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Hybridized attitude determination techniques to improve ballistic projectile navigation, guidance and control

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A B S T R A C T

Ballistic projectiles accuracy depends on measurement systems for position and attitude determination. Precise rotation determination is an expensive task in aircraft, as it is usually determined by strap-down sensors such as fiber optic gyros or MEMS. Particularly in ballistic projectiles, these gyro determination devices increase their price as they need to bear enormous accelerations during the initial stages but not during the ballistic flight. A new approach to improve ballistic projectile navigation, guidance and control, which integrates hybrid attitude determination methods and gravity vector estimation method, is presented in this paper. Measurements of accelerometers, GNSS-sensors and Semi-Active photo-detectors are hybridized to get such a result. The attitude determination method, avoiding the use of gyroscopes, measures pairs of vectors, i.e., gravity, velocity and line of sight vectors, in a pair of reference systems, i.e., body fixed and north–east–down reference frames. Gravity vector estimation is based on flight mechanics and aerodynamics of a ballistic projectile, which involves a deeply nonlinear behavior, but it may be extrapolated to any aircraft, and later employed in an attitude determination algorithm. Modified proportional navigation techniques and previously developed control methods are employed during flight. The presented approach is tested on a realistic nonlinear model flight simulations to prove accuracy of proposed algorithms.

1. Introduction

Precision on attitude calculation is one of the key-points of navigation guidance and control. The effectiveness of guidance and control is determined by the degree of precision of navigation systems, including inertial measurement units [1]. There is an extensive body of literature regarding attitude estimation using various sensor inputs in order to be employed in the Guidance, Navigation and Control (GNC) systems [2].

Accurate attitude values, in order to be implemented on GNC algorithms, are usually determined by expensive and/or weighty units, such as a combination of laser or fiber optic gyroscopes and accelerometers, or their MEMS equivalents, which usually are not prepared to bear the high mechanical solicitations required during the first launching stages of a ballistic projectile, (which might be higher than 1000 Gs for a shell projectile) [3]. This fact, forces to develop ad-hoc attitude measurement equipment to be employed on these applications, and to take many precautions on laser or fiber optic gyroscopes design, as these parts are especially delicate. Moreover, when high-demanding maneuvers are performed, this equipment may become extremely expensive. This problem becomes even more important when the vehicle cannot be reused. A complete design concerning the guidance and autopilot modules for a class of spin-stabilized fin-controlled projectiles is presented in [4]. Obviously, accuracy requirements usually cannot be satisfied by using inexpensive sensors [1]. Some applications for road vehicles proposing an innovative integrated Kalman filter (IKF) scheme to estimate vehicle dynamics, in particular the side-slip, the heading and the longitudinal velocity have been developed in [5]. Moreover, complex algorithm development as linear closed loop guidance laws employing optimal control laws [6], might be implemented.

Development of valid inexpensive attitude determination systems is the cornerstone for these non-reusable aircraft applications. For example,[7] develop an inexpensive Attitude Heading Reference System for general aviation applications by fusing low cost automotive grade inertial sensors with GPS. The inertial sensor suit consists of three orthogonally mounted solid state rate gyros. [8] describe an attitude estimation algorithm derived by post-processing data from a small low cost Inertial Navigation System (INS) recorded during the flight of a sub-scale commercial

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off the shelf UAV. Estimates of the UAV attitude are based on MEMS gyro, magnetometer, accelerometer, and pitot tube inputs. [9] describe an attitude determination system that is based on two measurements of non-zero, non-co-linear vectors. Using the Earth's magnetic field and gravity as the two measured quantities, a low-cost attitude determination system is proposed.

The main problem to employ the previously described fusion of sensors, is the difficulty to integrate them on the reduced available space on a ballistic projectile. Also, the interferences created by electronics on magnetic field or the impossibility of integrating a pitot tube in the projectile are key problems. These facts, combined with the low-cost requirements and the high solicitation demands, practically obliges to only integrate on the projectile GNSS sensors, accelerometers, and eventually a quadrant photo-detector sensor.

Low-cost GNSS receivers and antennas can provide a precise attitude and drift-free position information, but accuracy is not continuous as it is stated by [10]. Moreover, their availability and reliability has become a subject of concern for all kind of applications as they might be affected by jamming signals. Global Positioning System (GPS), are used throughout the world but the availability and reliability of these signals in all environments has become a subject of concern for both civilian and military applications [11]. Inertial sensors are robust to GNSS signal interruption and very precise over short time periods, which enables a reliable cycle slip correction, but low-cost inertial sensors suffer from a substantial drift. [10] propose a tightly coupled position and attitude determination method for two low-cost GNSS receivers, a gyroscope and an accelerometer. They obtain a heading with an accuracy of 0.25°/baseline length [m] and an absolute position with an accuracy of 1 m.

Furthermore, INSs cannot be jammed. The major error sources in the inertial navigation system are due to gyro and accelerometer sensors deficiencies, incorrect navigation system initialization, and imperfections in the gravity model used in the computations. If other sensors are available, they may be additional inputs to a filter, such as the Kalman filter. Multi-sensor systems are very powerful in the complex environments [12]. Therefore, they are excellent source of navigation information to be integrated with GNSS receivers [3]. Similar developments may be found within space vehicles, for example in [13].

In [14] the use of an INS and a multiple GPS antenna system for attitude determination of an off-road vehicle is developed, and in [15], it is stated that attitude determination using GPS carrier phase has been applied successfully to aircraft in experiments by a number of researchers. But reliability on these methods is not applicable on projectile attitude determinations due to the high rotating speeds, the reduced available space and the cost limitations because of the no-re-usability principle.

Traditional GNSS/IMU hybridizing systems provide acceptable solutions for ballistic projectiles. For those systems, the Circle Error Probable (CEP) is around 10–20 m for the best cases [3]. In order to lower costs, the replacement of inertial attitude determination systems with less accurate systems is proposed; this is done integrating a system such a quadrant photo-detector which may be employed on terminal phase. In [16] a new approach to estimate the orientation of a quadrotor using single low-cost inertial measurement unit (IMU) sensor is presented. The benefits of integrated data fusion have been demonstrated across the spectrum of antisubmarine, tactical air, and land warfare [17]. The benefits and issues in using different types of INS augmented with GNSS updates have been studied by many authors [18,19]. If other sensors are available, they may be additional inputs to a filter, such as the Kalman filter.

Note that in typical GNSS/IMU integrated navigation systems, there exist unknown disturbances and abnormal measurements, which are of key importance during terminal guidance. This fact encourages the need of a precise, but low-cost last phase sensor such as quadrant detector. For example, [20] present a novel imager-based guidance and control algorithm for small-diameter spin-stabilized projectiles. And [21] design a missile target tracker using a filter/correlator based on forward-looking infrared sensor measurements. Semi Active Laser Kits (SAL), and particularly quadrant detector devices, have been developed in order to improve precision in guided projectiles. Quadrant photo-detectors have been applied in many engineering ambit, such as measurement, control, laser collimation, target tracking, and particularly in ballistic rockets terminal guidance [22]. One of the greatest advantages of quadrant detector equipment is the high performance provided in terms of guidance, typically in the last stages of the trajectory, as compared to the low cost incurred.

The aim of this paper is to introduce a novel attitude determination method, avoiding the use of classical rotation determination methods through gyroscope measurement integration, and substituting them by determination of pairs of vectors (gravity, velocity and line of sight) expressed in two different reference frames (body fixed and north–east–down). These vectors will be estimated by combining the measurements of accelerometers, GNSS-sensors and Semi-Active photo-detector and hybridizing them by a Kalman-like filter. Gravity vector estimation is presented, based on the flight mechanics of a ballistic projectile, which may be extrapolated to any aircraft by changing the aerodynamic characteristics. An improvement in the understanding of maneuvering flight and reduce aerodynamic uncertainty of guided munitions to compress the iterative design cycle and realize enhanced maneuverability vehicles is described in [23]. Some other projectile and missile control methods based on aerodynamic parameters are discussed on [24], where the control objective is to track a reference angle of attack command signal in the presence of external disturbance and aerodynamic coefficient uncertainty with desired performance; and [25], where using proportional navigation (PN) and considering the aerodynamic characteristics of the missiles, a new law leads to a better performance than the PN law. Based on missile proportional navigation, [26] presents the unified cooperative strategies for the salvo attack of multiple missiles on the basis of the traditional proportional navigation (PN) algorithm.

The results of the hybridization are employed on a previously developed modified proportional navigation technique and control method for a ballistic spinning rocket [3]. Some other models for rockets and missile under thrust conditions are presented in [27]. Non-linear flight simulation models are developed in order to prove accuracy of the proposed algorithms.

The main **contributions** of this paper are the development of a new algorithm which substitutes gyroscopes in favor of lower cost sensors for attitude determination and the employment of an estimation method in order to obtain the gravity vector in body axes, which is only based on the aerodynamic parameters of the cell and the measurements provided by accelerometers. The objective is to get simplicity in attitude sensors and even to increase precision by applying filtering techniques, especially for artillery device purposes, where high solicitation acceleration conditions increase the price of precise attitude determination devices such as gyroscopes. In order to get high precision at impact points, multiple sensors are employed and a hybridization algorithm is employed and is based on based on an EKF hybridization which determines the terminal line of sight to be used on a modified proportional navigation law and on a rotatory control technique. The proposed control approach is based on a robust double-input double-output controller. This controller is able to handle the heavy coupling between the normal and lateral rocket nonlinear dynamics.

The use of a flight mechanics model, which takes in account the non-linearity in aerodynamic forces and moments, with the final goal of develop a realistic simulation campaign to reproduce