Chapter 1
Introduction

Estimation is the process of deriving the variables of interest, often referred to as state variables in a system model, “optimally” from observations or measurements that include noise [1]. A state estimate is optimal if it minimizes errors statistically between actual measurements and estimated measurements based on the estimated states. Application of Kalman-filter-based estimation methods requires mathematical models of the dynamics and measurements of the system under consideration. Dynamics models describe the time evolution of the states to be estimated, possibly with noise driving terms, and measurement models express measurement as functions of the states to be estimated and noise.

State estimation methods are used in a broad range of application areas encompassing tracking, trajectory determination, navigation, guidance, control, signal processing, and communications [1]. State estimation has had a profound impact in the areas of aerospace vehicle guidance, navigation, control, and tracking. These applications include missile tracking, orbit and attitude determination of satellites, navigation using the Global positioning system (GPS), integration of GPS/inertial navigation system (INS), and much more.

This thesis consists of three separate applications of state and parameter estimation methods to the areas of satellite navigation, vehicle attitude determination, and GPS receiver development. Each application is described in separate chapters. Chapter 2 describes magnetometer-based autonomous orbit determination, Chapter 3 reports experimental tests of attitude determination using a GPS antenna on a turntable, and Chapter 4 describes extended Kalman filter (EKF)/Smoother-based semi-codeless dual-frequency P(Y) tracking algorithms for weak GPS signals during strong ionospheric scintillations. The estimation methods that are used in these applications are batch filtering, extended Kalman filtering (EKF), and smoothing.

A batch filter estimates a static vector of parameters that minimizes a least square cost function, which is the sum of weighted squared errors between actual measurement and estimated measurements based on the estimated parameters. A batch filter processes an entire measurement data set and normally does not consider process noise effects on a system's state. Often the estimated parameters include initial conditions of a system whose dynamic model is assumed to be known exactly, at least in mathematical form. Model errors, in included, may be represented parametrically, and these unknown parameters may constitute additional estimated quantities.

An extended Kalman filter (EKF) is the extension of Kalman filter (KF) to non-linear system using linear approximations about estimates. A KF is a recursive optimal estimation method which estimates variables at a given time based on past and current measurements. It is recursive because it does not need to process all previous data whenever new measurement is available. Instead, a KF stores its best estimate of the state and the associated estimation error covariance based on all previous data. It estimates the state and the estimation error covariance using the next available measurement using only that new measurement and its most recent state estimation and estimation error covariance matrix. The recursive nature of the KF allows it to be applicable in real-time. A KF is the optimal solution to a linear/Gaussian estimation problem that considers process noise in its state dynamics model along with measurement noise.

A smoother algorithm is a variant of the KF that estimates states at given time using past, current, and future measurements. Since a smoother uses more data than a KF, its estimate is more accurate than that of a KF. It is, however, applicable only in non-real time because it processes future measurement to derive the estimate at a given time. Thus, a smoother is normally used only in an off-line setting.

The three separate applications of estimation methods in this thesis have the following motivations and goals.

The first application is magnetometer-based autonomous orbit determination. A magnetometer is a cheap and reliable sensor that is included on many spacecraft missions. It holds the possibility of fulfilling all attitude and orbit determination needs autonomously, which can lower the mission costs. Magnetometer-based attitude determination is a fairly mature field, but typical magnetometer-based orbit determination systems have a position accuracy from 8 km to 125km [2-6]. One of the biggest error sources is the uncertainty in the Earth's magnetic field [3]. The field model, however, can be corrected using data from a magnetometer along with data from an additional attitude sensor such as a 3-axis star sensor data [7] or a sun-sensor [8]. The current study applies the field-model-correcting magnetometer-based orbit determination filter which uses magnetometer and sun-sensor data and estimates orbit and field-model correction terms. The main goal of this research is evaluate the efficiency of this field-model-correcting filter with real flight data.

The second application is that of attitude determination using a GPS antenna on a turntable. Standard GPS attitude determination systems use interferometric measurements of the carrier phase difference between multiple antennas. Psiaki [9] suggested a single GPS antenna mounted on a rotating turntable for attitude sensing as a way of reducing the number of GPS antennas and receiver channels needed for attitude determination. In addition to the advantage of fewer antennas and fewer receiver channels, this method eliminates the need to resolve integer phase ambiguities between different antennas. The new GPS attitude sensor estimates the sinusoidal phase modulation of the GPS carrier signal due to the turntable rotation. The amplitude and phase of this carrier phase modulation can be tracked with modified phase-locked-loop. These amplitude and phase measurements provide an estimate of the unit direction vector to the tracked GPS satellite as measured in turntable coordinates. If two or more independent GPS satellites are tracked using this system, then it provides enough information to determine 3-axis attitude of the turntable. The main contributions of this study are to develop a prototype of this attitude sensor, to develop attitude estimation algorithms that are appropriate to using its data to determine 3-axis attitude, and to experimentally test this system's performance.

The third application is the development of EKF/Smoother-based semi-codeless dual-frequency P(Y) tracking algorithms for weak GPS signals. These are needed for tracking dual-frequency signals during strong ionospheric scintillations because of the deep power fades that are characteristic of these space weather events. The GPS signal has two carrier frequencies, one called L1 and the other called L2. The L1 signal carries a known civilian C/A pseudo-random number (PRN) code and an encrypted P(Y) PRN code, and the L2 signal carries only the encrypted P(Y) code. Tracking of the L2 signal by a civilian receiver is difficult due to the encrypted P(Y) code. One set of methods for tracking the P(Y) code on L2 are called semi-codeless methods. They use the known chipping rate of the unknown encryption chips, which is 480 kHz on average. Semi-codeless methods perform better than codeless methods which do not use any assumption about the encrypted code except that it is the same on both frequencies.

When there are strong ionospheric scintillations, codeless and semi-codeless P(Y) tracking receiver tend to lose lock easily. This is undesirable because important science data could be recovered if a dual-frequency receiver could maintain lock in such situations. Therefore, a pair of new EKF/Smoother-based semi-codeless tracking algorithms are developed to track weak dual-frequency GPS signals during strong ionospheric scintillation. The new tracking algorithms are optimal algorithms that use an a posteriori cost function with -log[cosh()] terms, which allow smooth transition between various encrypted bit decision techniques, such as squaring, cross-correlation, soft W-bit estimation, etc.

The primary goal of this last study is to develop these new tracking algorithms and test their performance to see whether these algorithms are less prone to lose lock during scintillations than are other semi-codeless P(Y) tracking algorithms. The algorithms have been tested with real dual-frequency GPS data with normal signal strengths and dynamics and with simulated scintillation data which includes deep power fades and rapid phase variations.

References

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