Graduate School of Creative Science and Engineering,
Waseda University

博 士 論 文 概 要
Doctor Thesis Synopsis

論 文 題 目
Thesis Theme

Indoor Positioning with GPS-compatible Signals:
Doppler Positioning and Proximate Multi-channel Pseudolite

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February 2012

In recent years, positioning technologies have become more and more important for our daily lives. Not only conventional location services such as car navigation systems and map services with cell phones and smart-phones have been improved, but also new services such as mobile adds, human navigation, and child tracking have been created. These direct services for people are called location-based services as a whole, and its market size is predicted to become about 12.7 billion dollars by 2014 (according to the report from Juniper Research). Moreover, new applications that are indirect services for humans such as unmanned car navigation, precision agriculture, and environmental monitoring are also being created. In many cases, these applications use satellite positioning to obtain an absolute position in a global reference frame.

The “global positioning system” (GPS), which is operated by the USA, is the de facto standard of the satellite positioning (that is, the de facto standard of outdoor positioning). In contrast, in the field of indoor positioning, many techniques, such as wireless LAN, ultra-wideband, vision and optical methods, and ultrasound, have been proposed; however, there is no de facto standard, although those techniques have their own strength. Here, given the convenience and availability of GPS, positioning with GPS-compatible signals are likely the best way even for indoor positioning because the same receiver hardware can be used both outdoors and indoors (i.e., billions of GPS receivers that have been shipped can be directly used indoors with minor changes to their firmware). (For convenience, an indoor positioning system with GPS-compatible signals is called “indoor GPS”, hereafter.)

Two indoor GPSs called “pseudolites” and “indoor messaging system” (IMES) have been studied until now. Pseudolites have a potential to achieve centimeter- to meter-level positioning accuracy but they have some fundamental problems for practical use; on the other hand, IMES is about to be put into practical use but its positioning accuracy is restricted to ten meter-level.

The objective of the research for this thesis is to propose alternative indoor GPS methods or systems that achieve centimeter- to meter-level positioning accuracy avoiding any fundamental problems that pseudolites have faced. If it is achieved, the proposed methods will create many applications that require higher accuracy than that of IMES, such as robot navigation, object tracking, precise human navigation for blind people. The central design philosophy of this research is that off-the-shelf GPS receivers and IMES transmitters are used with as little modification as possible because strength of the indoor GPS is in the reuse of billions of GPS receiver chips. To achieve the research objective based on this design philosophy, the research theme is divided to two research topics (research of a receiver unit and that of a transmitter). The former devises a GPS receiver unit while reusing IMES transmitters and GPS receiver chips, and the latter develops an indoor GPS transmitter reusing GPS receiver units and chips. For each topic, different approach is taken.

In the research for the receiver unit, an active sensing approach is taken; that is, by moving a receiver antenna, positioning accuracy is improved. Since the positioning method for this approach uses Doppler shifts to calculate the receiver’s position, this method is called “Doppler positioning method.” For the research of the transmitter, a multi-antenna approach is taken; that is, the receiver determines its position by using differences of phases of carrier waves transmitted from multiple transmitter antennas. Particularly, so-called “proximate multi-channel pseudolite,” which has almost the same architecture as that of pseudolites except its proximately-located antennas, is developed. This thesis consists mainly of the theory, experiment, analysis, and discussion of these two research topics.

In Chapter 1, the background and motivation of this research are described first. Two conventional indoor GPS methods, pseudolites and IMES, are then explained in detail, and their limitations are shown. Lastly, the contributions of this research are summarized.

Chapter 2 introduces the basics of Doppler positioning method as an active sensing approach. In this method, positioning is conducted by using the Doppler shifts produced by moving a receiver antenna. Since the Doppler observable includes frequency errors of the transmitter and receiver, by subtracting the Doppler observable of stationary receiver antenna from that of moving one, such errors are removed. In addition to the Doppler shifts, the three-dimensional attitude of the receiver obtained from a three-axis attitude sensor, and the magnetic declination, which is the angle difference between the Earth's true north and magnetic north, are also used for positioning. In this chapter, first, the positioning theory is described; that is, Doppler acquisition, position calculation algorithm, and the relation between the antenna movement and the dimension to be solved are explained. Moreover, an index used for error analysis called "dilution of precision" (DOP), which represents how the Doppler observation error influences positioning error according to the geometric relation between transmitter and receiver antennas, is defined. To evaluate the proposed method, a rotation-type movable receiver is developed, and a positioning experiment is conducted. The experimental results show that the Doppler positioning method can achieve centimeter- to decimeter-level positioning accuracy under the assumption that the errors stemmed from a magnetic compass (included in the attitude sensor) are zero. In this chapter, the design parameters for the Doppler positioning method (i.e., rotation radius and speed of the receiver antenna, and initial value for the non-linear least squares (NLLS)) are also analyzed. The results of the positioning experiment and simulation show that as the rotation radius of the antenna becomes smaller, the positioning accuracy decreases. It is also demonstrated that the relation between positioning accuracy and rotation speed of the antenna is a U-like curve; that is, there exists the optimal rotation speed. As for the initial value of the update process of NLLS, it is shown that if the initial value is set to the position of the transmitter, the estimated value of the receiver's position converges to an appropriate value. In the basic Doppler positioning method introduced in this chapter, a magnetic compass is used to obtain the receiver's orientation. In this case, the measured orientation contains two errors: one is the error of "magnetic declination (mentioned above)" and the other is "magnetic deviation." The magnetic deviation is the orientation error occurred due to the distortion of the local magnetic field, which is induced by metal objects and electric devices surrounding the compass. In the end of this chapter, the magnitude of these orientation errors is investigated. The experimental results show that the magnetic deviation sometimes more than 10 degrees, which is far larger than the error of magnetic declination. How those orientation errors influence the positioning error is also formulated. It shows that, in the worst-case scenario, the orientation errors induce meter-level positioning error.

Chapter 3 introduces so-called "Doppler pose estimation" in order to avoid the orientation error stemmed from using a magnetic compass. This method basically based on the basic Doppler positioning method introduced in Chapter 2; however, in this method, at least two IMES transmitters have to be visible to estimate both the position and orientation of the receiver simultaneously. As is the case of the basic Doppler positioning method, the positioning theory and DOP are formulated for the Doppler pose estimation method, and an experiment is conducted to evaluate the method. The experimental results show that the proposed method can achieve centimeter- to decimeter-level positioning accuracy and a-few-degree-level orientation estimation accuracy. In addition, a simulation is conducted to evaluate how the number of transmitters affects the position and estimation accuracy. The simulation results show that the accuracy improves as the number of transmitters increases, especially in the area surrounded by the transmitters. These experimental and simulation results suggest that magnetic compass error, which is a big issue of the Doppler positioning method on practical use, is completely removed.

In the Doppler pose estimation method proposed in Chapter 3, since the NLLS is used for position and orientation estimation, the real-time pose estimation is impossible. In Chapter 4, the Doppler pose estimation is modified so that it can cope with real-time pose estimation even while the receiver platform is moving. Moreover, the pose estimation method is also generalized so that the discrimination between movable and stationary antennas is removed, and any number of receiver antennas can be used. This modified Doppler pose estimation is called "real-time kinematic (RTK) Doppler pose estimation." To evaluate this positioning method, experiments with two types of robots (a mobile robot moving on rails without slippage and a normal mobile robot with two separate drive wheels) are conducted. The experimental results show that real-time pose estimation is basically possible but the number of visible transmitters and the measurement accuracy of the receiver platform's velocity (values obtained from wheel encoders) have an important role for the pose estimation accuracy.

Chapter 5 introduces a proximate multi-channel pseudolite (PMC-PL) as a multi-antenna approach. The PMC-PL has at least three antennas located at intervals of 95 mm (half wavelength of the GPS L1-band carrier wave). Those antennas transmit GPS-compatible signals with different channels, whose carrier waves are synchronized to each other by sharing a single radio generator. The receiver determines its position by using the difference between phases of carrier waves (i.e., difference between transmission distances of carrier waves) in conjunction with hyperbolic positioning. The devices are developed, and an experiment and a computer simulation are conducted to evaluate the proposed method and developed system. The experimental results show that the positioning accuracy is decimeter-level when the distance between the receiver and antennas of the PMC-PL is less than 1000 mm; when the distance is more than 1000 mm, the positioning accuracy becomes sub-meter- to meter-level. The simulation results are largely consistent with experimental results.

Chapter 6 concludes this thesis. The goal of this research, which is to propose indoor GPS methods that achieve centimeter- to meter-level positioning accuracy (as alternatives of conventional pseudolites), is achieved; that is, the Doppler positioning method achieves centimeter- to decimeter-level positioning accuracy, and the PMC-PL achieves decimeter- to meter-level accuracy. Chapter 6 also mentions future works. The Doppler positioning method can be applied for robots with multi-joints (such as humanoids), and the PMC-PL is extended to three-dimensional positioning. As for the applications for them, the Doppler positioning method is especially suitable for applications for robots and vehicles since it uses mechanical parts; on the other hand, the PMC-PL is suitable for applications for people because of-the-shelf GPS receiver units can be directly used. New applications are expected to be created based on these methods and systems.

早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Eng.), Waseda University)

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（As of November, 2012）

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(List of research achievements for application of doctorate (Dr. of Eng.), Waseda University)

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早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Eng.), Waseda University)

種 類 別 By Type	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
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