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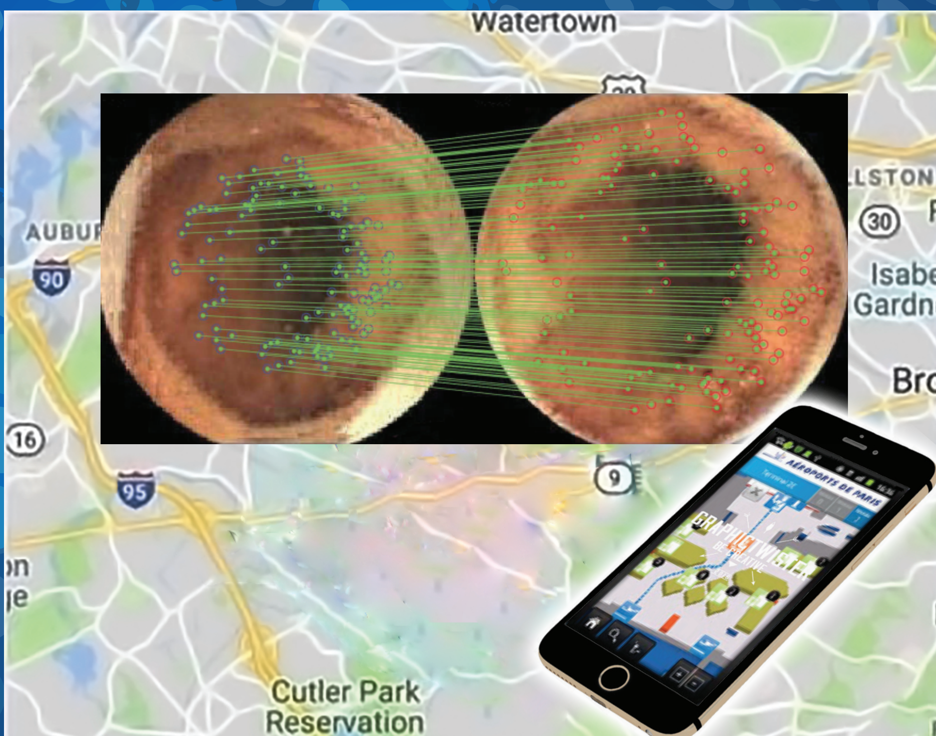
# INDOOR GEOLOCATION SCIENCE AND TECHNOLOGY

## At the Emergence of Smart World and IoT




Kaveh Pahlavan

River Publishers

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# Indoor Geolocation Science and Technology

## At the Emergence of Smart World and IoT

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*Published, sold and distributed by:*
River Publishers
Alsbjergvej 10
9260 Gistrup
Denmark

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Lange Geer 44
2611 PW Delft
The Netherlands

Tel.: +45369953197
www.riverpublishers.com

ISBN: 978-87-7022-051-4 (Hardback)
978-87-7022-050-7 (Ebook)

*To my wife, Farzaneh, my children, Nima, Nasim, and Shek,*
*and my grandchildren, Roya, and Navid*

# Contents

# Preface

The evolution of wireless localization technologies for indoor and urban area applications, where the Global Positioning System (GPS) does not work properly, has been an active area of research for commercial and public safety applications since the mid-1990s. At the time of this writing, received signal strength (RSS)-based Wi-Fi localization has been dominating the commercial market in smart devices complementing cell tower localization and GPS technologies using the time of arrival (TOA) technology. These smart devices include smart phones, note pads, book readers, notebooks, and laptops, and in many of these devices, there is no cell phone or GPS. Wi-Fi localization technology takes advantage of the random deployment of Wi-Fi devices worldwide to support indoor and urban area localization with reasonable accuracies for hundreds of thousands of applications on smart devices, from modern location-based services for finding businesses, such as Yelp, to traditional turn by turn navigation. Public safety and military applications demand more precise localization for first responders, and they are discovering more sophisticated techniques for such precise indoor geolocation using hybrid techniques. Radio frequency (RF) localization techniques for these hybrid technologies are intent on more precision through TOA-based localization. Hybrid algorithms use a variety of sensors to measure the speed and direction of movement and integrate them with the absolute RF localization. In this book, we address the practical aspects of these technologies used for geolocation in indoor and urban areas for commercial and military applications. In addition, we will examine challenges in localization inside the human body that is emerging as an area of research for the future of the wireless health industry.

Science and engineering disciplines are going through a “transformation” from their traditional focused curriculum to a “multi-disciplinary” curriculum and “inter-disciplinary” research directed towards innovation and entrepreneurship. This situation demands more frequent updates and adjustments in the curriculum, project-oriented delivery of educational content, and the ability to form inter-disciplinary cooperation in research programs. A successful transformation of this form demands entrepreneurship and visionary talents to adapt to these frequent changes, and industrial experiences to direct the transformation towards emerging inter-disciplinary industries. Indoor and urban area opportunistic localization is an excellent example of a multi-disciplinary area of research and scholarship, which has emerged in the past few decades. Material needed for teaching opportunistic localization for indoor and urban areas includes several disciplines such as radio propagation analysis, signal processing, detection and estimation theory, and positioning algorithms. The content of courses on opportunistic localization is useful for traditional ECE and CS students as well as students in emerging multi-disciplinary programs such as Robotics and Biomedical Engineering as well as traditional Mechanical and Civil Engineering programs, which are similar to ECE, shifting towards inter-disciplinary curriculums. Therefore, there is a need for academic courses and a comprehensive textbook to address principles of opportunistic localization to be taught in these multi-disciplinary programs.

To prepare a textbook to be taught in academic courses in a multi-disciplinary area of technology, we need to provide selected details of practical aspects of a number of disciplines to give to the readers an intuitive feeling of how these disciplines operate and interact with one another. To achieve this goal in this book, we describe important positioning systems technologies, classify their underlying science and engineering in a logical manner, and give detailed examples of successful science and engineering that has turned into popular applications. Selection of detailed technical material for teaching courses in a multi-disciplinary area with a large and diversified set of technical disciplinary is very challenging, and this challenge becomes more difficult because people with different background skills are using the results.

This book provides a comprehensive treatment of the opportunistic localization science and technology applied to opportunistic positioning in indoor and urban areas. The novelty of the book is that it places emphasis on radio propagation and physical layer issues related to how the received wireless communication signals can be used for opportunistic RF positioning in a variety of wireless communication networks. The structure and sequence of material for this book was first formed in a lecture series by the author at the graduate school of the Worcester Polytechnic Institute (WPI), Worcester, MA, entitled “Wireless Access and Localization”.

The book begins with an introduction chapter underlying the importance of localization in the emergence of the smart world, followed by nine chapters and an appendix chapter. The nine technical chapters of the book are divided into three parts. Part I consists of two chapters on RSS-based positioning. Part II consists of three chapters on TOA-based positioning. The Direction of Arrival (DOA) systems are treated as a part of TOA systems, because they rely on TOA estimation. In Parts I and II, the tool for analytical performance evaluations is the Cramer-Rao Lower Bound (CRLB) that is compared with the empirical results of performance evaluations. Part III presents the details of applied algorithms for positioning in four chapters on: basic positioning algorithms, pattern recognition algorithms used in RSS-based systems, TOA-based algorithms used for refining the TOA estimation, and hybrid algorithms to integrate relative and absolute localization techniques. The appendix chapter of the book is an independent chapter devoted to the review of the classical estimation theory applied to ranging and positioning applications. This chapter covers principles of estimation theory and derivations for CRLB applied to RSS- and TOA-based positioning techniques.

The emerging multi-disciplinary fields such as wireless networking, Robotics, or wireless positioning involves a variety of disciplines. Researchers with different skills work on different aspects of a unique project, but the experience that they gain in that endeavor is different and focused around their individual skills. Therefore, details of the research work, contents of the courses that emerge from the results of the research, and the books that are written on the same topic are based on the author's technical experiences. The author of this book has pioneering research experience and industrial exposure in design and performance evaluation of indoor geolocation based on empirical measurement and modeling of the behavior of the radio propagation in indoor areas and inside the human body. The presentation of the material is based on examples of research and development that his students have performed, his teaching experiences as a professors, and his experiences as a technical consultants to startup companies. As a result, this book organizes the result of research papers by his students, patents with the industrial colleagues, and his course notes to present the results of the research findings over more than a couple of decades to his graduate students beginning their education in this emerging area of research.

Since much of the material in indoor geolocation and in localization inside the human body are extracted from research work of the students at the center for wireless information network studies (CWINS), at the Worcester Polytechnic Institute (WPI), Worcester, Massachusetts, we are pleased to acknowledge the students' and colleagues' contributions to advancing the understanding of wireless channels and its application in opportunistic positioning using wireless communications signals. In particular, the author thanks Prof. Prashant Krishnamurthy of the University of Pittsburgh, also his first PhD student in this field, for careful editing of the material in the first few chapters of the book and weekly conference calls during preparation of the book. Without him, the author would have not completed the manuscript on time and with its current quality of presentation. Most of the MATLAB codes presented in the book and the solution book for the problems at the end of the chapters are prepared by Julang Ying, the author's current lead PhD student. He also helped in formatting the references and proof reading the equations. In addition, the author thanks Prof. Jacque Beneat, Prof. Xinrong Li, Dr. Ahmad Hatami, Dr. Robert Tingley, Dr. Bardia Alavi, Dr. Nayef Alsindi, Dr. Mohammad Heidari, Dr. Ferit Akgul, Prof. Muzzafer Kanaan, Dr. Yunxing Ye, Dr. G. Bao, Dr. Yishuang Geng, Dr. Umair Khan, Dr. Fardad Askarzadeh, and Dr. Nader Bargshady, and many other students of the CWINS; Prof. Mika Ylianttila and Dr. Juha-Pekka Makela of CWC, University of Oulu, Finland ; Prof. Sergey Makarov of WPI; Prof. Pratap Misra of Tufts University; Mr. Ted Morgan and Dr. Farshid Alizadeh of Skyhook Wireless; Prof. Jie He and Dr. Liyuan Xu of University of Science and Technology of Beijing (USTB), China; and Prof. Yongtao Ma of Tianjin University of China, who have directly or indirectly helped the author to extend his knowledge in this field and shape his thoughts for preparation of the new material in this book in a variety of research projects and associated publications. The author also acknowledges the Defense Advanced Research Projects Agency (DARPA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), Department of Defense (DoD), Department of Homeland Security (DHS), United Technology and Skyhook in the United States as well as Finnish Founding Agency for Technology and Research (TEKES), Nokia, Elektrobit, Sonera, and the University of Oulu in Finland, whose support of the CWINS research program at WPI enabled graduate students and the staff of the CWINS to pursue continuing research in this important field. A substantial part of the new material in this book has flowed out of these sponsored research efforts. The author also appreciates Dr. Allen H. Levesque for his contributions in other books with the author, which has indirectly impacted in formation of thoughts and the details of material presented in this book.

Much of the writing of the lead author in this book was accomplished during his sabbatical leave from WPI during spring and summer semester of 2018. He expresses his deep appreciations to the Worcester Polytechnic Institute, in particular to Prof. Yehia Massoud, Head of the ECE Department, Prof.

Winston Soboyejo, Dean of Engineering, and the Prof. Bruce E. Bursten, the Provost of WPI, for their approval of his sabbatical leave for work on this book-writing project. The author dedicates the income of this book to the educational fund of his grandchildren, Roya and Navid Kablan, for the love and energy they gave him to complete this challenging mission, a large part of this writing occurred when they were around him giving him the needed energy to continue!

The author also thanks Mark de Jongh of River Publishers for his assistance and useful comments during various stages of the production of the book, and Junko Nakajima and her team for help during manuscript proofreading and publication.

# 1

# Introduction: Localization in Smart World

## 1.1 Introduction

Location and time are the prominent underlying features for any scientific and engineering observation. Every experience and every observation that is formed by an intelligent mind in a scientific and engineering sense is fundamentally associated with location and time. So, ever since the human being, a social animal equipped with linguistics to communicate with others, began to analyze and record its experiences intelligently, measuring the time of the experience and the location of the events has been an essential part for gathering intelligence for individual humans and the human society at large. In the same way as we humans transformed our civilizations from the farming economy to the industrialized world during the first industrial revolution in the late eighteenth century, over the past few decades we have transformed our civilization to the cyber physical world. In this modern industrial revolution, smartness and intelligence have become more important and so also is the importance of knowing the time and location of events, to analyze the behavior of objects, individuals, crowds, and society itself.

Historically, we began measuring time using the sun and the moon a few thousands of years ago at the dawn of civilization, eventually to have an *absolute* value of time, needed for intelligent agricultural processing and associated festivities and administrates. The granularity of time here was over longer horizons. Around the same time, we began measuring *relative* time with devices such as sand clocks for other important events with shorter durations. In the past few centuries, since the industrial revolution, human beings have discovered how to measure time precisely and the corresponding industry has learned how to make this information about time available and accessible to everyone, everything, and everywhere (Figure 1.1(a)). Today, every "Person" carries a device such as a smart watch or a smart phone, capable of measuring time with near-atomic clock accuracy and almost every

"Thing" has a clock with similar accuracies. However, this is not necessarily true for the location information.

The "location industry" also began in the early days of civilization using the sun, moon, and stars for navigating travelers on the ground and over the seas with a coarse precision. Later, these coarse technologies were complemented by compass and other devices using the Earth's magnetic field. Popular and more precise location technology is going through a similar discovery and metamorphosis as those of the time measurement industry, only in the past few decades.

Figure 1.1(b) illustrates the chronology of the evolution of localization technologies in recent years. Today's most popular localization system, Global Position System (GPS) with accuracy of tens of meters (and better under ideal conditions) was introduced in the 1970s for military applications and became available to commercial applications in the early 1990s. In the past decade, the dramatic fall of the costs of GPS chips have made them popular in smart phones and many other devices, to the extent that even some wearable fitness devices now have GPS. Since GPS signals do not work properly in indoor areas and the indoor applications normally need accuracy on the order of meters or less, research efforts in indoor geolocation science and technology began in the late 1990s and became prolific in the late 2000s

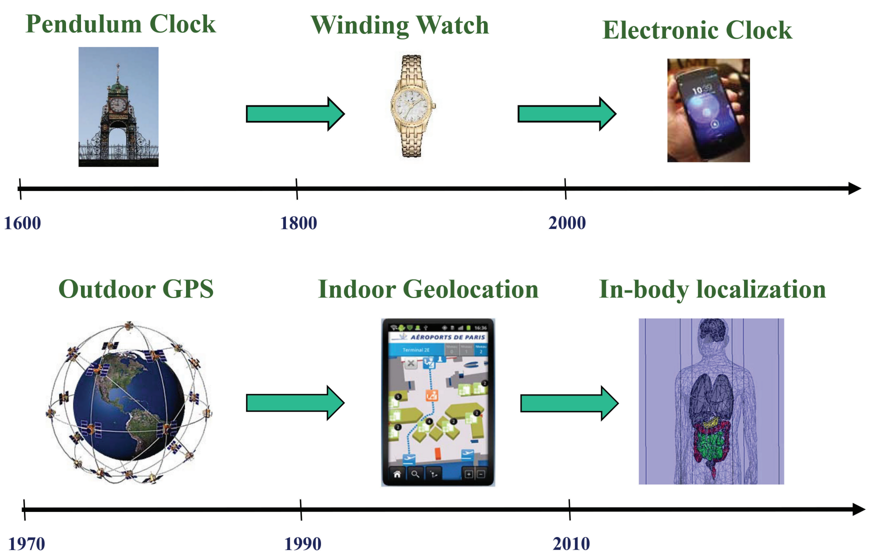



**Figure 1.1** Comparison of evolution of time and location measurement methods (a) time measurement techniques in past few centuries, (b) positioning technologies in past few decades.

[Pah02, Pah10]. More recently, localization science has been progressing towards positioning medical devices inside the human body, where an accuracy on the order of a sub-centimeter is required [Pah12, Dav13] to locate the area where a medical problem may exist. These localization technologies have their own challenges, which are resolved in completely different scientific domains, resulting in significant applications-related useful scientific and engineering research. Because of complexity and diversity of science and technology involved in indoor geolocation, this area has emerged as its own discipline over the past two decades.

This multidisciplinary book presents the fundamentals of positioning and navigation science and technology used for the Smart World and the Internet of Things (IoT) applications in different platforms such as: smart devices, unmanned ground and flying vehicles, and existing cars operating as a part of intelligent transportation systems. Material taught in the book are beneficial for graduate students in the Electrical and Computer Engineering, Computer Science, Robotics Engineering, Biomedical Engineering, or other disciplines who are interested in integration of navigation into their multidisciplinary projects. The book provides for modeling the behavior of radio frequency and mechanical sensors used for localization applications. Then, it introduces the Cramer–Rao Lower Bound (CRLB), which uses these models for comparative performance evaluation of different localization techniques. Finally, it introduces variety of algorithms used for ranging, localization, navigation, and fusion of different sensor readings. We classify these algorithms into logical categories and provide practical example of specific algorithms. The examples include Wi-Fi localization algorithms, Ultra-Wideband (UWB) localization algorithms, and multi-sensor localization algorithms integrating mechanical sensor readings with radio frequency localization. We will provide examples with supporting MATLAB codes and hands-on projects throughout the book to improve the ability of the readers to understand and implement variety of algorithms. The book can be beneficial for both the academia, as a textbook with problem sets and projects, and the industry professionals, as a practical reference book.

## 1.2 Elements of Localization Science

The complexity of localization technology arises from the fact that the variety of applications require different precisions; different smart devices hosting these applications carry different sets of sensors, behavioral characteristics of the different sensors in different environments are complex;

and the availability of maps and the need for the visualization platform for different applications are quite diversified [Pah02, Bir11, Tar11]. As a result, the behavior analysis of the characteristics of the sensors and selection of the suitable algorithms to provide the needed precision for an application implemented on a platform has become a scientific area of research in the past couple of decades and the industry is in need of highly educated professionals in localization science and engineering [Pah13, Gu15].

Figure 1.2 illustrates the functional block diagram of a wireless geolocation system, which focuses on the functionality for positioning. The main elements of the system are as follows: (*i*) a number of location-sensing devices that provide metrics related to the relative position of a mobile station with respect to a known landmark, called reference point, (*ii*) a positioning algorithm that processes metrics reported by location sensing elements to estimate the location coordinates of the target moving object, (*iii*) a display system that illustrates the location of the target on a map, and (*iv*) a location intelligence engine that extracts useful features of location data tailored to generic applications.

The most popular location metrics for wireless localization are extracted from radio frequency (RF)-based localization systems [Zha90, Bar03]. The RF location metrics may indicate the approximated received signal strength (RSS), direction of arrival (DOA), or the time of arrival (TOA) of the signal or it can be a packet of information with the identity of an object read through RF signals [Col13, Col15]. Other localization metrics include imaging cameras used to extract visual information by direct image processing techniques [Hil08, Mul09, Dav07] such as the plate number of a car or by comparing features of consecutive images to analyze the motion of an object [Bis12, Moh14]. There are a number of mechanical sensors such as accelerometer, magnetometer, and barometer, which are used to determine the speed, direction, and height of a device such as a smart phone or a

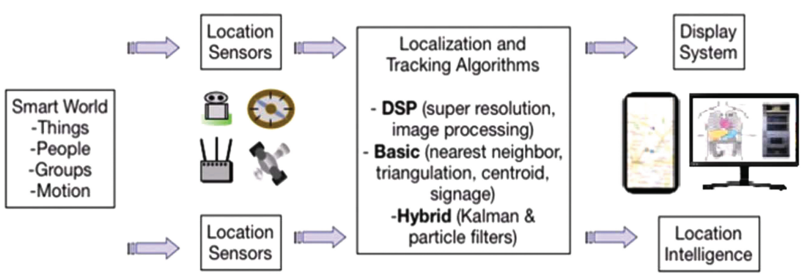
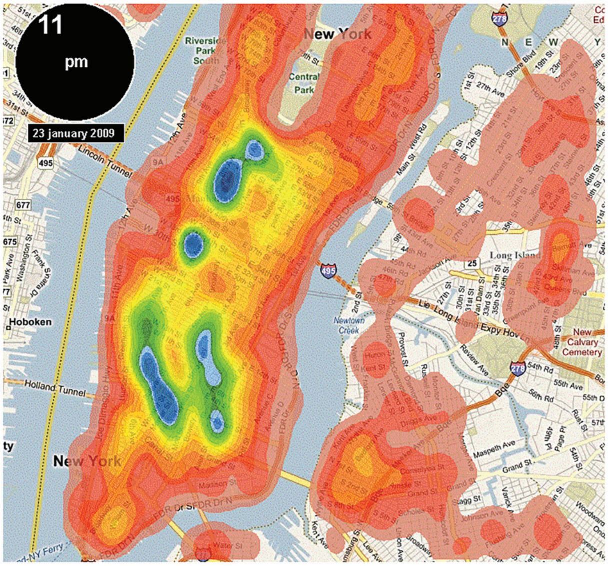



**Figure 1.2** Elements of localization science and technology in the Smart World.

robotic platform. The positioning algorithm processes the received metrics to determine the coordinates of the target object. These algorithms may use signal processing algorithms such as super-resolution algorithms [Li04], to refine the sensor data and prepare better metrics, algorithms to process metrics and come up with a location estimate. As the measurement of metrics becomes less reliable or exact, the complexity of the position algorithm increases. In navigation applications, when we have some information regarding the movement of the target object, we combine the position estimates with the information on the pattern of movements of the object to refine the location estimates [Gen13] or algorithms such as Kalman filters [Au13, He14, Che12] or Particle filters [Bar15] to take advantage of the history of other location estimates as well as combining metrics obtained from different sensors [Kel11, Cas12a].

The display system pins the estimated location coordinates to a map of an environment. In the most traditional localization application, in direction finding for car driving, we refer to a geographic map with absolute coordinates. In other contexts, such as indoor areas or within a human body, it may be better to employ local or relative coordinates and an alternative "map" of the indoor area or body [Bao15]. In indoor areas, we have multiple maps associated with different floors of a building, when a smart device carried indoor and outdoor, we need different maps and a smart display system needs to sense the environment for selection of the appropriate map [Yin15]. In any case, the display system could be a service or an application residing in a server or a mobile locating unit, locally accessible software in a local area network, or a universally accessible service on the web such as Google maps. Obviously, as the horizon of the accessibility of the information increases, the design of the display system becomes increasingly complex.

Location intelligence is extracting information for a specific intelligent application using location and track information. Location information uses pattern of movement of a device to analyze the behavior of the person or a mechanical platform carrying the device [Wan11]. Such location intelligence includes location-time traffic analysis, Geo fencing (for elderly people, animals, prisoners, suspicious people, etc.), real-world consumer behavior, location certification for security, positioning IP addresses, and customizing contents and experiences. Video Clip 1.1 illustrates the customer behavior of Wi-Fi localization requests in New York City in different times of a day, collected by Skyhook, Boston, MA. Marketing agents of different organizations for targeted marketing use this type of location intelligence.




**Video Clip 1.1** Customer behavior for Wi-Fi localization requests in NYC for different hours of a day. (Source: Skyhook Wireless). (Note: Animation is a supporting video).

## 1.3 Localization Technology and Applications

The word "smart world" became popular because a number of ***smart applications*** began to emerge to solve problems using time, location, sensor data, and general context. Figure 1.3 provides an overview of several popular and important smart applications leading to evolution of the smart world.

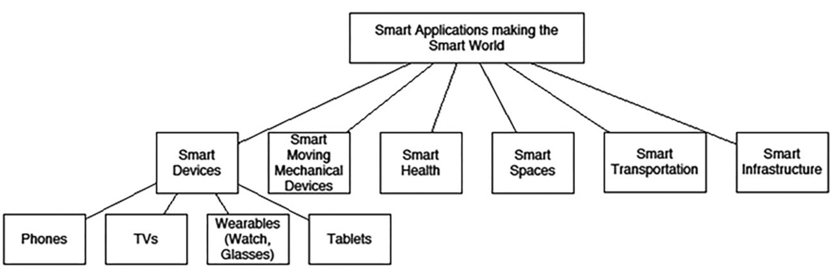



**Figure 1.3** Overview of popular smart applications associated with the emergence of the Smart World.

As we integrated extensive computing abilities to mobile phones, starting with the iPhone, we began to call it a "smart phone". As we increased the artificial intelligence of moving mechanical devices using computer programs and electronic circuits, we called them Robots, to connote the fact that they benefit from computing intelligence. More recently, we have used the words "smart health" for better processing of a patient's data to improve the health outcomes and to reduce the cost of improving health services. We refer to buildings with extensive pervasive programmability and intelligence, such as knowing when to increase the thermostat, as smart spaces [Hel05] and we expect these environments to use RFID tags, iBeacon, and other technologies to enable intelligent location-aware robotic applications [Bae07]. We use the words "smart transportation" in the context of adding substantial computational intelligence to traffic monitoring and management. The electric grid that can adapt itself to changing weather and diverse sources of energy as well as intelligently handling electric usage in homes and buildings is now called the "smart grid". In essence, we are realizing a vision of the "smart world" through the variety of smart applications with intelligent capabilities to solve problems. All of these applications demand location information. In this section, we describe examples of some of these applications to show their need for localization information.

### 1.3.1 Localization for Smart Devices

Smart devices are the most popular platforms used for the creation of smart environment and the smart world. Billions of smart devices such as smart phones, tablets, smart watches, smart glasses, and smart TVs use location information for hundreds of thousands of applications either directly in applications, such as turn-by-turn direction finding, recommendations through Yelp, flight fares through Kayak, or indirectly as part of applications for gaming or customer behavior analysis. The accuracy and precision requirements for these applications are quite diversified and range from centimeters in gaming to meters in indoor geolocation, tens of meters in turn-by-turn direction, and hundreds of meters for broadcasting advertisements in targeted areas.

Smart phones are perhaps the most popular smart devices, and the overvaluing majority of those hundreds of thousands of applications have been designed for mobile application in smart phones. Smart phones also carry a number of location sensors. These sensors include the most popular RF-based location sensors such as GPS, Wi-Fi signal, cell phone signals, iBeacon (low-energy Bluetooth) as well as mechanical location sensors such as magnetometer, barometer and accelerometer, and of course high-quality cameras and microphones. Because of diversity of applications and their requirements, availability of multiple sensors on the platform, and the inherent mobility of the device, which demand operation in diversified environments, most of the research and developments for localization in smart devices have been initiated for smart phone applications.

### 1.3.2 Localization for the Robots

Robotic platforms are another essential components of the evolving smart world. A variety of ground rolling and flying robots of different sizes are emerging to facilitate operation in the smart environment of the smart world in a variety of applications in warehouse management, manufacturing, military missions, security, commercial delivery, aerial photography, and health. Every robot moves and we need to know where it is, so it should have a location and mapping system. The visualization platform for land robots is usually a 2D map, while flying robots need the more complex 3D localization and mapping. Robot localization systems need to know a landmark as origin or destination and a method to track the movement of the robot. Traditionally, robots benefit from 2D simultaneous localization and mapping (SLAM) algorithms for navigation [Hua11, Bru13] and, more recently, 3D localization for flying robots and for micro-robots inside the human being are emerging [Pah12, Hen12, Fue15].

Location sensors in robotic platforms include camera, speedometer, RF communication devices, RFID readers, and optical measuring meters. A land robot may carry all of these sensors while a flying robot or a robot with medical mission inside the human body may only carry a camera and an RF device to communicate between the controller and the robot [Idd00].

The accuracy and precision needs of moving mechanical devices vary by the application, size, and environment of operation of these devices and it may range from millimeters for robots operating inside the human body to a few meters for robots operating in indoor areas and tens of meters for outdoor robots. The mission of the robot also affects these values. For example, a robot operating in a laboratory in an indoor area or a flying miniature robot may need precisions on the order of centimeter or millimeter for certain tasks rather than a few meters accuracy commonly perceived for indoor operations [Gen15a].

### 1.3.3 Localization in Smart Health

Since we cannot see inside the human body directly and the inside of the human body comprises a number of complicated organs, each treated by a separate specialist doctor, the term "localization" in medicine is commonly used for locating a lesion, tumors, bleeding, or pain inside the human body. The term is also used for locating an external device such as intrusive surgery equipment or an endoscopy capsule inside the human body [Pah12]. In addition, in hospitals, there are numerous localization applications ranging from locating, doctors, patients, nurses, and visitors to locating commonly used equipment such as wheelchairs and specialized tools such as surgery equipment inside the surgery room. With the current wave of elderly health monitoring research using sensor networks [Hac14, Gen15b], localization technology for patients is needed everywhere. Technologies used for locating people or objects inside the hospitals are one of the major applications for the emerging indoor geolocation science and technologies [Pah02]. Other commonly used technologies for indoor and outdoor localizations are used for health monitoring whenever tracking and location of the patients are essential.

The accuracy and precision needed for localization inside the human body may vary from a fraction of a millimeter for neurons inside the brain to centimeters inside the GI-tract. Localization precision of the people and equipment in health-related applications follows the same guidelines as smart devices and robots.

For in-body localization and mapping, traditional 2D and, more recently, 3D X-ray [Mar14], 3D ultra-sound imaging [Yim13], 3D magnetic resonance imaging (MRI) [Tha12], and computer-aided tomography scan (CAT-scan) [Kut06] are used. More recently, RF signals [Pah12] as well as hybrid RF and imaging techniques have been used for locating micro-robots inside the human body [Bao15]. An animated video clip demonstrating the RF and visual elements of hybrid localization inside the human body is available at [Bao12]. Since there is no map in vivo for tracking inside the gastro-internal tract (GI-tract) and the vascular tree, mapping inside the organs has been another current area of research.

### 1.3.4 Smart Spaces and Localization Using RFID

Radio-frequency identification (RFID) tags are another essential elements of the emerging smart worlds. Currently, passive RFID tags are used in numerous popular applications such as tagging newly born babies or patients in the hospitals, checking cars in the highway pay tolls, checking progress in long assembly lines, tracking small items in warehouses, implanting microchip IDs in animals and the human being, and tracking robots in indoor areas [Moa11]. It is expected that RFID tags become widely deployed in the smart buildings [Ma14, Spi10] and smart phones of the future carry RFID readers [Liu14, Hol09]. We expect trillions of RFID tags to be used for numerous applications in the smart world of the future. As important as it is to connect these tags through the Internet of Things (IoT), a need for localizing RFID tags is becoming essential. Passive RFID readers are simple proximity check localization systems communicating the tag information with the cyber domain. The real-time location system (RTLS) technology addresses indoor localization for RFIDs tags using Wi-Fi, iBeacon (Bluetooth), and UWB Technologies [Mil08]. As important as is to know the location of an RFID, if the RFID is installed in a fixed location, it can be used for opportunistic location and smart evacuations in challenging environments for RF localization such as inside the tunnels [Dea12] or they can be used to improve the accuracy of indoor geolocation systems as a component of a more complex hybrid localization system [Liu14].

### 1.3.5 Localization for Smart Transportation Systems

Indeed, smart transportation is an important part of smart cities and the smart world. As a result, smart transportation systems have received considerable attention in the literature [Gan13]. We know absolute location of the ground and air transportation systems operating in outdoor environments. If properly networked, this information revolutionizes efficiency of the transportation systems resulting in huge saving in fuel cost and transportation costs. The vehicular navigation systems primarily rely on GPS and mechanical sensors measuring the speed and direction of movement of the car [Pah13]. The weakness of current vehicular systems is lack of networking infrastructure to coordinate these movements in an intelligent manner. This is a long process involving networking standardizations. Another emerging localization application for vehicles is finding the relative location with respect to surrounding mobile and fixed objects. Such application is used to assist drivers in maneuvering the vehicle movements with respect to other moving vehicles as well as the fixed infrastructure surrounding the move. With the investments on the thousands of sensors on those moving vehicles and surrounding infrastructures, ideally we expect to know their locations as well as the trace. Such information carries mobility patterns of dynamic individuals and it enables further data mining-based applications such as smart itinerary guidance, trace-based social event analysis [Kar12], urban traffic planning [Cas12b], land usage monitoring [Hag12], smart public security [Gan13], and even traffic flow-based smart advertising [Lee12]. All these applications need a smart transportation system as the backbone; therefore, localization science and technology has a wide variety of applications in the emerging smart transportation systems as well.

### 1.3.6 Localization for Smart Infrastructure

Several critical national infrastructures are becoming smart – in particular, the electric grid, intelligent transportation, water systems, etc. [HLS]. Managing the resources of the critical infrastructures efficiently and for enabling their resilience and smooth operation, localization is essential. Although there is limited work in this area (see, for example, [He11, Fan14] for localizing faults in the smart grid), identifying where a resource is being constrained or added becomes important. When sensors are used for sampling water quality, or to assess the load in the electric grid, the locations of these sensors are important as they relate to the measured quantities and the infrastructure that is in place near the sensor. In terms of accuracy and precision, there are a variety of requirements – at a macroscopic level, it may be sufficient to know the locations of various components at the granularity of several tens of meters on a map, but within a specific component (e.g., an electric sub-station), the localization accuracy may have to be on the order of centimeters.

## 1.4 Some Existing Challenges in Localization

Localization science and engineering has made considerable fundamental growth in the past few decades, which has enabled a spurt in the number of smart applications [Pah13]. As the smart applications in the world expand, the need for localization in challenging environments grows. At the time of this writing, a number of challenges are facing the location science and technology as a fundamental enabling technology for the evolution of the so-called smart world.

Localization in crowded environments during the events in outdoor, such as stadiums, or indoors, such as large lecture halls, is an existing challenge for a number of smart applications tailored for these environments. These applications involve 3D map of the environment and an accuracy of less than a meter to locate targeted seats for delivery of a smart service. To support the audience with wireless access for smart phone as well as localization for delivery of physical services, most probably we need temporary infrastructure deployment using Balloons and Drones that can cover the areas of interest during the events attracting the crowd. To guide people intelligently to their seats, we may need to resort to hybrid and cooperative localization using RF signals, RFID-based signs, as well as mechanical sensors commonly available in smart phones. The map could be a 3D map layered into 2D map of individual floor or step levels or an interface with direction of movement pointers guiding the target smart phone to the seat location.

Finding *cost-efficient* locating systems for smart item finding in shelves of a department store is another long-standing problem for localization systems. Smart shopping of the future needs that type of technology to direct customers to the location of the desired products. Similar challenges may exist for localizing specific entities in the various critical infrastructures to enable smart applications. Such challenges are created in layers – as an example, first we have to find which floor the human being is located to select the associated map for the floor [Ye12, Yin15]. Next, we have to identify which shelf in which aisle contains the item of interest. The accuracy needed for this type of localization intelligence is around few centimeters to differentiate small items from one another. The most commonly used indoor localization of today is Wi-Fi localization with accuracy of a few meters, which is not adequate for this type of application. We need additional RF infrastructure and more complex hybrid and cooperative localization algorithms to achieve the needed accuracy. iBeacon technology, using mechanical sensors and Bluetooth in smart phones, or adding UWB infrastructure seem to be useful for such applications, but the technology has not yet stabilized, nor are the costs associated with it.

Another challenge for localization in the emerging smart world is locating flying smart tiny robots in indoor areas. 3D localization needed for these flying robots demands accuracy on the order of the size of these robots to navigate them intelligently without any crash incident. The display map for these applications needs to be 3D and certain amount of details for the furniture and other large items and people in the room is needed to control the movements of the robots. This is a very complex technology and very far away from the current states of the art. Similar to smart finding of items in the shelves, here accuracy of existing Wi-Fi infrastructure is not adequate and we may need additional RF infrastructure and integration of visual and mechanical sensors.

Application of microbots in the emerging smart medicine delivery and health monitoring systems has opened another horizon for localization of microbots inside the human body [Li12, Mar12]. Challenges for localization inside the human body begin with issues related to the map. We do not have any map for the path of movements of these microbots inside the specific human GI-tract or vascular tree in vivo. All we have is the general anatomic cartons of the shape of the organs and the paths, not the real 3D map needed for navigation inside the human body. Most microbots carry a camera, if the path of movement is reconstructed, the camera pictures can be used to reconstruct the inside of the individual organs in vivo. The infrastructure for localization in these scenarios is body-mounted sensors, which are always moving with respect to one another with the human body moves. Intelligent localization in an infrastructure that is in motion needs new algorithms to be discovered. Intelligent navigation of these microbots needs hybrid localization using RF signal and the images taken by the cameras [Bao15, Bao14]. RF propagation inside the human body is very complex because it is a non-homogeneous and liquid immersive environment, which opens a new horizon for scientific discoveries [For06, Mak11].

Finally, associated with the localization of objects and humans is the challenge of privacy and securing the information so that it is available to only authorized entities (e.g., the human whose location is being captured). While research work on location privacy has been ongoing in recent years, there are open questions on how location privacy can be maintained, while providing the utility of this information in a smart world.

## 1.5 Overview of the Book

This book is prepared as a textbook to guide the reader to learn the fundamental technical aspects of localization science and technology for indoor and urban areas. There are three fundamental technical skills needed for understanding the design and performance evaluation of these systems, modeling the behavior of the location sensors, performance evaluation using CRLB, and design of algorithm for optimize the precision of a positioning system. In the first chapter, we first explained technical complexity, applications, and open challenges for localization science and engineering in the emergence of the Smart World and IoT. We explain why localization science is a complex multi-disciplinary area of research and technology and identify the technical aspects associated with this field of research. We categorized different applications, the precision they need, and technologies they use; we introduced a few technical challenges and explained what is needed to overcome these challenges; and finally we provided an overview of the rest of the book.

The remainder of the book is divided into three parts and an appendix chapter. Part I cosists of two chapters on received signal strength (RSS)-based systems. It begins with Chapter 2 on behavior of RSS and range estimation followed by Chapter 3, describing popular RSS systems. Part II consists of three chapters on Time-of-Arroval (TOA)-based positioning. It begins with Chapter 4 on principles of TOA ranging, followed by Chapter 4 on description of opportunistic TOA positioning techniques using existing communication system infrastructure and technologies. The Direction of Arrival (DOA) systems are treated as a part of TOA sytems, because they rely of TOA estimation. Since the analysis of the effects of multipath in indoor and urban areas on the performance of TOA systems is vital, Chapter 6 is devoted to the analysis of the effects of multipath. In Parts I and II, the tool for analytical performance evaluations is the CRLB that is compared with the empirical results of performance evaluaitons. Part III presents the details of applied algorithms for positioning. It begins by Chapter 7 to ppresent the basic positioning algorithms. Then, it presents applied algorithms used for RSS- and TOA-based positioning Chapters 8 and 9, respectively. Since RSS is an unreliabe measure of rangings, pattern recognition algorithms are the center of discussion. The TOA is much more reliabe, but it is very sensitive to multipath. The algorithms introduced for TOA are signal processing algorithms to mitigate the effect of multipath. The final Chapter 10 of this part is devoted to hybrid positioning algorithms for integration of relative and absolute positioning. We begin by introducing different sensors for measurement of speed and direction of movement for reltive localization. Then, we provide examples of Particle and Kalman filtering applications for integration of absolute and relative localization. Since understanding of certain basic concepts in the classic estimation theory is an important analytical background for understanding of the book, Appendix A is devoted to the review of the parameter estimation theory and derivations of the CRLB. In classical estimation theory, ranging and positioning are referred to as single and multiple parameter estimation and CRLB is a mean for calculation of variance of these estimates. We review all these specific parts of the estimation theory in Appendix A.

The emerging multi-disciplinary fields such as wireless networking, robotics, or wireless positioning involve a variety of disciplines. Therefore, people with different skills work on different aspects of a unique project. But the experience that they learn in that endeavor is different and focused around their individual skills. Therefore, details of the research work, contents of the courses that are taught, and the books that are written on the same topic are based on the author's experiences. The author of this book has pioneering research experience and industrial exposure in design and performance evaluation of indoor geolocation based on empirical measurement and modeling of the behavior of radio propagation. The presentation of the material is based on examples of research and development that he has been engaging with as a professor or as technical consultant to startup companies. As a result, this book organizes results of research papers, patents, and course notes of the author to present the results of his research findings and educational experiences over a couple of decades to his students.

## Assignments

### Answer the following questions:

(you can use all information available at the Internet found by search engines such as Google or Wikipedia)

1. Why localization is becoming more important for the information networks?
2. What are the elements of the Smart World and what is the role of localization in formation of these elements?
3. Explain the meaning of "location intelligence".
4. Why smart phones apps are of interest in knowing the user's location information?
5. Why do we need special skills to get into the field of opportunistic positioning, and what are the types of skills needed to understand this field?
6. What is SLAM and how it is used in robotics?
7. What is the role of positioning systems in emerging "smart transportation technologies"?
8. Why localization with millimeter accuracy is needed for inside the human body and what are the challenges in developing that technology?
9. Identify the name, location (City and Country), and the indoor navigation technology of three companies providing indoor geolocation.
10. What are the challenges for the future of the positioning systems?
11. Why cellular service providers are interested in location-based services? Give some examples of location-based services.
12. What are the basic elements of a wireless geolocation system?
13. Name the three major distance-based techniques used for location finding and explain how are they different from each other?

14. How can nodes in an ad hoc or sensor network determine their locations even if they are not directly connected to nodes that are location aware?
15. What is Wi-Fi localization and how does Wi-Fi localization complement GPS technology?
16. Explain why millimetric localization inside the body is important and what are the challenges in developing that technology?
17. Explain why we need special skills to get into indoor geolocation science and technology, and what type of skills is needed to understand this field?

### Project 1.1:

Search Chapter 1 and the Internet (IEEE Explore, Wikipedia, Google Scholar, ACM Digital) to identify one area of research and one area in business development which you think are the most important for the future of the positioning industry. Give your reasoning why you think the area is important and cite at least one paper or a website to support your statement.

### Project 1.2:

Use Google Scholar to find the two most sited popular interesting articles related to indoor positioning and navigation in the last three years. Read these articles and write a half-page summary for each of them.