MEMS-Based Attitude Determination and Waypoint Navigation System for Mini/Micro Unmanned Air Vehicles

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Abstract

This paper investigates the development of a MEMS-based attitude determination and waypoint navigation system for the autonomous fixed-winged mini/micro UAVs. An improved loose coupled Kalman filter is developed for the integration of the GPS and micro inertial navigation system based on low cost MEMS inertial sensors. The GPS/MEMS-INS and guidance, control modules are integrated to close-loop GN&C to stabilize and guide mini/micro UAVs. Real-time flight demonstrations and experimental results indicate that the integrated navigation algorithm can be satisfied with the demand of mini/micro UAVs and that the GNC system of the autonomous mini/micro UAVs in NUAA is valuable in engineering.

1. Introduction

Mini/Micro Unmanned Air Vehicle (MUAV), including Micro Air Vehicle (MAV) and Small Unmanned Air Vehicle (SUAV), is very potential to be used in many special military and civil missions such as close reconnaissance and surveillance, urban anti-terrorism, battle damage assessment, search and rescue, and environment monitoring[1,2]. In recent years, MUAV has been focused on widely in many countries all over the world. A lot of prototypes were designed, for example, Dragon eye, Pointer, Hornet, Wasp and iSTAR of USA, MicroDrones and Carolo of Germany and many others in some competitions[3,4]. The autonomy of MUAV becomes the key to expend their use and the micro guidance, navigation and control system is also more and more important.

According to the aerodynamic configuration of the MUAV, they can mainly be classified into the three categories, which are the fixed-winged aircrafts, VTOL (vertical Take-Off and Landing) and the flapping-winged air vehicles. The former two has attracted more attention in reaching and improving the autonomy than the last one up to now[2,5,6]. MEMS inertial sensors, micro GPS receiver and micro computer technology drive the development of light and compact autopilots. There are many researchers and faculties working on the autonomous flight technology which includes attitude determination, attitude stabilization, position and navigation, trajectory generation, optimization and control for the MUAV.

The Navigation Research Center (NRC-www.nuaanrc.com), Nanjing University of Aeronautics and Astronautics (NUAA), is engaged in the research of navigation and traffic technology. The researches focus on: Modern Inertial Navigation System, New Inertial Integrated Navigation Theory and Application, Mini Low Cost Navigation System for Vehicles and GIS application and so on. In the present research work of the autonomous MUAV in NUAA, the fixed-winged MUAV adopts tailless flying wing configuration in order to obtain high lift-drag ratio. And three types of flying winged MUAV (figure 1) with span of 20, 30 and 60 centimetres respectively are designed. For their fully autonomous flight, NRC employs small and low cost MEMS gyroscopes, accelerometers to develop a MEMS-based inertial navigation system ,and further integrate the MEMS-INS and GPS to determine the attitude of the MUAV and navigate the MUAV to track the trajectory between waypoints. This paper mainly investigates the development of the attitude determination and waypoint navigation (also called as inertial integrated navigation in this paper) system and algorithm in GNC close loop of the MUAV.

2. MEMS-based inertial integrated navigation for the MUAV

2.1 Error calibration and compensation of MEMS inertial sensors in inertial navigation system

Figure 1: the MAV (20cm) and SUAV (60cm) developed in NUAA

MEMS inertial sensors used are ADXRS150 gyroscope with a range of +/-150 deg/s and ADXL202E accelerometer with a range of +/-2g. MEMS inertial sensors are integrated into MEMS-IMU by SMT (surface mount technology) soldering and their sensing axes of the gyros and accelerometers are expected to be orthogonal each other. In the MEMS-IMU, the voltage signals of the MEMS inertial sensors are sampled and processed by a TI DSP processor.

The performance of low cost MEMS inertial sensors is modest. The biases and scale factor errors are significant and change with the ambient temperature. The misalignment in MEMS-IMU may infect the measurement. Tests and calibrations of the MEMS-IMU were taken in laboratory in the following steps: 1) Place the MEMS-IMU on a level platform; 2) sample the output of the gyros, accelerometers and temperature sensors in the MEMS-IMU in static state; 3) model the biases over temperature in the rapid change after start-up by curve fitting and the in-run bias stability of the inertial sensors after compensation of the temperature effect is illustrated in figure 2 and 3; 4) Mount MEMS-IMU on the rate and angle position table to calibrate the scale factors and misalignment errors; 5) Compensate the biases errors with temperature, scale factor and misalignment errors following the flow shown in figure 4.

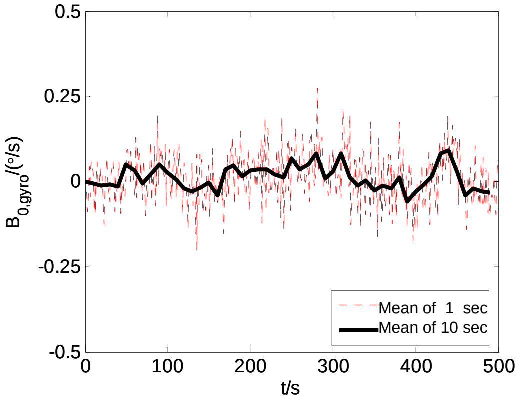

Figure 2: Bias stability curve of a gyro after compensation of temperature effect

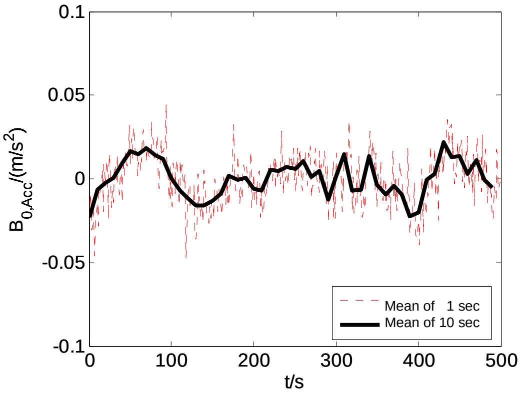

Figure 3: Bias stability curve of an accelerometer after compensation of temperature effect

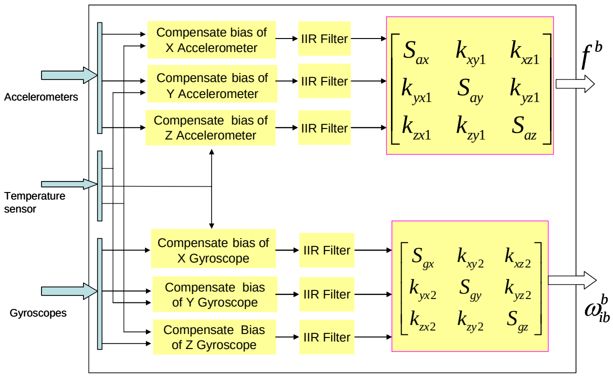

Figure 4: Errors compensation flow for MEMS-IMU

2.2 MEMS inertial navigation system

The basic idea of a pure INS is to track some coordinate system using the gyro stabilized physical or mathematic platform, and to integrate accelerometer signals to determine velocity and position in the desired coordinate system. In the navigation system, the strapdown MEMS-INS mechanization is based on the local level coordinates system. The attitude matrix, velocity, position and can be calculated by Eq. (1), Eq. (2) and Eq. (3).

$$\dot{C}_n^b = C_n^b \begin{bmatrix} 0 & -\omega_{nbz}^b & \omega_{nby}^b \\ \omega_{nbz}^b & 0 & -\omega_{nbx}^b \\ -\omega_{nby}^b & \omega_{nbx}^b & 0 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix} = \begin{bmatrix} f_N \\ f_E \\ f_D \end{bmatrix} - \begin{bmatrix} 0 & -(2\omega_{ieD}+\omega_{enD}) & (2\omega_{ieE}+\omega_{enE}) \\ (2\omega_{ieD}+\omega_{enD}) & 0 & -(2\omega_{ieN}+\omega_{enN}) \\ -(2\omega_{ieE}+\omega_{enE}) & (2\omega_{ieN}+\omega_{enN}) & 0 \end{bmatrix} \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \dot{L} \\ \dot{\lambda} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} \dfrac{V_N}{(R_m+h)} \\ \dfrac{V_E}{(R_n+h)\cos L} \\ -V_D \end{bmatrix} \tag{3}$$

In Eq. (1), Eq. (2) and Eq. (3), C_n^b denotes the strapdown attitude matrix, $V, f, \omega, L, \lambda, h$ denote respectively velocity, specific force, angle rate, longitude, latitude and height, R_m, R_n denote the main radius of the curvature of the reference ellipsoid, subscript N, E, D denote North, East and Down.

2.3 Improved integrated GPS/MEMS-INS for the MUAV

The attitude and position is basic feedback to complete attitude stabilization and waypoint navigation for MUAV. MEMS inertial sensors and MEMS-INS are not completely compatible with the requirement of MUAV although the significant errors of MEMS-IMU have been compensated. So other navigation aids are needed. GPS is an important aid, which can provide position, velocity and trajectory heading, but in MUAV, micro GPS antenna and receiver are very close to data link transceiver and the on-board processor, and also EMI may make GPS not work normally. Considering that the safety is correlative with the attitude determination of the MUAV, direct attitude measurement is also needed and it must be available during the outage of GPS. In our research, the accelerometers are be used as the tilt sensors to measure roll and pitch of the MUAV.

The integrated GPS/MEMS-INS has been improved by importing the attitude observation information. In order to estimate and compensate the three attitude errors, the three velocity errors and the three position errors in the onboard MEMS-ins, the strapdown MEMS-INS error dynamics equations are selected as the Kalman filter state equations with nine states. The discrete state equations can be combined to form a matrix representation $X_{k+1} = \Phi_{k+1,k} X_k + W_k$,where $X = \begin{bmatrix} \phi_N & \phi_E & \phi_D & \delta v_N & \delta v_E & \delta v_D & \delta L & \delta\lambda & \delta h \end{bmatrix}^T$ is the state variable, which contains three platform error angles, north east and vertical velocity errors and longitude, latitude and altitude errors, $W = \begin{bmatrix} \varepsilon_x & \varepsilon_y & \varepsilon_z & \Delta_x & \Delta_y & \Delta_z \end{bmatrix}^T$ is the noise vector composed of the measurement noise of the gyros and accelerometers, $\Phi_{k+1,k}$ is state transition matrix[7], subscript $k+1$, k denote discrete filter time.

The Kalman filter takes the horizontal attitude estimated by specific forces, the heading angle, velocity and position of the MUAV from GPS as the measurements. In the strapdown MEMS-INS, the mathematic platform coordinates (n') tracks the navigation frames, and the corresponding attitude matrix or direction cosine matrix (DCM) is $C_{n'}^b$. On the other hand, the roll and pitch angle can be estimated by using the signal of accelerometers[8]. Roll angle γ_a and pitch angle θ_a are extracted by $\gamma_a = \tan^{-1}(A_y / A_z)$ and $\theta_a = \tan^{-1}(A_x / (-A_y \sin\gamma - A_z \cos\gamma))$. The course angle ψ_G from GPS, Roll angle γ_a and pitch angle θ_a can compose a group of Euler angles; a corresponding attitude matrix $C_{n''}^b$ can be obtained. Comparing $C_{n'}^b$ with $C_{n''}^b$, $C_{n'}^b$ will drift without long term calibration and $C_{n''}^b$ will be influenced by motion accelerations, but $C_{n''}^b$ remains long term stability in the flight of the MUAV. Then, considering their complimentary characteristics, we can get measurement of math platform errors from $Z_\phi = f(C_b^{n'} C_{n''}^b) = \begin{bmatrix} Z_{\phi N} & Z_{\phi E} & Z_{\phi D} \end{bmatrix}^T$ by multiplying two DCMs[9]. The product of the two DCMs is followed as Eq. (4).

$$C_b^{n'} C_{n''}^b = \begin{bmatrix} 1 & (\phi_D - \phi_{Da}) & -(\phi_E - \phi_{Ea}) \\ -(\phi_D - \phi_{Da}) & 1 & (\phi_N - \phi_{Na}) \\ (\phi_E - \phi_{Ea}) & -(\phi_N - \phi_{Na}) & 1 \end{bmatrix} = \begin{bmatrix} 1 & Z_{\phi D} & -Z_{\phi E} \\ -Z_{\phi D} & 1 & Z_{\phi N} \\ Z_{\phi E} & -Z_{\phi N} & 1 \end{bmatrix} \tag{4}$$

$C_b^{n'}$ and $C_{n''}^b$ are already known. The velocity and position measurement $Z_v = \begin{bmatrix} Z_{vN} & Z_{vE} & Z_{vD} \end{bmatrix}^T$ and $Z_P = \begin{bmatrix} Z_L & Z_\lambda & Z_h \end{bmatrix}^T$ can be obtained by comparing the MEMS-INS and GPS. The full measurement model $Z = HX + V$ of the integrated navigation system can be illustrated as equation Eq. (5).

$$\begin{bmatrix} Z_{\phi N} \\ Z_{\phi E} \\ Z_{\phi D} \\ Z_{vN} \\ Z_{vE} \\ Z_{vD} \\ Z_L \\ Z_\lambda \\ Z_h \end{bmatrix} = \begin{bmatrix} 1 &&&&&&&& \\ & 1 &&&&&&& \\ && 1 &&&&&& \\ &&& 1 &&&&& \\ &&&& 1 &&&& \\ &&&&& 1 &&& \\ &&&&&& R_m && \\ &&&&&&& R_n \cos L & \\ &&&&&&&& 1 \end{bmatrix} \begin{bmatrix} \phi_N \\ \phi_E \\ \phi_D \\ \delta v_N \\ \delta v_E \\ \delta v_D \\ \delta L \\ \delta\lambda \\ \delta h \end{bmatrix} + \begin{bmatrix} V_{Na} \\ V_{Ea} \\ V_{DG} \\ V_{vN} \\ V_{vE} \\ V_{vD} \\ V_{LG} \\ V_{\lambda G} \\ V_{hG} \end{bmatrix} \tag{5}$$

If the GPS is in the outage during the flight of the MUAV, GPS/MEMS-INS integrated system changes the couple mode. The roll and pitch estimated by the accelerometers are guaranteed. It will work as long as the measurement equation is reduced to two observations in the outage of GPS.

3. GNC close loop and the MUAV system

The MEMS-based inertial integrated navigation system provides real time real time position, heading angle and height to guidance module and provides pitch, roll and body rate to attitude controllers. Pitch, roll and heading controllers adapting proportional-derivative (PD) control law are in the inner loop; and height controller adapting proportional control law is in the outer loop. Outer controllers generate desired input of the inner controllers and a line in sight guidance law has been adapted in the guidance module. The inner controllers control a couple of aerodynamics surfaces, which are called as elevons. The throttle is controlled by the height and throttle controllers. The MAUV rotates aroud its body axes under the drive of the aerodynamics moments of the elevons or accelerates under the propulsion. The angle and line motions are measured by MEMS-based inertial integrated navigation system. The GNC close loop is illustrated as Figure 5.

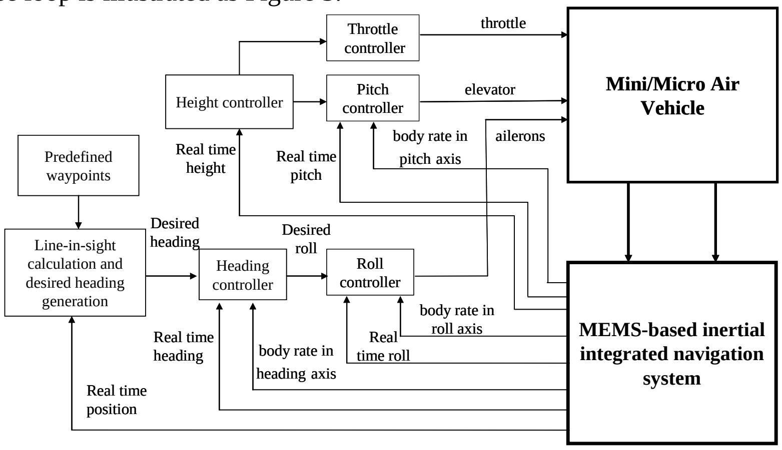

Figure 5: GNC close loop of the MUAV

The MUAV system consists of two parts: the ground control station (GCS) and the aircrafts with GNC avionics (see figure 6). The GCS is used to generate flight planning, set parameters into the in-run GNC, switch control mode between manned control and autonomous mode, display and record data of the MUAV flight state. When some payload such as a video camera or IR sensor is equipped with, image can be transmitted to the GCS. A data link modem exchanges messages between GCS and the aircraft. The MUAV is powered by polymer lithium batteries and small electromotor. The DSP processor runs strapdown MEMS-INS program and Kalman filter to determinate the attitudes velocities and positions, feeds the navigation parameters back to guidance module and calculates control value to output PWM signal to the steer engine.

Figure 6: Integrated hardware of micro GNC avionics

4. Test experiment in laboratory and flight demonstration

4.1 Test experiment in laboratory

The performance test in the laboratory mainly focused on the attitude determination of MUAV. The MUAV with MEMS-based inertial integrated navigation system is placed on the rotating table of NRC. Firstly, The GPS/MEMS-INS on the rotating floor is horizontal and some period of time later, the system is rotated to tilt and readout the roll angle and pitch angle from the rotating floor. Due to the GPS is invalid in the room, the experiment can proof-test the MEMS-based inertial integrated navigation system in MUAV during the outage of GPS.

Figure 7 is a scene of the test experiment in NUAA NRC. Roll and pitch angle curves are presented in Figure 8. The steady readout of the rotating floor in experiment process is successively 0 deg, pitch 20deg, pitch -20deg, roll -20deg. In the experiment, the attitudes provided by the MEMS-based inertial integrated navigation system rapidly track the motion of the rotate table and they keep low drift when the rotate table is static. The roll and pitch errors are no more than 1 degree. The test demonstrates the measurement performance of the MEMS-based inertial integrated navigation system in static (no line motion) environment and in the outage of the GPS.

Figure 7: The MUAV system test in the NUAA NRC and the interface of data processing software

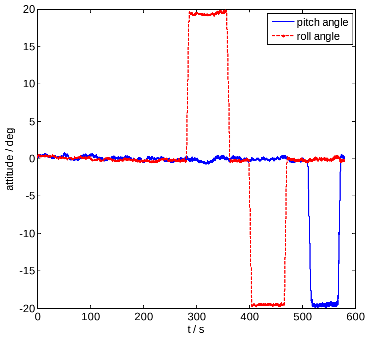

Figure 8: Roll and pitch angle curves in lab test

4.2 Close range flight demonstration for attitude stabilization and waypoint navigation

Short range flight demonstration was taken to proof-test the whole MUAV (see figure 9) system in a big open farm. A thermo-anemometer (see figure 9) was used to measure the strength of the wind in the flight environment. In the demonstration, three-waypoint-navigation was selected to test GNC algorithms. The predefined waypoints (see figure 10) are WP#1 (-100, -100), WP#2 (50, -300) and WP#3 (0, 0). Each waypoint is all around a broken line circle with the radius of 30 meters. The MUAV began autonomous flight when it flew away the first waypoint. Based on the real-time feedback of MEMS-based inertial integrated navigation system, the line-in-sight guidance law calculated the desired heading angle and roll angle, and the attitude controller control the MUAV rolling to the desired roll angle, so the MUAV was navigated to the desired waypoints. The MUAV flow over the area around the waypoints and the waypoint navigation errors were less 30m. The roll and pitch angles in the flight are illustrated in the figure 11. The error between the real time roll angle and the desired roll angle is about within the zone of 5 degree.

Figure 9 Thermo-anemometer to measure the strength to the wind and the MUAV in flight

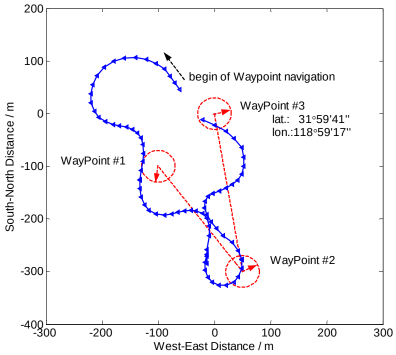

Figure 10: Flight trajectory in close range flight demonstration

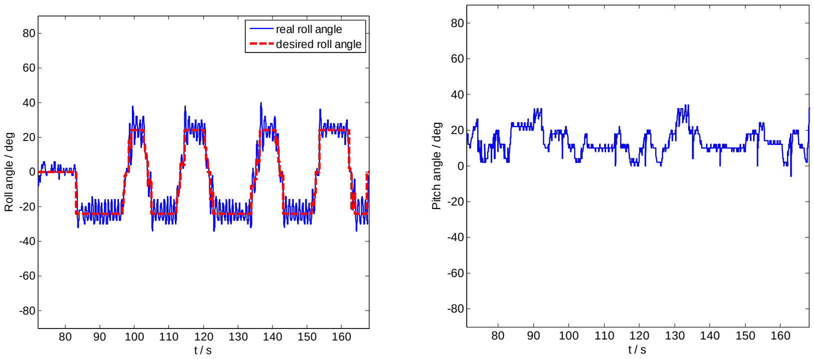

Figure 11: Attitudes in close range flight demonstration

4.3 Farther range flight demonstrations

Farther range flights were also demonstrated. Two typical waypoints were selected according to the landform of experiment field. Figure 12 illustrates two flight trajectories with the lengths of about 2000 meters and 2700 meters. The flight results show that the MUAV can autonomously fly beyond visual range and fly back under the control of the GNC avionics.

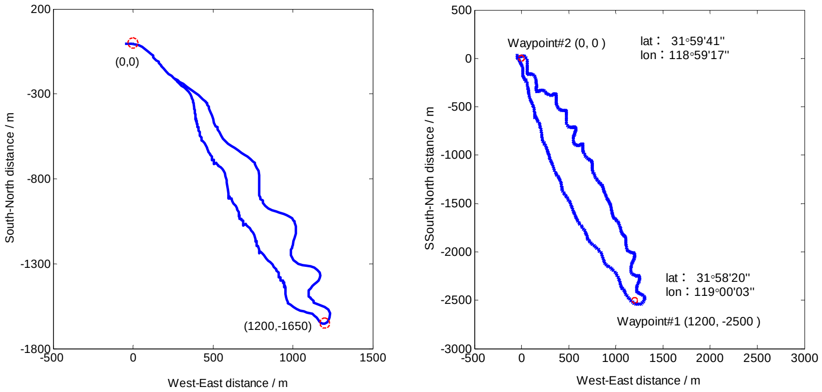

Figure 12: Flight trajectories in farther range flight demonstration

4.4 Discussions

The test experiment in laboratory and the flight demonstrations indicate that the MEMS-based attitude determination and waypoint navigation system is reliable. The attitudes are accurate enough to implement the stabilization and the navigation algorithm and the line-in-sight guidance law can guide the MUAV to fly according the predefined plan.

The flight trajectories are S-shape in some sections. This is mainly related to the dynamics and control mechanism of the MUAV, and is also related to delays of the GPS to some extent.

5. Conclusions

This paper details the development and demonstration of a MEMS-based attitude determination and waypoint navigation system for the Mini/Micro UAV. The error calibration and compensation are adapted as a measure to reduce the measurement errors in the MEMS-IMU. The loose Kalman filter is also improved to maintain the attitude accuracy during the outage of GPS. The MEMS-based attitude determination and waypoint navigation system in GNC close loop is proof-tested through autonomous waypoint navigation flight. Based on the GNC avionics, the autonomous MUAV show the potential to be used in many fields mentioned in front.

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