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Attitude determination method using single-antenna GPS, Gyro and Magnetometer

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Abstract

In this paper, we propose the attitude estimation algorithm integrating SAGPS (Single Antenna GPS), Gyroscope and Magnetometer. Pseudo-attitude from SAGPS has low output rate and time delay property. And it differs from actual attitude according to flight condition of airplane because it is based on velocity measurements of GPS. We adopted gyroscope and magnetometer to improve attitude accuracy and output rate of the pseudo-attitude. For validation of the algorithm, simulation is performed and flight data of small UAV is post-processed and compared with commercial AHRS.

Keywords: Attitude, SAGPS, Magnetometer

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1. Introduction

Today's attitude determination algorithm for AHRS (Attitude and Heading Reference System) mostly depends on inertial sensor. MEMS inertial sensors are getting cheaper and its performance is getting higher. It is very useful for small and economical system such as small UAV or MAV system. D. Gebre-Egziabher proposed constitution of AHRS system using MEMS sensors [2]. This method gives good performance in stable and low dynamic maneuver condition. However, its performance is getting erroneous in constant turning or high dynamic maneuver condition because accelerometer cannot divide its measurement to gravity and body acceleration.

There are several attitude determination algorithms using GPS. Among them, SAGPS (Single-Antenna GPS) attitude determination algorithm which was proposed by R. P. Kornfeld is simple and stable method for fixed-wing aircraft [4]. This method provides pseudo-attitude which is differ from true attitude slightly and its output rate is quiet low compared to AHRS algorithms using inertial sensors. In spite of these aspects, S. Lee and A. Cho successfully conducted fully automatic control of UAV from takeoff to landing and proved its usefulness [1], [5].

After that, we proposed integration of SAGPS and gyroscope [3]. This integration resolves low output rate and time delay of SAGPS algorithm. But it is still providing pseudo attitude. In this paper, we propose additional integration of magnetometer to resolve attitude accuracy. And its derivation, simulation and experimental result will be provided.

2. Pseudo Attitude

2.1 SAGPS algorithm

SAGPS algorithm is proposed by R. P. Kornfeld [4]. This algorithm determines attitude of fixed-wing aircraft using velocity measurement of Single-antenna GPS receiver. Determined attitude is called pseudo attitude because it is differs from true attitude slightly. Its pseudo pitch angle is equal to FPA (Flight Path Angle) and its pseudo yaw angle is equal to angle between true north and ground velocity vector. In normal cruising condition, we can ignore small difference of pseudo attitude. However, its difference is getting larger in low speed landing approach or sharp bank turn. Moreover, measurement output rate of GPS receiver is quiet low (generally 1~10Hz) compared to AHRS based on inertial sensor (generally over 100Hz). It also has significant time delay.

2.2 Integration of SAGPS and Gyroscope

Integration of SAGPS and gyroscope can resolve mentioned low output rate and time delay issues. These issues were discussed in previous work [3].

3. Attitude determination using Magnetometer

3.1 Conventional Accelerometer & Magnetometer method.

In conventional method, roll and pitch angle are determined by accelerometer which measures Earth's gravity vector. And then yaw angle is determined by magnetometer. This method works well in static or low dynamic condition. Accelerometer measures not only gravity vector but also vehicle's body acceleration. Therefore determined attitude is getting erroneous in high dynamic condition.

3.2 Proposed SAGPS & Magnetometer method

The Earth's gravity is vertical to local horizontal plane on the Earth. In contrast, the Earth's magnetic field direction is varies with position on the Earth. NGDC (National Geophysical Data Center) of NOAA (National Oceanic and Atmospheric Administration) provides global magnetic field model. If we know our position, we can calculate magnetic field using this model and attitude can be determined by magnetometer measurements.

- Case of $\phi = 0°, \psi = 0°$

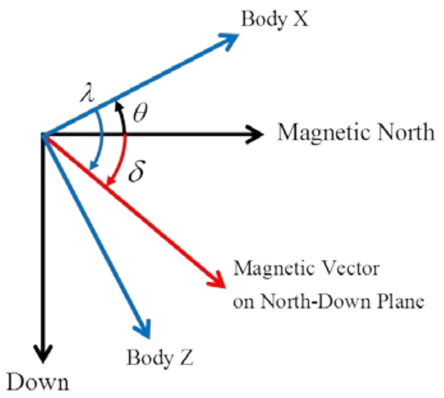

Figure 1. Attitude determination when heading is pointing to magnetic north

$$\theta = \lambda - \delta$$

$$\lambda = \tan^{-1}\left(\frac{H_Z^b}{H_X^b}\right)$$

where (1)

λ : Angle between magnetic vector and body x axis

δ : Magnetic dip angle

H^b : magnetic vector in body frame

$$H^b = \begin{bmatrix} H_X^b & H_Y^b & H_Z^b \end{bmatrix}^T$$

In case of Figure 1, roll angle is zero and heading of vehicle is pointing to magnetic north. In this case, X-Z plane of body frame coincides with magnetic north-down plane. We can measure λ from measurement of magnetometer, H^b. We already know magnetic dip angle, δ from magnetic field model. Therefore we can determine pitch angle, θ subtracting δ from λ.

Figure 2 shows general case. In general case, we need to calculate β and δ_T. Rotate measurements of magnetometer about body X axis, amount of minus roll angle. Then we can measure λ. From magnetic field model, we already know magnetic field vector in NED frame. Rotate magnetic field vector about down axis, amount of yaw angle. Then we can obtain temporary magnetic dip angle, δ_T. Therefore we can determine pitch angle, θ subtracting δ_T from λ in general case.

- General case $(\phi \neq 0°, \psi \neq 0°)$

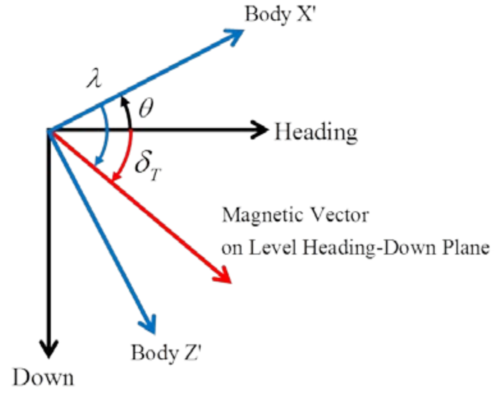

Figure 2. Attitude determination in general case

$$\theta = \lambda - \delta_T$$

$$\lambda = \tan^{-1}\left(\frac{H_Z^{b'}}{H_X^{b'}}\right), H^{b'} = R(1,-\phi)H^b$$

$$\delta_T = \tan^{-1}\left(\frac{H_Z^l}{H_X^l}\right), H^l = R(3,\psi)H^n$$

where (2)

λ : Angle between magnetic vector and body X' axis in body' frame

δ_T : Temporary magnetic dip angle in heading-down plane

H^b : magnetic vector in body frame

H^n : magnetic vector in NED frame

R : Rotation matrix

3.3 Verification

To verify proposed method, we simulated attitude calculation with known attitude and magnetic vector.

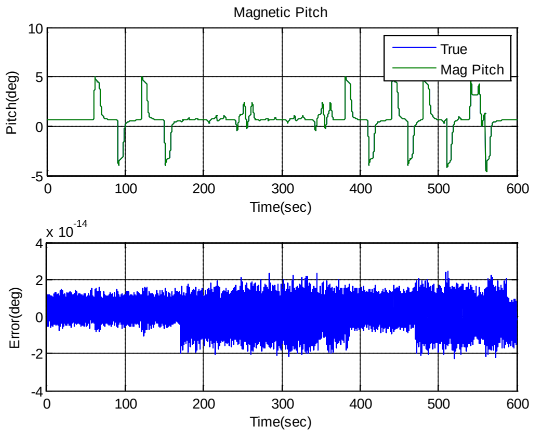

Figure 3.Verification of Magnetic Attitude determination

For magnetic measurement without any error, proposed method determines pitch angle correctly as Figure 3.

4. Implementation of Kalman filter

Implementation of Kalman filter using proposed algorithm is structurally almost similar to previous attitude estimation using SAGPS and gyroscope [3].

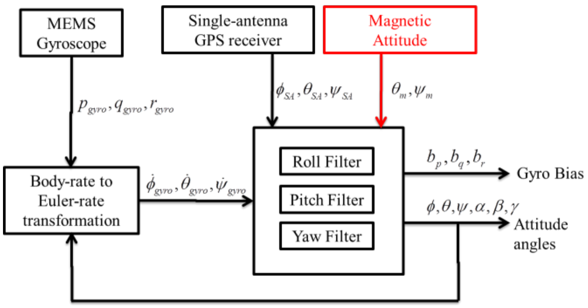

Figure 4. Block diagram of Attitude Estimation

Compared to previous method, proposed method uses magnetic pitch and yaw angle as additional measurement. As a result, we can estimate true pitch angle, not pseudo pitch angle. And we can estimate AOA (Angle Of Attack), side slip angle and FPA (Flight Path Angle) also. According to this change, system state equation is modified like (3)~(5).

$$x = \begin{bmatrix} \phi_{SA} & \phi & \dot{\phi}_{gyro} & b_p \end{bmatrix}^T$$

$$u = \begin{bmatrix} 0 \\ -\sin\phi \cdot \tan\theta \cdot b_q - \cos\phi \cdot \tan\theta \cdot b_r \\ 0 \\ 0 \end{bmatrix} \quad \textbf{(3)}$$

$$\dot{x} = \begin{bmatrix} -1/\tau_\phi & 1/\tau_\phi & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} x + u + w$$

$$z = \begin{bmatrix} \phi_{SA} & \dot{\phi}_{gyro} \end{bmatrix}^T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x + v$$

$$x = \begin{bmatrix} \gamma_{SA} & \theta & \dot{\theta}_{gyro} & b_q & \alpha \end{bmatrix}^T$$

$$u = \begin{bmatrix} 0 & \sin\phi \cdot b_r & 0 & 0 & 0 \end{bmatrix}^T$$

$$\dot{x} = \begin{bmatrix} -1/\tau_\theta & 1/\tau_\theta & 0 & 0 & -1/\tau_\theta \\ 0 & 0 & 1 & -\cos\phi & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} x + u + w \quad \textbf{(4)}$$

$$z = \begin{bmatrix} \gamma_{SA} \\ \theta_m \\ \dot{\theta}_{gyro} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} x + v$$

$$x = \begin{bmatrix} \psi_{SA} & \psi & \dot{\psi}_{gyro} & b_q & \beta \end{bmatrix}^T$$

$$u = \begin{bmatrix} 0 & -\sin\phi / \cos\theta \cdot b_q & 0 & 0 & 0 \end{bmatrix}^T$$

$$\dot{x} = \begin{bmatrix} -1/\tau_\psi & 1/\tau_\psi & 0 & 0 & -1/\tau_\psi \\ 0 & 0 & 1 & -\dfrac{\cos\phi}{\cos\theta} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} x + u + w \quad \textbf{(5)}$$

$$z = \begin{bmatrix} \psi_{SA} \\ \psi_m \\ \dot{\psi}_{gyro} \end{bmatrix}^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} x + v$$

In this system, AOA and sideslip angle is estimated using difference between SAGPS and magnetic attitude. They are not equal to AOA and side slip angle form air flow because we cannot measure actual airflow using equipped sensors. Under no wind assumption, they are exactly equal.

5. Simulation

Using matlab, proposed method simulated and compared to SAGPS attitude.

5.1 Simulation setup

6-DOF nonlinear simulation is performed using Navion aircraft model. Magnetometer measurements are generated IGRF11 model of NGDC.

Aircraft is maneuvered in roll and pitch angle direction as shown in Figure 5. After 300sec, aircraft turned steady with constant roll angle.

5.2 Simulation results

In Figure 6, error of pseudo attitude from SAGPS is getting larger when aircraft maneuver. This error is mainly induced from time delay of pseudo attitude. When aircraft is in steady turn, pseudo attitude is biased because small AOA and side slip angle assumption of pseudo attitude is broken.

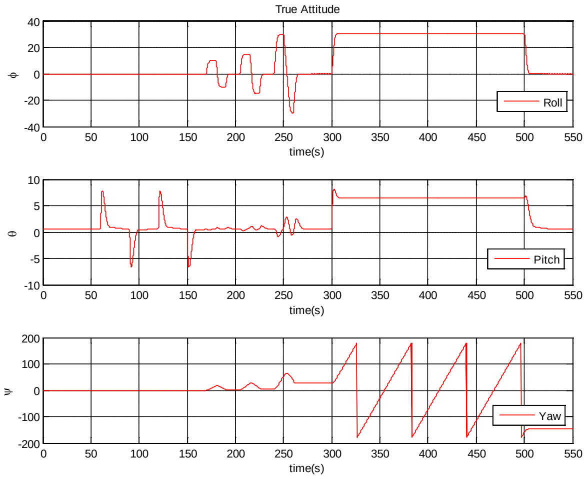

Figure 5. Aircraft manuver in Simulation

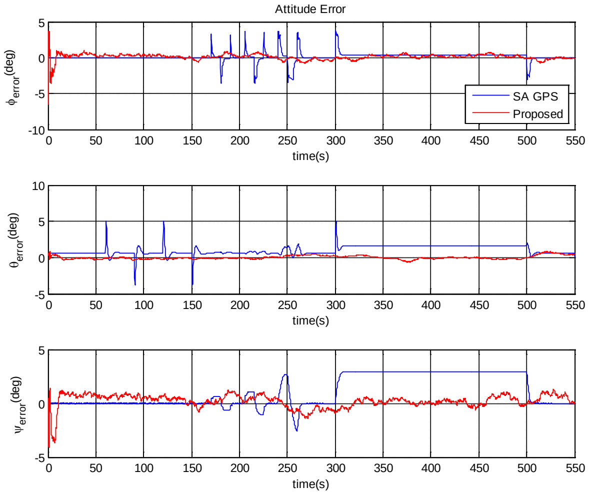

Figure 6. Attitude Estimation results in Simulation

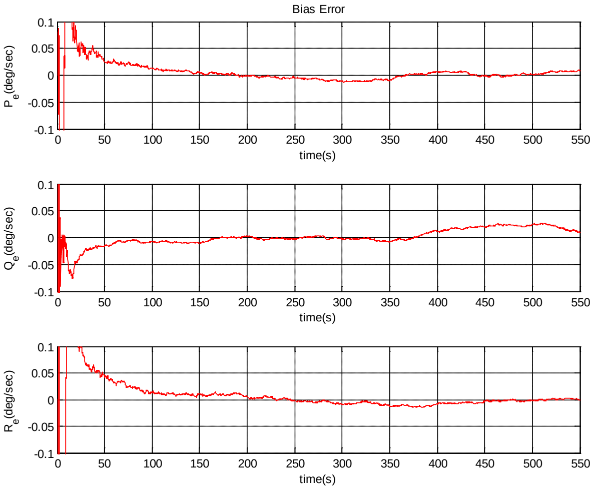

Figure 7. Gyroscope bias estimation results in simulation

On the other hand, proposed method estimated attitude accurately compared to SAGPS. This method is working better about especially pitch angle. In steady turn, it maintains its performance. Simulation results are summarized in table.

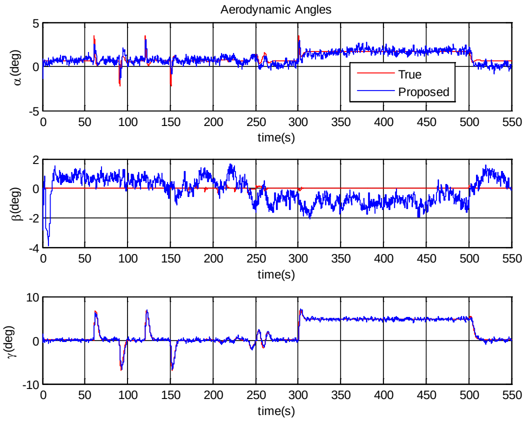

Figure 8. Aerodynamic angle estimation results in simulation

Table 1. Sensor data spec. in simulation

	Noise Std.	Bias stability
Gyroscope	0.03deg/s	0.007deg/s
Magnetometer	5mgauss	

Table 2. SAGPS Attitude spec. in simulation

Noise Std.	Roll:2deg, Gamma/Yaw:0.5deg
Delay	Roll/Gamma/Yaw:0.3sec

Table 3. Simulation results summary

	SAGPS	Proposed	Improvement
Roll RMSE	2.10deg	0.43deg	80%
Pitch RMSE	1.29deg	0.26deg	80%
Yaw RMSE	1.89deg	0.65deg	66%
Output-rate	4Hz	100Hz	-
Time delay	0.3sec	<0.05sec	-

6. Experiment

For experimental verification, flight data of small UAV is post-processed.

6.1 Experiment setup

Figure 9. UAV used for experiment

UAV used for experiment is electric powered fixed-wing aircraft of 2.7m wing span. The UAV is equipped with MEMS Gyroscope triad, MEMS magnetometer triad, GPS Receiver and commercial AHRS. Model names of used sensors are in Table 4.

The equipped AHRS has two mode of operation. First is conventional AHRS mode which uses gyroscope triad and accelerometer triad for attitude determination. Second is GPS/INS integrated navigation mode. Each mode is running independently. We logged data of both modes for verification.

Table 4. Used sensors

Sensor	Model Name
Gyroscope	Analogdevices ADIS16364
GPS	U-blox LEA-6T
Magnetometer	Honeywell HMR2300
AHRS	Microstrain 3DM-GX3-45

6.2 Experiment Results

In flight experiment, we performed sharp bank turn up to 60 degree and steady helical turning to verify attitude estimation performance under high dynamic condition.

Conventional AHRS which uses accelerometer gives erroneous attitude in all axes when aircraft is under acceleration such as turning because accelerometer measure both gravity and body acceleration. This makes AHRS determines wrong attitude.

SAGPS attitude gives biased attitude when AOA and sideslip are getting significant. And attitude error increase when aircraft performs sudden maneuver. Time delay of pseudo attitude is a major cause for this error.

Proposed method maintains its error under 4 degree for roll, 2 degree for pitch and 5 degree for yaw. Performance of this method is not affected acceleration maneuver. Integration of gyroscope improves attitude output rate from 4Hz to 100Hz. Time delay model in system equation reduced time delay of pseudo attitude from 0.7 sec to under 0.05sec.

Aerodynamic angles are estimated but they are not verified because we have no reference measurement. Strictly speaking, in these results, estimated aerodynamic angles mean compensation for difference between pseudo attitude and true attitude, not the true AOA and sideslip angle.

Table 5. Experiment results summary

	SAGPS	AHRS	Proposed
Roll RMSE	8.04deg	19.10deg	1.49deg
Pitch RMSE	5.49deg	12.19deg	0.89deg
Yaw RMSE	4.72deg	18.89deg	2.94deg
Output-rate	4Hz	100Hz	100Hz
Time delay	0.7sec	<0.05sec	<0.05sec

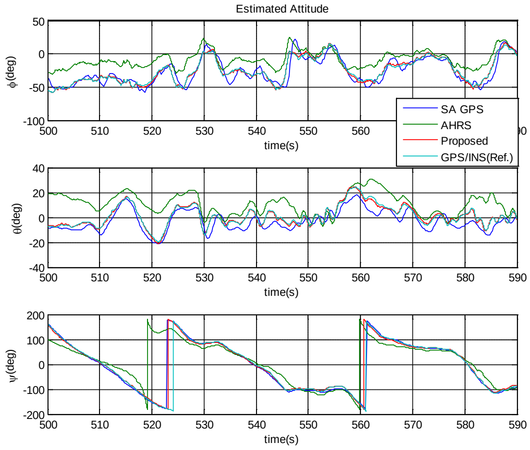

Figure 10. Estimated attitude in experiment

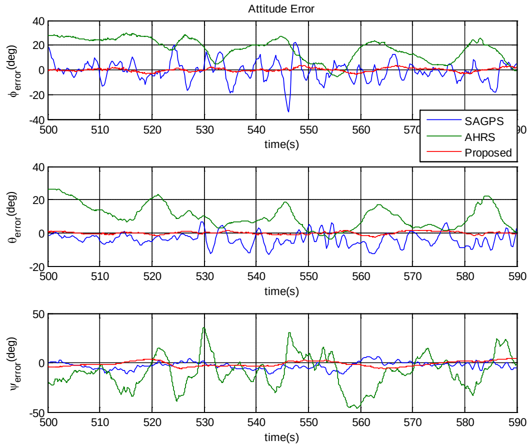

Figure 11. Attitude error in experiment

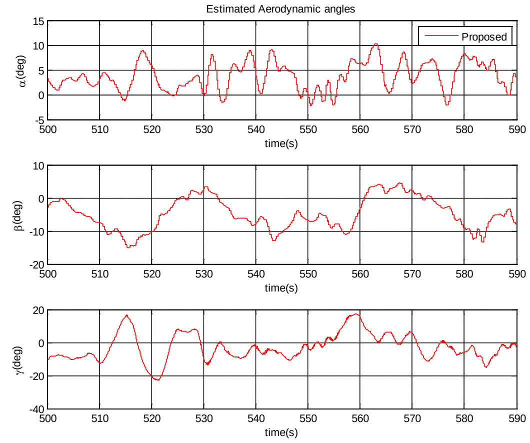

Figure 12. Estimated aerodynamic angles in experiment

7. Conclusions

Proposed method, integration of SAGPS, gyroscope and magnetometer resolved weak points of pseudo attitude. This method estimates true attitude and improves time delay and output rate of estimation. Moreover, this method shows more stable result under high dynamic condition compared to AHRS with inertial sensors. The hardware system for this method requires small GPS module, MEMS gyroscope triad and MEMS magnetometer triad. Small sized and cost effective aspects make proposed method easy to be implemented to small and low-cost UAV system.

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