Position Location Techniques and Applications

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Academic Press is an imprint of Elsevier

Academic Press is an imprint of Elsevier
30 Corporate Drive, Suite 400
Burlington, MA 01803

This book is printed on acid-free paper. ∞

Library of Congress Cataloging-in-Publication Data
Application submitted.

ISBN 13: 978-0-12-374353-4

For information on all Academic Press publications
visit our Website at *www.books.elsevier.com*

Printed in the United States
09 10 11 12 13 10 9 8 7 6 5 4 3 2 1

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Preface

Purpose of This Book

Obtaining information on position location is, along with current regulatory requirements, one of the critical elements for the creation of location-based and context-aware services. It is also an important support for resource management and for the swift deployment of assistance services such as law enforcement.

The location problem has existed for many years and has motivated a great amount of research in and development of cellular-aided positioning algorithms and systems. In the satellite context, two global examples of such systems is the global positioning system (GPS) in the United States and the GALILEO system in the European Union. Diverse types of wireless network infrastructures are being deployed throughout residential areas, city commercial centers, university and company campuses, hospitals, amusement parks, and restaurants.

Wireless networking devices constitute the main infrastructure to be utilized for wireless location algorithms. Besides emergency services, several applications can be envisioned with these position estimation schemes. They include real-time display of self-location information; monitoring and mapping of potentially hazardous zones in disaster areas; fleet management and real-time traffic information retrieval; real-time amusement park, museum, and tourist guides; mobile databases; location-aware gaming systems; and location-sensitive billing.

Currently, several sources need to be consulted to obtain a comprehensive understanding of the location estimation problem, making the learning process lengthy and without a unified focus. The proliferation of mobile computing devices and wireless technologies has fostered a growing interest in the development of location-aware systems and services. Location estimation systems depend on a number of variables and scenarios that must be thoroughly understood, all at once, in order to cope with system design trade-offs, complexity issues, and design of efficient positioning algorithms.

However, most of the literature on cellular, ad hoc, and wireless sensor networks fails to treat the localization problem thoroughly. Very few books address the topic explicitly and, when they do, they tend to tackle it from the perspective of a single technology. Moreover, in most cases theoretical background and fundamental limits to the localization problem are neglected. For these reasons with this book, it is our intention to provide readers with the necessary location estimation expertise without their having to endure a cumbersome learning process. Further, we want to introduce the challenges and problems posed by the ever growing need to localize nodes in ad hoc and sensor networks.

The purpose of this book, then, is to develop a comprehensive and unified view of the wireless location-information acquisition problem and its solutions. More than providing an exhaustive survey of current location estimation techniques, we set a theoretical path that will allow practical engineers and researchers to understand and improve existing location schemes as well as to develop new ones within different scenarios.

The audience for this book includes those who work in, and end users of, related areas within the communications sector, such as operations, manufacturing, and service provision, as well as those in development engineering, consulting, academia, higher education, planning and resource management, and research. Applications-oriented professionals will also find support through discussions of the networking aspect of the problem, such as network architectures that support position location applications and services, as well as through discussion of the problem's algorithmic aspects.

Features

The presentation of the information in the book is self-contained, allowing readers to acquire the fundamentals for development, research, and operation of position location techniques. The book presents ideas and techniques such that readers will be capable of applying, evaluating, and extending them. Further, it introduces the ideas behind the algorithms, supplying concepts that show the generality of such techniques in terrestrial and satellite systems. The book can be considered as a reference by many engineers in the communications area and as a textbook in universities. It will also present a solid base for members of academia who are looking for an introduction to position location.

Although many books on position location can be found, most of them are technology driven or business oriented, which limits their scope to killer applications or services with a limited treatment of or orientation toward general scenarios that can be applied and extended to present and future scenarios and technologies. Other books concentrate on a particular technology, protocol, or scenario, limiting their usefulness once new technologies appear.

Information on location acquisition is sparse in the cellular systems literature. Few books address the topic explicitly, and those that do tend to tackle the problem from the perspective of a single technology with little emphasis on theory and fundamental limits. We provide a global, unified treatment of the position acquisition problem.

Trends in reconfigurable and multihop networks, which are not treated at all or only incompletely in other books, pose new challenges in location acquisition. For that reason, we revisit some traditional methodologies from a new perspective. We also consider some heuristic techniques suitable for a limited number of landmark references, multihop scenarios, and three-dimensional cases.

Organization

The material in this book is organized as follows. Chapter 1 addresses the relevance of position location (PL) information as a critical resource in improved network planning, development of new location-based services, fast deployment of assistance services as well as surveillance and security support, and many other applications such as fleet and crew management, environmental monitoring, and control. Conflicting criteria present in algorithm design due to PL information requirements, and achievable goals (e.g., accuracy, cost, processing load, implementation times) are reviewed in terms of service, environment, and technology.

As Chapter 1 discusses, location estimation methods can be implemented based on field intensity, angular or time-related measurements, or combinations of these factors. These signal measurements may be used to determine the length (range) or direction (angle) of the radio paths to/from a node of interest from/to multiple reference nodes. Alternatively, they may be used to constrain the position of a target node to circular or elliptical loci around multiple reference nodes.

Chapter 2 describes radio signal strength (RSS), angle of arrival (AOA), and time of arrival (TOA) measurements, and discusses techniques to estimate these variables, paying careful attention to the major sources of estimation errors such as channel fading, non-line of sight, and noise. Bounds on estimation performance of RSS, AOA, TOA, and range are also provided. A set of measurements originating at or being received by several reference nodes can be combined in optimal or suboptimal ways to estimate the position of a target node.

Chapter 3 presents optimal and suboptimal methods that combine RSS, AOA, TOA, and range measurements originating at several reference nodes to obtain estimates of the position of a target node. Cooperative and noncooperative data fusion techniques are discussed. Positioning algorithms are presented for static and dynamic scenarios. In the latter case, velocity is included in the model and filtering techniques are applied to predict the next position of the transmitting terminal. Introduced are important performance metrics that capture the system–network performance dependence, such as the dilution of precision that describes the amount by which estimation errors are degraded by the network geometry, and the Cramer-Rao bounds, which are lower bounds on the covariance of estimates of unbiased estimators.

In many scenarios, observable parameters are insufficient to provide accurate location information; however, broad location estimation may be feasible and sufficient for some purposes. In Chapter 4, heuristics applicable to both single-hop and multihop scenarios are introduced along with some of their major limitations. Sensitivity to errors or limited knowledge of the environment is also discussed, and practical and theoretical limitations such as measuring errors, impact of a reduced number of landmarks, multihop, uncertain node location, and mobility are presented.

In Chapter 5, we review the fundamentals of wireless networks to develop a thorough understanding of the basic functions involved in position location scenarios. PL is seen as part of the wireless network system; mobility is brought into the discussion because it imposes limits on network performance. It is also important to introduce how these scenarios evolve according to technology within new paradigms and architectures such as cooperative networks, cognitive radio, multihop scenarios, and reconfigurable networks.

In Chapter 6, the PL problem is treated as part of a network, with discussions and presentations of architectures and system points of view in different scenarios. Some technologies, such as WiFi, and ZigBee, are addressed as part of the general scenarios that have been presented up to this point. Sensor and ad hoc networks are also presented. Trade-offs that further comparison of different technologies are fundamental in PL decision making. This discussion includes received signal strength, time of arrival, and angle of arrival, as well as new ideas on connectivity and reachability in reconfigurable networks.

Chapter 7 describes the concepts behind the technology used by any satellite system for space positioning. The intention is twofold: a comprehensive development of underlying technological and scientific ideas and a foundation for appropriate and novel business applications. The basics of augmented systems are also presented.

Acknowledgments

The fundamental idea of a book on position location came from our research, course development at the graduate level, and publications, which would not have been possible without the support of the Nortel Networks–ITESM Monterrey Research Chair at the Center for Electronics and Telecommunications. We also must acknowledge the continuing support of the Mobility and Wireless Systems Research Chair at ITESM Monterrey and the many colleagues and research assistants who make up this group and who have contributed to our research and results over the years.

This book was also made possible by the support of SEP-CONACyT through project 61183, "Coordinate Determination in Ad-hoc and Sensor Networks," within the Basic Science Program.

We are grateful to our friends and former graduate students who assisted us by making their thesis research work available. Among the many who contributed ideas and technical insights through discussions and suggestions are Rafaela Villalpando, Elodia Sanchez, Oziel Hernandez, Raul Torres, Pekka Perala, Michel Z. Antonio, Lluvia G. Suarez, Cynthia Castro, Armando Garcia-Berumen, Enrique Stevens, Eric Baca, Jose I. Bermudez, Martha L. Torres, and Aldo Lopez Gudini.

It was a pleasure to work with the team at Academic Press/Elsevier, and we would like to thank Tim Pitts, Melanie Benson, and Marilyn Rash for their understanding and guidance.

Finally, we thank our families for all of their support during this incredible adventure.

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Contents

CHAPTER 1

The Position Location Problem

Simply put, the fundamental problem of position location (PL) can be formulated as that of finding or estimating the location, in a two-dimensional (2D) or three-dimensional (3D) space, of a point of interest within a coordinate system constructed using some known references. In general location scenarios, and at the point of interest, a new location is determined bearing in mind the displacement from a previously known reference location. This may imply some direction and inertial estimation. Due to the widespread penetration of wireless systems, we consider devices with transmission or reception capabilities that somehow assist in the location procedure.

In this book, and according to the context of the scenario being discussed and in agreement with terms used in the open literature, we will interchangeably use the terms *point of interest, node, tag, location device, user, subscriber unit*, and *mobile*, among others, to make reference to the location coordinates that need to be estimated. In the same sense, the set of known references used to locate the device will be denoted as references, reference nodes, landmarks, land references, beacons, and anchor nodes.

This chapter addresses the relevance of location information as an important resource that includes other applications for better network planning, development of new location-based services, and fast deployment of assistance services, as well as support of surveillance and security policies. Conflicting criteria in the algorithm design due to PL information requirements and achievable goals (e.g., accuracy, cost, processing load, implementation times) are reviewed. Practical and theoretical limitations, such as measuring errors, impact of a reduced number of landmarks, multihop, uncertain node location, and mobility are introduced. Current trends in sensor and three-dimensional systems are also presented.

1.1 THE NEED FOR PL AND HISTORICAL DEVELOPMENTS

The construction of landmarks can be traced back to the ziggurats on the Shinar plains. These landmarks were meant to be religious as well as geographical references. The usefulness of referencing location to an adopted landmark was soon recognized, and some time in the third century B.C., Eratosthenes of Cyrene devised a system of latitude and longitude.

Today, we accept the Greenwich meridian, the equatorial circle, and mean sea level as references that allow us to specify unique locations on Earth. Global coordinates may be very useful in some applications; however, in other cases, the locations are to be contextualized to other references of regional or local importance. Therefore, location description in a reference system often needs to be translated into another coordinate description suitable for the application at hand. Location information has been an important tool for enabling multiple applications (e.g., community settlement planning; traveling; mining; surveillance; monitoring; military applications; and nowadays the development of location-based services (LBS) and engineering).

In some cases, location information may mean survival. This is the case for a variety of species that have evolved diverse migrating practices and capabilities such as orientation systems based on geomagnetic field sensing. Early humans used star gazing to aid in seasonal migration, farming, and crop cycles. In time, they developed sophisticated astronomic tools, such as the astrolabe, that years later were used by mariners to determine the latitude of a ship at sea by measuring the elevation of a star of known declination in a given season. The presence of the quasistationary North Star in the northern hemisphere allowed the determination of latitude. In contrast, the latitude calculation in the southern hemisphere was more demanding because a fixed visible astronomic reference above the South Pole sky does not exist.

In all cases, longitude had to be calculated from estimated direction and traveled distance, which demanded time references as well. Time measurements also became important references because astronomic observations had to be related to the time of day in a particular season. This led to large navigation almanacs used to cross-check current observations to determine the geographic position of a given site. Although sun dials were among the first time-measurement instruments, they had serious drawbacks such as limited portability and latitude- and season-dependent performance. Thus, water clocks (*clepsydra*) and sand devices soon found a place as timekeeping references. The importance of these devices derives from the fact that they allowed speed measurements since one could now relate travel distance to a given time interval. The magnetic compass became an important navigation tool because it could combine latitude information with travel direction. This combination of techniques prevails as a common practice since no single technique is best for all scenarios, and feasibility must be assessed for each application environment.

Early humans established landmarks to develop relational frameworks that provided location information relative to known references. Their methods relied on major landmarks that were assumed static, a valid assumption for the purpose and time scale of the observations. These developments promoted map construction. Maps used by early sailors were usually distorted and subject to slow iterative processes where current observations were confronted to previous maps and cross-checked with somebody else's map. As location information became critical for commercial, travel, and military purposes, the search for more accurate maps and precise instruments gained great importance and became strategic. This caused the work of navigators to be considered crucial in any journey. Newly acquired and more accurate maps and instruments had such value that they were usually kept secret and/or locked away.

Lighthouses, like those located in Pharos near ancient Alexandria, were among the first human-made landmarks. They were references that could be spotted from afar, allowing proximity estimations of distance. Soon afterward, chains of lighthouses were constructed along common navigation routes for maritime and eventually aviation purposes. In navigation, vessels estimated their location by inferring the direction and traveled distance from the last known landmark. This technique, which became known as *dead-reckoning*, was also applied in early aviation. Limitations of dead-reckoning are due to errors in the parameter estimation process, as well as other undetected disturbances (e.g., tidal and wind drifts). Location updates were applied at the time of the observation of the next known landmark, which was assumed to have an accurate location. At first, without the satellite surveillance technology available today, landmarks' relative locations were quite inaccurate; and, as mentioned earlier, iterative processes were necessary to develop more accurate map tracing and thus more accurate dead-reckoning schemes. Soon after radio systems had been developed, dead-reckoning schemes were also used in applications for the determination of bearings, routes, or locations of vessels and in-flight aircraft.

Modern location systems still rely on basic information such as distance and observable angles, which can be indirectly obtained through multiple related parameters (e.g., field strength, arrival times, arrival time differences, phase differences, and phase variations). Technological advances have contributed not only to a faster acquisition of location-related parameters and improved accuracy but also to the design of new architectures such as cooperative and data-fusion systems.

Advantages, accuracy, and limitations of particular location techniques depend on the costs involved, the number of locations to be determined,