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Unmanned Aerial Vehicle Attitude Determination Strategies: A Review

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Abstract

The attitude of an unmanned aerial vehicle is a very important flight parameter that needs to be known at every time during its flight. Throughout the ages, as technology has evolved, different approaches have been applied to determine this quantity. These approaches have often made use of an angular velocity source, linear acceleration information or magnetic field measurements. In this study, we present a review of these techniques, covering single- and multi-sensor approaches, deterministic and optimal strategies, as well as filter-based approaches. In the end, a method for deriving the attitude as is carried out in the present is suggested.

Keywords: *Unmanned aerial vehicle, attitude estimation, Euler angles, quaternion, Kalman filter.*

1. INTRODUCTION

Unmanned aerial vehicles (UAVs), popularly known as drones, refer to aircraft that fly without an onboard pilot [1]. They have proven to be very useful in several scenarios including surveying and mapping, package delivery, surveillance, precision agriculture, and recreation, not forgetting military uses such as intelligence gathering, target acquisition and warhead delivery [2].

The attitude of a UAV refers to its orientation with respect to a given reference frame [3]. Perhaps, the first parameters associated with vehicle attitude are *Euler angles;* these refer to the rotations necessary to bring the navigation frame into coincidence with a body-fixed frame [4]. But, several other representations of attitude are used as well, and include coordinate transformation matrices and quaternions, each possessing a particular significance related to the specific application.

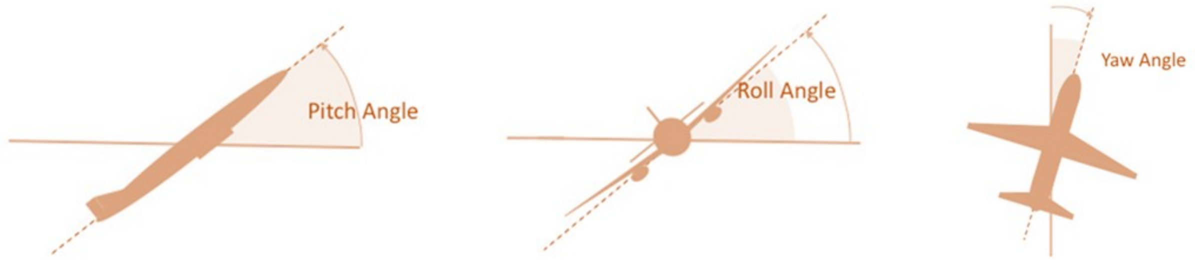

Figure 1. Aircraft attitude expressed as roll, pitch and yaw angles [3,4]

Knowledge of the attitude of an aircraft is important because it is necessary to make changes to this parameter in order to alter the flight path of the vehicle [5, 6]. Thus, in essence, an awareness of the aircraft's orientation is obtained, and then it can serve as an input to automatic control systems (autopilots) which are used (even more so) in unmanned aerial vehicles. Most UAVs come with a sensor suite that usually includes accelerometers, gyroscopes and magnetometers in addition to a global navigation satellite system (GNSS) sensor. Several techniques have been applied to determine vehicle attitude using information from these sensors. We present a summary of these methods from the literature.

2. SINGLE-SENSOR APPROACHES

Schuler, et al. [7] described methods that could be applied to determine the angular velocity of a vehicle using linear accelerometers only. They presented five different configurations from which both the angular and linear motion of the vehicle could be determined. Their systems consisted of a minimum of six accelerometers which could be placed on an axis system that could either coincide with the vehicle's centre of mass or be displaced from it. They derived equations based on the motion of the vehicle relative to inertial space. Placing the accelerometers strategically ensured that the linear and angular motions were coupled. From this it was then possible to determine both the linear accelerations and angular velocities required to determine the attitude. Larsson [8] developed a system that could be used to measure the thrust of a small satellite. A side function of his system was its use to determine the attitude of the satellite. His system used a dual gyroscope configuration which he arrived at after several simulations of the spacecraft attitude and thrust configurations. GNSS-sensor-only based attitude determination has also been studied by several researchers including [9, 10, 11]. The technique involves the transformation of differential carrier phase measurements from multiple antennas at fixed locations on the aerospace vehicle into attitude estimates, using the optimal strategies presented later in Section 2.2.

3. MULTI-SENSOR APPROACHES

It is possible to determine the attitude of the UAV using observation and reference vectors from two or more sources [12, 13]. This section recounts applicable strategies.

3.1 Deterministic Algorithms

Lerner [14] presented a method for determining the attitude of spacecraft using vector information from two sources, for example a sun sensor and a magnetometer, provided in two coordinate frames, usually the spacecraft body frame and a reference frame. His algorithm, popularly known as TRIAD (TRIaxial Attitude Determination) computes the rotation matrix which transforms the (non-parallel) vectors from the reference frame to the body frame. Some information derived from the vectors is inherently discarded in the computation and hence there is the need for scalar validation of the attitude result.

Natanson, et al. [15] provided a means for determining spacecraft attitude using magnetometer data only. In order to do this, it was necessary to calculate the derivative of the magnetic field vector. Using these two, and the angular velocity derived from a gyroscope, it was possible to uniquely determine the attitude of the spacecraft using Lerner's TRIAD algorithm. The finite differencing approach was used to determine the derivative in his case. If it was desired to determine the attitude from magnetometer data only, it was required that the second derivative of the magnetic field vector be computed; also, knowledge of the angular acceleration was necessary, which could be obtained from the equations of motion of the spacecraft. This second method is usually referred to as the DADMOD (Deterministic Attitude Determination using Magnetometer Only Data) method.

Searcy [16] followed Natanson, et al. [15] closely, utilizing the same measurements, but employing a Kalman filter and magnetometer measurements to estimate the magnetic field and its derivatives. He went ahead to incorporate the spacecraft equations of motion, which were required to determine the angular acceleration, assuming that all control torques were known.

Shuster & Oh [17] elaborated on the TRIAD algorithm, providing an improvement in the determination of the attitude covariance matrix. They proposed a method that yielded the error angles relative to the spacecraft body axis, rather than that derived from the Euler angles. They went on to derive the latter, and showed the relationship between the two methods, highlighting the advantages of the former.

Li, et al. [18] implemented an attitude determination system using GPS, magnetometer and inertial measurement unit data. They employed an infinite impulse response differentiator to obtain vehicle acceleration from GPS data. Using this information, and together with magnetometer measurements they employed the TRIAD algorithm to compute attitude.

de Celis & Cadarso [19] also tackled the attitude determination problem. Their solution was the use of accelerometers and a GPS sensor. They followed the conventional TRIAD algorithm using as one set of inputs the velocity of the vehicle derived from GPS and integrated accelerometer data, and the gravity vector as the other. Their method made extensive use of the vehicle's dynamics.

Ellum & El-Sheimy [20] followed de Celis & Cadarso [19] closely, using also a GPS sensor and a tri-axial accelerometer. They determined the gravity vector by fusing GPS acceleration and accelerometer data. From this, they calculated the pitch and roll angles of the vehicle. In order to obtain the azimuth angle (heading), they made use of the velocity vector derived from the GPS measurements.

Many other researchers including [21, 22] have proposed modified deterministic algorithms for determining the attitude of aerospace vehicles. These have provided simplified means of determining the attitude matrix (or quaternion) to similar accuracy as the classical methods, although with reduced computing burden.

3.2 Optimal Methods

Optimal algorithms that may be applied to determine aerospace vehicle attitude have been proposed by several authors. They are mostly based on the derivation of attitude that leads to the minimisation of a loss function. The loss function usually used is that proposed by Wahba [23]. This function produces a least-squares estimate of the rotation matrix which transforms between two sets (one in the vehicle-fixed frame and the other in a given reference frame) of any number of observations.

Farrell, et al. [24] derived solutions for Wahba's problem based on matrix theory. Equations for determining the rotation matrix were presented, and these differed slightly depending on the value of the determinant of the matrix formed by multiplying out the observation and reference matrices. Their algorithms allowed the use of more than just two vector sets.

Davenport [25] went on to provide another solution to the least squares attitude determination problem. His approach was the use of vectors derived from the angle and axis of rotation as the basis for the determination of the attitude matrix.

Keat [26] built upon Davenport's work. He described a new method for determining the least-squares attitude in the form of a quaternion. This quaternion is the eigen vector corresponding to the largest eigen value of a symmetric matrix derived from the observation and reference vector sets.

Shuster [27] also worked on deriving the optimal quaternion that transformed a set of reference vectors to their observations. Building on Davenport's work, he provided new ways of determining the quaternion that circumvented the traditional way of finding the eigen vectors, leading to improvements in computation time. He also presented approximations that could be used, for example, in the case of small rotations, all aimed at ensuring fast, real-time computation of the attitude solution. Several other authors such as [28, 29, 30, 31, 32] have contributed to the solution of the least-squares attitude estimation problem, suggesting modifications that simplify the process of solving for the attitude matrix (or quaternion).

3.3 Kalman Filter-Based Methods

The Kalman filter, discovered by Kalman [33] has been explored by many authors concerned with the attitude determination problem. It is usually employed together with information obtained from one of the former methods. Theil, et al. [34] and Humphreys & Fullmer [35] worked on attitude determination systems for small satellites. They used data from sun sensors and magnetometers as measurements in an Extended Kalman Filter to aid the satellite equations of motion, using the angular rates and attitude quaternion components as state vector. Wondosen, et al. [36] designed a system for determining UAV attitude using a gyroscope, accelerometer and magnetometer. They determined roll and pitch attitude from the accelerometer and gyroscope readings and heading from the magnetometer readings. They implemented an extended Kalman filter, using a double quaternion as the state vector, effectively separating the determination of pitch and roll attitude from heading. They also employed disturbance rejection with the magnetometer in order to improve the heading accuracy.

Patonis, et al. [37] developed a system for determining the attitude of a mobile device, such as a smart phone. They made use of the Euler-Cardan angles and rotation matrix representations in their work. They implemented an extended Kalman filter that carried out attitude fusion in two steps: accelerometer-gyroscope fusion and magnetometer-gyroscope fusion. Lee, et al. [38] in addition to estimating attitude using a Kalman filter, presented a method for estimating the external acceleration of the vehicle in order to improve the attitude estimation during periods of increased dynamic activity. Wang, et al. [39] and Euston, et al. [40] implemented complementary filters to solve the attitude estimation problem. Their systems consisted of tri-axial accelerometers and gyroscopes. Their goal was to get the best of two worlds with low frequency estimates coming from the accelerometers and high frequency estimates from the gyroscopes. Valenti, et al. [41] developed a quaternion-based attitude determination system useful for inertial and magnetic sensors. They made use of a complementary filter and split the determination process into that for the pitch and roll attitude and heading. Their approach was to determine the quaternion directly from the sensor observations without resorting to direction cosine matrices or Euler angles. The Kalman filter, and modifications thereof have continued to be applied to the attitude determination problem by authors such as [42, 43, 44, 45, 46, 47]. Each one proposes slight improvements, using different sensors and/or state vectors, seeking to minimise the estimation error.

4. SUGGESTED APPROACH

A typical approach applied to determine the attitude solution of a UAV at present is now described. The accelerometer and magnetometer provide vehicle acceleration and components of the earth's magnetic field, respectively, in the body frame. Acceleration in the reference (local geographic) frame is obtained by differentiating GNSS velocity measurements, using for example, Al-Alaoui's filter [48]; whereas the earth's magnetic field in the reference frame is obtained from a model such as that provided by Chulliat, et al. [49]. This information is used to derive the attitude quaternion using the algorithm proposed by, for example, Mortari [32]. In order to make use of measurements from the gyroscope, a Kalman filter [50] is implemented. The state vector is the attitude quaternion, and the process model is driven by the gyroscope. The measurement is provided by the attitude quaternion obtained from the magnetometer and accelerometer and is used to correct gyroscope drift [51].

4.1 Attitude Determination Example

The suggested approach was applied to data provided by Laidig, et al. [52], and the output compared to that obtained by using MATLAB's *ahrsfilter* object on the same. For the

"02_undisturbed_slow_rotation_B" dataset, root-mean-square error values of 0.23, 0.32 and 4.84 degrees were obtained along the roll, pitch and yaw channels, respectively.

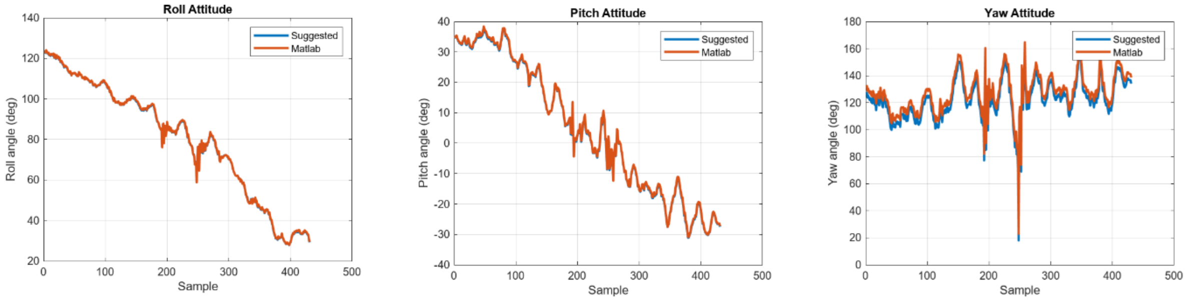

Figure 2. Sample attitude [52]

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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