A Numerical Study of Low-cost Wind Velocity Estimation using Extended Kalman Filter and Tethered, Spherical Helium Balloon

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Abstract

The objective of this work is to investigate the feasibility of low-cost wind-characterization using an inertial measurement unit (IMU) attached on a helium balloon. The balloon system acts as a measuring instrument for wind characterization. The wind velocity and direction are to be determined using only a standard set of on-board sensors (i.e., accelerometers, gyroscope, thermometer, and barometer). An Extended Kalman Filter (EKF) technique is implemented with the formulation of equations of motion describing the dynamics for the spherical balloon configurations (i.e., slung motion and free motion). The ability of the system to capture both a low frequency component and a turbulence component (i.e., high frequency variations) is determined. The effects of design parameters (such as balloon size and sensing errors) are investigated and analyzed with the use of numerical simulations. The feasibility of low-cost wind-characterization is found for the wind with a frequency lower than 0.05 Hz. It is found that the limitation is due to the error of gyroscope.

Keywords*:* Extended Kalman Filter, Wind Characteization, Estimation.

1. Introduction

Wind information can be crucial for many applications. Especially in the wind turbine applications, wind data can be used to optimize the design of wind turbine blade and structure as well as enable an improved fatigue-life modeling which could increase turbine lifetime and reduce costs at the same time. Since the variation of the wind speed is highly depended on the area and on the atmospheric conditions, corresponding wind information is required to be measured on-site and for a long period of time. To obtain wind information for a desired height in a specific area, many conventional methods (e.g., meteorological mast, weather station, tethered balloon, etc.) are available to be used. However, these conventional methods mostly require expensive structure, equipment, and sensors.

The fundamental objective of this study is to investigate the feasibility of using a tethered balloon with a standard, low-cost sensor set as a wind measuring instrument. The dynamic behaviors of a tethered helium balloon installed at desired height are interpreted for wind characterization. A standard set of on-board sensors (i.e., accelerometers, gyroscope, thermometer, and barometer) is installed on the balloon to capture the balloon dynamics for the wind characterization process. The extended Kalman Filter (EKF) technique is implemented to estimate the wind velocity corresponding to the sensor measurements. In this study, numerical simulation is utilized to determine the feasibility of low-cost wind-characterization using IMU on a tethered balloon and show the effects of design parameters. In this paper, the effect of balloon size and sensing errors in the wind characterization are focused. The following sections first describe the details of simulation models and the wind estimation model (EKF). Then, the discussion on numerical results and conclusion are presented.

2. Simulation Models

In this study, the physic behaviors of wind speed and tethered balloon motion are represented using mathematical models. An EKF with an imperfect model of the tethered balloon in the present of wind is then formulated.

2.1 Van der Hoven Spectrum Wind Model

The Van der Hoven Spectrum method divides the wind speed into two components; a low frequency component which presents slow variations in wind speed and a turbulence component which presents fast, high frequency variations. Figure 1 shows the Van der Hoven spectral model of wind speed in [2] which identifies the two components. The model also considers the turbulence component as a zero