentations and techniques for vibration measurement and analysis has become increasingly important. Conventional vibration sensing elements comprise displacement or velocity transducers. One of the most widely used is the accelerometer. A piezoelectric-based accelerometer can produce an electrical output proportional to the vibratory acceleration of the target it is attached to. Another contact measurement instrument is the linear variable differential transformer (LVDT), which works as a displacement transducer that can measure the vibratory displacement directly.

Some of noncontact vibration measurement instruments are laser based, such as laser Doppler vibrometer, laser interferometer, and laser displacement sensor. These devices are usually expensive and have
their limitations as well, such as inevitable calibration and narrow detection range. On the other hand, microwave/millimeter-wave interferometer or vibrometer has been used for applications in instrumentation such as plasma diagnostics and nondestructive characterization of material.

Millimeter-wave interferometric sensor with submillimeter resolution has been reported by Kim and Nguyen (2003). Resolving displacement within a fraction of a carrier wavelength, the sensor has high resolution in submillimeter range. The sensor system operates in Ka-band and is completely fabricated using microwave and millimeter-wave integrated circuits. Radio frequency (RF) vibrometer based on nonlinear Doppler phase modulation effect (Li and Lin, 2007a) has also been reported most recently. It detects vibration movement by analyzing the relative strength of vibration-caused harmonics at the radar baseband output. With a quadrature architecture supporting a complex signal demodulation technique, the RF vibrometer realizes the measurement of not only a purely sinusoidal periodic movement, but also vibrations comprised of multiple sine waves of different frequencies. Compared with laser-based sensors, microwave/millimeter-wave interferometer and vibrometer can have a low cost and a much larger detection range.

1.2.2 Noncontact Vital Sign Detection

The principle of detection based on frequency or phase shift in a reflected radar signal can be used to detect tiny body movements induced by breathing and heartbeat, without any sensor attached to the body. There are several advantages to a noncontact vital sign detection solution: physically, it neither confines nor inhibits the subject, making the detector ideal for long-term continuous monitoring applications. Also, the reliability can be increased as a subject is unaware of the measurement and therefore is less likely to alter their vital signs. Additionally, accuracy is enhanced because of the lack of surface loading effects that have been shown to reduce the accuracy of some other measurement methods. This noncontact remote detection of vital signs leads to several potential applications such as searching for survivors after an earthquake and monitoring sleeping infants or adults to detect abnormal breathing conditions.
INTRODUCTION

While the concept of noncontact detection of vital signs has been successfully demonstrated by pioneers in this field before 2000 (Lin, 1975; Chuang et al., 1991; Lin, 1992; Chen 1986), research efforts in this century have been moving the technology development toward lower power, lighter weight, smaller form factor, better accuracy, longer detection range, and more robust operation for portable and handheld applications. Among many possible applications this technology can be used for, healthcare seems to be drawing most of the interest. As an example, a baby monitor using this technology was recently demonstrated (Li et al., 2009a). The baby monitor integrates a low power Doppler radar to detect tiny baby movements induced by breathing. If no movement is detected within 20 s, an alarm will be triggered. With growing interests in health and life sciences by the engineering community, many researchers have been contributing to technology advancement in this field. Although, many results were demonstrated using bench-top prototypes or board-level integration, their architectures still show the potential of being implemented on chip. In fact, there have been several reports of vital sign radar sensor chips based on various architectures (Droitcour et al., 2002; Droitcour et al., 2003; Li et al., 2008b; Li et al., 2009c; Li et al., 2010b).

1.3 ABOUT THIS BOOK

Although, many researchers are working on the microwave motion sensing technology and a large number of articles have been published in recent years on state-of-the-art applications such as vital sign detection and interferometry, it is difficult to find a book that reviews this technology and unveils the trends of future development. This book first reviews the theory and fundamentals of microwave motion sensor in Chapter 2. It then discusses the hardware development of microwave motion sensor in Chapter 3, including radar transceiver architectures, antenna systems, and special building blocks. In Chapter 4, advances in detection and analysis techniques will be discussed, covering system consideration, modeling, and signal processing. Several application case studies will be provided in the first part of Chapter 5, followed by the discussion on development of standards and state of acceptance. Finally, future development trends and microwave industry outlook will be presented in Chapter 5.
This book not only covers the theory and technical details of related technologies, but also plenty of applications. The tight connections of this technology to healthcare, industrial, and military services will be exemplified in this book. Potential research opportunities will also be illustrated to scientists from the microwave, electronic circuit, signal processing, and healthcare points of view. The intended audience of this book includes microwave engineers and researchers, microwave application engineers, researchers in healthcare institutes, developers of military and security equipment, and scientists in biomedical engineering.
2

THEORY OF MICROWAVE NONCONTACT MOTION SENSORS

2.1 INTRODUCTION TO RADAR

The word “radar” originally stands for *radio detection and ranging*. It is so commonly used today and the word has become a standard English noun. Although, it is often conceived as a technology developed during World War II, the history of radar actually extends back to the time well before World War II when researchers in many countries started the research that led to the development of radar (Page, 1962; Shipton, 1980; James, 1989; Chernyak and Immoreev, 2009; Guarnieri, 2010). In 1904, the first patent on the detection of objects using radio waves was given to the German engineer Hülsmeyer, who experimented with target detection by bouncing waves off a ship. The device was called *Telemobiloskop* by Hülsmeyer. In 1922, Marconi advocated this idea again. In the same year, Taylor and Young of the US Naval Research Laboratory demonstrated ship detection by radar, which was based on an interference pattern when a ship passed between transmitting and receiving antennas. In 1930, Hyland, a colleague of Taylor and Young, first detected an aircraft by radar, setting
off a more substantial investigation that led to a US patent for today’s
continuous wave (CW) radar in 1934. After that, in the middle and
late 1930s, largely independent developments of radar accelerated and
spread in countries including the United States, the Soviet Union, the
United Kingdom, Germany, France, Japan, Italy, and the Netherlands
(Swords, 1986; Watson, 2009; Richards, 2005).

Military applications, including surveillance, navigation, and
weapons guidance for ground, sea, and air vehicles, were the early
driving force for radar development. In recent years, however, radar
has started to enjoy an increasing range of applications in civilian
life. One of the most common applications is the police traffic radar
used to enforce speed limits. This technology is also used to measure
the speed of baseballs and tennis serves. Other civilian applications
include automotive collision avoidance radar, Doppler weather radar,
air traffic control system for guiding commercial aircrafts, and
aviation radar. Also, spaceborne or airborne radar is an important
tool in mapping earth topology and environmental characteristics
such as water and ice conditions, forestry conditions, land usage, and
pollution.

In this section, radar basics will be reviewed. The review starts with
antenna, which is followed by wave propagation, radio system link,
Friis equation, radar cross section, radar equation, and radar signal-
to-noise ratio (SNR). Finally, radar signal processing basics will be
briefly introduced.

2.1.1 Antennas

As an indispensable building component of a radar system, an antenna
is a device for radiating or receiving radio waves. It is a transitional
structure between free space and a guiding device such as transmission line. It converts radiated waves into guided waves, or vice versa. Antennas are inherently bidirectional, in that they can be used for both transmitting and receiving functions. Examples of antennas include dipole antenna, monopole antenna, patch antenna, horn antenna, reflector antenna (such as dish and parabolic antenna), and phased-array antenna (Balanis, 2005).

Antenna radiation pattern is generally used to describe the radiation of electromagnetic waves into the space. It is a graphical representation of the radiation intensity of the antenna as a function of space.