Deeply-Coupled GPS/INS Integration Using Adaptive Prediction Filter

by

Younis H. Karim Al-Jewari

(1040210533)

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DECLARATION OF THESIS

Author's full name: Younis H. Karim Al-Jewari

Date of birth : 18 – 01 - 1973

Title: Enhancement of a Deeply-Coupled GPS/INS Integration using Adaptive Prediction Filter.

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LIST OF ABBREVIATIONS

ANFIS	Adaptive Neuro-Fuzzy Inference System
ANNs	Artificial Neural Networks
APF	Adaptive Prediction Filter
AS	Anti-Spoofing
BP	Back Propagation
C/A-code	Coarse Acquisition code
CDU	control display unit
CSOC	Consolidated Space Operations Centre
CTS	Conventional Terrestrial System
DGPS	Differential Global Positioning System
DNSS	Defense Navigation Satellite System
DOD	Department of Defense
DOT	Department of Transportation
ECEF	Earth-centered Earth-fixed
ECI	Earth - Centered Inertial
EKF	Extended Kalman Filter
FFANNs	Feed-Forward Artificial Neural Networks
FPGA	Field Programmable Gate Array
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
I/O	Input/output
IDDN	Input delayed Dynamic Neural Network
INS	Inertial Navigation System

IOC	Initial operating capability
JPO	Joint Program Office
KF	Kalman Filter
MATLAB	Mathematical Laboratory
OSD	Office of the Secretary of Defense
P-code	Precision code
PDOP	position dilution of precision
PF	Particle Filter
PPS	Precise Positioning Service
PSD	Power Spectral Densities
RMS	Root Mean Square
SA	Selective Availability
SPS	Standard Positioning Service
TOA	Time of Arrival
UKF	Unscented Kalman Filter
WGS-84	World Geodetic System

LIST OF SYMBOLS

$\hat{\delta}$	RMS of an estimator
a	Acceleration
E{}	Expected value
F	Force
H	Height
R	Distance
t	Time
W_z	Angular velocity
x	Position
α	Inclination of the orbit plane
Δt	Time period
Ω	Angle in the equatorial plane
$\Omega 0$	Angle of the satellite
G_{lat}	Geodetic Latitude
G_{long}	Geodetic Longitude
K_k	Kalman gain
m	Mass
$P\hat{}_k$	Covariance matrix
Q_k	$(n \ x \ n)$ transition matrix
R_k	$(r \ x \ n)$ observation matrix
V	Velocity
V_e	Velocity in east

V_k	white noise sequences
V_n	Velocity in north
V_v	Velocity in vertical
W_k	uncorrelated white noise sequences
X_k	$(n\ x\ 1)$ state vector
$\hat{X}_k$	State vector
Z_k	$(r\ x\ 1)$ observation vector
v	Velocity
wk	white noise sequence
δ	Estimated parameter
θ	Position of the satellite within the orbit plane
$\theta 0$	Satellite Angular location
τ	Time constant

Deeply-Coupled GPS/INS Sepadu Menggunakan Penyesuaian Penapis Ramalan

ABSTRAK

Kebanyakan aplikasi yang menggunakan Sistem Kedudukan Global (GPS) memerlukan ketepatan data navigasi yang jitu sepanjang masa. Data GPS yang ralat akan mengurangkan ketepatan maklumat berkenaan dalam kedudukan dan halaju. Untuk mengatasi masalah tersebut, integrasi diantara GPS dan sistem pelayaran inersia (INS) membolehkan satu sistem navigasi mancapai kejituan yang tinggi. Walaupun terdapat banyak peningkatan ketepatan data kebelakangan ini, namun begitu masih ada lagi ruang penambahbaikan prestasi sistem integrasi ini. Laporan didalam tesis ini adalah berkenaan menggunakan kaedah integrasi Deeply-Coupled GPS / INS berasaskan penggunaan penyesuaian penapis ramalan (APF) untuk meningkatkan kejituan dan kebolehpercayaan data pandu arah dengan mengurangkan kesilapan pengumpulan data. Masalah utama didalam sistem sedia ada adalah yang berkaitan dengan gangguan atau kelemahan isyarat GPS. Terdapat beberapa faktor yang menyebabkan berlakunya gangguan isyarat GPS seperti terowong, bangunan tinggi, dedaunan yang besar dan gunung yang tinggi. Punca kelemahan dalam isyarat GPS termasuklah isyarat pelbagai arah, kesan tropospheric, perubahan orbit satelit, dan lain-lain. Yang diwakili dalam tesis ini adalah simulasi dan analisis sistem INS dan kesilapan dengan komponen terperinci daripada X-paksi, Y-paksi, dan pecutan Z-paksi dan komponen halaju, dan prestasi INS di Euler angles (pitch, roll, dan yaw) untuk mencari sikap badan tegar. Simulasi dan analisis GPS dengan kesilapan dalam latitud, longitud, dan ketinggian dan juga diwakili di sini. Simulasi trajektori untuk kenderaan pada Banked Figure-Eight trek telah dicadangkan dalam kajian ini. Trajektori ini adalah untuk trek 1500 m dengan 10 m crossover dan kenderaan kelajuan 25 m / s. Perisian MATLAB telah digunakan didalam proses simulasi kajian ini. Pelaksanaan ini juga untuk menunjukkan fungsi autokorelasi kedudukan, halaju dan pecutan dan ketumpatan kuasa spektrum. Simulasi bagi parameter INS dan sistem GPS telah dilakukan dengan menggunakan kaedah integrasi menggunakan APF dan dibandingkan dengan EKF untuk menilai prestasi dan ketepatan. Ia telah menunjukkan satu peningkatan kejitian yang lebih baik. Simulasi Punca min kuasa dua (RMS) bagi ralat kedudukan jam bias dan jam drift dan Kuasa ketumpatan spektral (PSD) telah dikira di sini untuk menunjukkan kesan menggunakan APF penapis untuk mengurangkan ralat berbanding dengan menggunakan EKF. Hasil kajian menunjukkan bahawa sistem bersepadu GPS / INS yang digunakan penapis cadangan APF memberi kejituan yang tinggi serta pengurangan kesilapan berbanding EKF dengan kaedah yang sama iaitu kaedah Deeply-Coupled. Perbandingan kedudukan anggaran dengan kedudukan sebenar di longitud dan latitud telah dijalankan didalam thesis ini. Sistem yang dicadangkan ini boleh diaplikasikan didalam pelbagai bidang awam serta tentera diudara, didarat serta dilautan berdasarkan keputusan kajian yang tepat. Sistem GPS / INS bersepadu telah menjadi penting didalam penyediaan sistem yang kejituan yang tinggi untuk penyelesaian navigasi.

Deeply-Coupled GPS/INS Integration Using Adaptive Prediction Filter

ABSTRACT

Most applications using Global Positioning System (GPS) require constant, highly accurate navigation data with available satellite signals. GPS error sources can lead to reduction in accuracy of navigational information relevant to position, velocity, and attitude. For this reason, the integration of GPS and Inertial Navigation System (INS) produces a high-precision navigation system. In spite of considerable progress in recent years, it is still possible to improve the performance of this integration system. This thesis addressed Deeply Coupled GPS/INS Integration method based on using Adaptive Prediction Filter (APF) to increase accuracy and reliability of navigation data to mitigate effects of data collection errors. The main problem is outage or weakness of the GPS signal. There are several reasons for the outage of GPS signals, such as tunnels, high-rise buildings, urban canyons, heavy foliage, and high mountains. Reasons for weakness in a GPS signal include multipath signals, tropospheric effects, satellite orbit changes, etc. Represented in this thesis are the simulation and analysis of the INS system and its errors with detail components of X-axis, Y-axis, and Z-axis acceleration and velocity components, and INS performance in Euler angles (pitch, roll, and yaw) to find the attitude of a rigid body. Simulation and analysis of GPS with errors in latitude, longitude, and height and also represented here. Simulation trajectory for a vehicle on a banked figure-eight track has been proposed in this research. This trajectory is for a 1,500-meter track with 10-meter crossover and vehicle speeds of 25 meters per second (m/s). MATLAB software has been used to implement simulation in this approach. This implementation also shows the autocorrelation functions of position, velocity, and acceleration along with Power Spectral Density (PSD) errors. A simulation has been implemented for parameters of INS and GPS systems with their errors and integration method using APF by comparison with Extended Kalman Filter (EKF) to evaluate the performance and accuracy to indicate which method have the most improvement. Simulation of Root Mean Square (RMS) position error of clock bias and clock drift and Power Spectral Density has been calculated here in order to demonstrate the impact of using APF filter to mitigate the error compared with using EKF. The results show that the integrated system of GPS/INS, which used the proposed filter APF, performed with high accuracy and mitigated the errors compared to EKF under the same deeply coupled method. Comparison of estimation positions with true positions in longitude and latitude is implemented in plan view in this thesis. The proposed system can be employed in many civilian and military applications, such as air, land, and marine projects, to show reliability and very promising results. The GPS/INS integration system has become a core positioning component, providing high accuracy to navigational solutions.

CHAPTER 1

INTRODUCTION

1.1 Background

The Global Positioning System (GPS) is one of the newest navigation systems that is widely used. The GPS provides all navigational information covering the world at all times. Its working principle depends on satellites and ground stations that feeds necessary navigational information. The GPS is a highly accurate system, while for some time still containing errors because of outages or the reception of weak satellite signals (Bekir, 2007; Grewal, Weill, & Andrews, 2007; McNeff, 2002; Park, 2004). The Inertial Navigation System (INS) is a self-contained navigation technique that provides required navigation information. Its working principle depends on accelerometers and gyroscopes used to track the position, velocity and attitude related to a known starting point. To obtain accurate INS measurements, there should be periodic updated information because the sources drift at low frequencies (Britting, 2010; Grejner-brzezinska, Toth, Sun, Wang, & Rizos, 2008; Hassansin, Taha, Noureldin, & El-Sheimy, 2004; Kayton & Fried, 1997; Woodman, 2007).

For the purpose of obtaining a highly accurate navigation system, GPS is integrated with INS to provide a reliable navigation system that has excellent performance in comparison with either a GPS or an INS system alone. GPS/INS integrated systems occupy a wide range of applications in many civilian and military uses as modern navigation systems. Scientific progress and the achievement of consistently outstanding scientific advances in the field of navigation, control and guidance systems in land, air and marine activities, and the vital role in the development of the use of advanced navigation has reached a high level recently, especially in the areas of airplanes, ships, automobile, and space applications (Godha, Lachapelle, & Cannon, 2006; Jin-ling, Lee, & Rizos, 2003; Rönnbäck, 2000). Such crucial developments require that the navigation systems must be at the same stage of evolution in all applications. System performance in terms of high accuracy in position, velocity and attitude are the most important and basic requirements in navigation systems.

Because of the nonlinearity of the system models, estimation and prediction filtering are exploited in a powerful synergism between GPS and INS. This synergism is possible because GPS and INS have very complementary error characteristics. There are three methods for obtaining a GPS/INS integrated system: Loosely, Tightly and Deeply Coupled. Several approaches have been used for the purpose of these integration methods. The Extended Kalman Filter (EKF) is the most common among them (Ding, Wang, Rizos, & Kinlyside, 2007; Grewal et al., 2007; Siddiqui, 2013; Qian Zhang & Li, 2014). In spite of development that has occurred in the integration systems by using EKF, there is still room for enhancement of the performance of a system for high accuracy and reliability of navigation solutions and for reduction of error to the least possible amount.

The Deeply Coupled GPS/INS integration method utilizing Adaptive Prediction Filter (APF) is proposed in this thesis. MATLAB software is used to implement simulation in this approach. The proposed simulation trajectory is of a vehicle on a banked Figure-Eight track. Results obtained for both approaches by using EKF or APF will be compared in order to find out the accuracy of each one, and how they can be improved.

1.2 Problem Statement

Most important of the problem statements associated with using a GPS/INS navigation system is outage or weakness of the GPS signal, which is the cause of reduction in accuracy of navigational information. There are several reasons for the outage of GPS signals such as tunnels, high-rise buildings, urban canyons, heavy foliage and high mountains. The reasons for weakness in the GPS signal include multipath signals, tropospheric effects, satellite orbit changes, etc.

Many researchers have used the deeply coupled GPS/INS integration method with a utilized EKF filter in their studies, which is the optimization approach to address this problem and has been especially popular in the past few years (Edwards, Clark, & Bevly, 2010; Kennedy & Rossi, 2008; Markus Langer & Trommer, 2014; Petovello & Lachapelle, 2006; Yang, Zhou, Nies, Loffeld, & Knedlik, 2013).

In this thesis the APF approach has been proposed for enhancement of a deeply coupled GPS/INS integration to increase accuracy and reliability of the navigation solutions and to mitigate the errors within the parameters of navigation systems for position, velocity and attitude. Hence, this new approach has the further advantages of enhancing the excellent features of the GPS/INS integrated system with the simple design of an APF filter, and the exploitation of the integration system elements that are required to utilize a simple design and produce low cost in the manufacturing process.

1.3 Research Objectives

The main objective of this work is to enhance a deeply coupled GPS/INS integration using APF filter and validate a novel approach to provide high accuracy and reliability of these navigation parameters: position, velocity, and attitude. The objectives of this research can be summarized as follows:

1. To implement a simulation for parameters of INS and GPS systems with their errors to evaluate the performance and the accuracy.
2. To enhance a deeply coupled GPS/INS integration method by using APF and compare with EKF to analyze the proposed method.
3. To propose a trajectory for a vehicle on a banked figure-eight track and compare the accuracy of the GPS/INS system with the true trajectory by using APF and EKF.
4. To implement a comprehensive simulation plan to validate the proposed approaches through computer simulation.

1.4 Scope of Research

In this thesis, a new approach is presented to increase the accuracy and reliability of the navigation systems by mitigating errors resulting from outage or weakness of a GPS signal. This research focuses on a deeply coupled GPS/INS integration system by using an APF filter to orient the system to the desired output and possibly mitigate errors. Performance and accuracy of GPS will be analyzed and evaluated in two cases depending on arrangement of available satellites and accuracy of the system by simulation of error for position, velocity, and acceleration with respect to variance of time and the attitude and fixed rotation rates in Euler angles (pitch, roll, and yaw).

The APF filter proposed in this research utilizes a GPS/INS integration method. Simulation trajectory, which is a vehicle on a banked figure-eight track, will be proposed to evaluate system accuracy. Performance is evaluated by comparing EKF with the true track. Plan view will be implemented to compare simulation position with true position in latitude and longitude.

Finally, a survey of the theoretical background of GPS/INS integration systems using APF to provide high accuracy and readability of the navigation solutions and proposals raised to enhance this issue will be presented in this thesis.

1.5 Thesis Outlines

This thesis consists of five chapters and is organized as follows:

Chapter 1 introduces an overview of a deeply coupled GPS/INS integration system utilizing APF filter and the problem statement that clarifies the motivation of the research. In addition, the objectives of the thesis and the thesis outline are presented.

Chapter 2 describes the literature review of GPS/INS integration navigation systems in detail. First, a general overview of the basic principles of GPS system is presented. In particular, GPS sections, coordinate systems, and system error sources are featured. Then, the INS system, including main features with his components, gyroscopes and accelerometers is described in detail. In addition, the integration methods between GPS and INS are presented, including the deeply coupled GPS/INS integration method that is proposed in the literature. Their main features are described and analysed. Also, a general overview of the other integration methods is presented.

Chapter 3 describes the methodology of the current research. The chapter focuses on addressing the deeply coupled GPS/INS integration approach and suggests utilizing the APF filter instead of EKF to mitigate effects of data collection errors resulting from outage or weakness of the GPS signal. In addition, MATLAB software is presented to simulate INS and GPS with their errors, as well as mathematically analyse the methods and present their corresponding algorithms in detail. Furthermore, simulation of the comparison between APF and EKF is presented.

Chapter 4 discusses and evaluates the performance analysis results of the proposed approaches through the simulation trajectory of a vehicle on a banked figure-eight track. Comprehensive simulation is devised in order to simulate the integration technique using APF filter in position, velocity, and acceleration and in Euler angles, and to evaluate the efficiency of these results. In addition, results of APF and EKF with true trajectory are compared. Moreover, plan view for comparing simulation positions with true positions in longitude and latitude is illustrated.

Chapter 5 summarizes the important concepts in the research together with the contributions, conclusions, and future work.