A Review: The Survey of Attitude Estimation in Autonomous UAV Navigation

Zhaomin Ma[1,*], Zhengqiang Chen[1] and Ling Huang[1]

[1]College of Electric and Information Engineering, Guangxi University of Science and Technology, Liuzhou, Guangxi, China
*Corresponding author

Abstract—**Recently, UAV has been widely used in various fields. The attitude estimation of autonomous UAV is an important basis for its autonomous flight mission. The attitude estimation technique based on GNSS is a traditional positioning method. However, it is a challenge to provide a high precision estimation when GNSS signal cannot be used. This paper summarizes the research status of attitude estimation based on vision or other multi-sensors when GNSS signal is not available. And the various improved methods of KF in UAV attitude positioning are introduced. Then the attitude estimation methods of UAV in multi-aircraft cooperative flight are analyzed. In the end, several issues worthy of attention in the further research are proposed. It should contribute to the further research on autonomous UAV navigation.**

Keywords—autonomous unmanned aerial vehicle (UAV); attitude estimation; kalman filter (KF)

I. INTRODUCTION

UAV is unmanned aircraft system that operates by remote control and programmed control devices. UAV system generally consists of three main modules: aircraft platform system, information acquisition system and ground control system. Initially UAV is controlled by human, modern UAV aims to achieve a higher level of autonomy as it becomes more widely used in various fields. Therefore, the navigation of autonomous UAV has become a research hotspot.

The navigation of autonomous UAV mainly involves three parts: (1) aircraft attitude estimation; (2) obstacle detection and obstacle avoidance in flight; (3) aircraft control in autonomous flight. The first part is the foundation of the others. And the precise attitude estimation of UAV is also the basis of completing the whole flight task. Moreover, it is a very difficult problem to estimate the attitude of UAV within the unknown environment due to UAV own flight height and motion vary dynamically, and the fact that UAV can be affected by external environment and its own changed state in flight operations.

II. ATTITUDE ESTIMATION OF AUTONOMOUS UAV

The attitude estimation of UAV aims to estimate its own position and attitude in two-dimensional or three-dimensional representation. Traditional flight attitude estimation is based on the Global Navigation Satellite System (GNSS). Because there are always interference and shielding problems for GNSS, in recent years researchers have continuously carried out attitude estimation methods based on vision as the main sensor or other multiple sensors fusion in the case of GNSS-denied at low altitude or indoors. And various improved algorithms of KF (Kalman Filter) were proposed in order to improve the accuracy of attitude estimation. The estimation of UAV attitude in multi-aircraft cooperative flight needs to consider the cooperation between two and multiple aircraft.

A. Autonomous UAV Attitude Estimation Mainly Based on Vision in the Case of GNSS-denied Conditions

Vision sensor can provide detailed information of the surrounding environment for UAV. In the past, vision was mostly adopted for position and speed estimation rather than attitude estimation. In the recent research, UAV attitude estimation algorithm mainly based on vision has been further developed. Since the flying area of UAV can be divided into indoor and outdoor areas, the research on the attitude estimation of UAV based on the vision system as the main sensor was carried out based on different methods according to the respective characteristics of indoor and outdoor areas. The reference target was necessary for the attitude estimation of UAV either outdoor or indoor environment based on vision system as the main sensor. In the literature, different target was chose such as landmarks, water surface and surrounding characteristic objects in the river environment, located buildings, the known positions ground targets, road centerlines, etc.

In [1] the image positions of the landmarks and IMU information were fused and the visual inertial navigation system of UAV was designed to determine the absolute attitude parameters of the uav: position, speed and attitude of UAV body. VINAS 'state and observation equation were established by establishing the each other's transformation relationship between camera, UAV body and ground coordinate system. The research showed that it had a great influence on the selection of landmark image points in attitude determination. In the experiment three landmarks were selected and the locations of the landmarks were arranged in different positions. Experiments showed that the more scattered the image points formed by landmarks, the stronger the observability of the system. In [2] Pico-ITX Computer, IMU, Magnetometer, Camera and Altimeter were equipped to the UAV platform. They were used to obtain and compute measurement update about attitude parameters in the river area when the UAV flied along the river side. The robot-centric mapping method, multiple-view geometry and world-centric localization methods of UAV were used to further enhance the observability of the UAV attitude estimation. In [3] the novel UAV attitude determination method based on vector measurement pair was

proposed. In the UAV system, aerial images were acquired by airborne aerial camera. The main steps of this algorithm were: firstly, the images were processed to detect and identify the visible landmarks on the ground. Secondly, the vector measurement values related to the direction from camera to landmarks were calculated. These vector measurements were obtained by multiple sensors, such as solar sensor, magnetometer, overhead camera, star sensor, horizon sensor, etc. Finally, the method of Monte Carlo simulation was used to estimate the UAV attitude by using vector measurements. In [4] when GNSS was unavailable /unreliable, the UAV attitude was estimated by combining the visual system and UWB equipment. The ground feature points in the world coordinate system were obtained with the calibrated camera, and photogrammetric calculation was carried out in Direct Georeferencing (DG), then metric reconstruction was built. At least three UWB devices were used to estimate the correct scaling factor of the reconstruction on a local coordinate system. In [5] a loop of high level decision algorithm based on observation, orientation, decision and action was developed to estimate UAV pose. In this study, dji 450 UAV was used and a Raspberry Pi 2 computer was installed as on-board computer to run real-time navigation algorithm. The local position information was continuously sent to the autopilot of the main node through Mavros to realize the navigation of the UAV. In location stage, when the flight altitude of the aircraft remains unchanged, the target position estimation method can navigate the UAV moved laterally to x and y target positions. The algorithm program of the whole UAV navigation process was given. In the actual flight test, the success rate of automatic navigation was 92%. In the experimental analysis, one of the reasons for the test failure was that the hover phase of the navigation algorithm took time out. In [6] aiming at the GPS-denied environment, the UAV automatic navigation was carried out by detecting the semantic features of targets such as the road center line, intersection, forest and river contour in the aerial image. Firstly, vertical mounted camera was used to obtain aerial images and the object's features of important identification objects (such as road center line, etc.) in images were extracted by image processing algorithm. Then by matching those features with the pre-built data set, the uav's position was calculated. In addition, the optical flow method based on aerial images was used to calculate the UAV speed update. In [7] a six-dimensional positioning method based on visual odometry and Monte Carlo localization was designed to realize the development of UAV autonomous navigation system with high robustness. After more than two years testing, the autonomous navigation UAV system in this paper can realize the autonomous positioning and state estimation of UAV without the assistance of any external positioning system.

B. Autonomous UAV Attitude Estimation Mainly Based on Other Multiple Sensors Fusion in the Case of GNSS-denied Conditions

In addition to the research on UAV attitude positioning carried out by vision as main sensor, recently researchers have also carried out research on it based on other types of sensors fusion.

In [8] aiming at the environment of foliage the navigation system of small-scale autonomous flying UAV was designed based on the motion estimation module composed of two laser range finders. The laser range finder mounted overhead was mainly used to detect the horizontal position of the aircraft. The laser range finder at the bottom was mainly used to scan the vertical position. In the hardware design of the aircraft, the whole avionics system was shielded from the interference signals by four mechanical isolators which were mounted on the UAV platform. The experiment showed that IMU acceleration measurement noise was 5 times lower than that before the vibration isolation measurement. The flight trajectory was smoothed by GraphSLAM technology, and the real-time attitude estimation of UAV based on KF was realized by the fusion of planar velocity measurement data matched by continuous scanning of laser range finders and acceleration measurement data of IMU. In [9] the UAV integrates two Light Detection and Ranging (LiDAR) (UTM-30LX-EW and URG-04LX-UG01) and IMU sensors devices. The IMU sensor device was used to stabilize the LiDAR measurement plane, and then the point-to-point scanning matching algorithm was used to effectively calculate the plane position of the UAV. Based on the vertical scanning method, another LiDAR instrument was used to accurately obtain the height relative to the ground of the UAV. Combining the two-dimensional position and altitude data, the aircraft pose state was deduced based on KF method. In [10] a multi-sensor information fusion algorithm based on factor graph was proposed to realize navigation of UAV. The development UAV system was equipped with a variety of sensors, including IMU, GPS receiver, magnetometer, barometer, optical flow sensor and sonar sensor. The system was also equipped with Xbee wireless communication module, motor, electronic governor, and other devices. Based on the algorithm factorizing the global optimal solution according to the chain structure of the factor graph, the fusion matter can be converted into the connection factors on the factor graph which were defined by the data obtained by each sensor without considering the relation between the update frequency of the data obtained by the sensor and the fusion period. For the estimation of UAV speed and position, the computational accuracy of factor graph filtering algorithm was higher than that of extended KF (EKF) method. In [11] a UAV attitude determination system based on polarization sensor was developed. Because the polarization sensor is not affected by the magnetic field, the system can work in the magnetic interference environment. Experimental results showed that the proposed attitude measurement system had higher measurement accuracy than the general attitude measurement system and can provide precise parameters for the flight control of uav.

In the indoor space, conventional positioning methods based on GPS are unreliable due to the relatively narrow space. But it also facilitates the provision of third-party equipment for UAV positioning and attitude estimation. In [12] the autonomous navigation system in the indoor flight environment that integrates the structural light scanner, ultra-wideband and inertial navigation system (INS) into the existing UAV system platform was developed. The structured light scanner consists of a structured light and a camera. The structured light module can improve the positioning accuracy of UAV in specific

indoor areas. The results of simulation and real flight experiments showed that the UAV system based on structured light scanner significantly improved the positioning accuracy in the motion and hover states compared with using the single vision sensor. In [13] this paper proposed the autonomous flight positioning system based on the acousto-optic hybrid module in the indoor flight environment. The Time-Code Division Multiple Access (T-CDMA) scheme was used to constitute the acoustic module. The system calculated the horizontal position of UAV based on the sequential emission of five spread spectrum ultrasonic codes, and applied a recursive algorithm to improve the accuracy of position estimation. The initial estimation of UAV altitude was obtained from images taken by the TOF-camera. The experimental results showed that the mean square error of the positioning system was 70-80% higher than that of the uav's positioning using the acoustic module alone.

C. Improvement of KF in Attitude Estimation of Autonomous UAV

KF is often used to fuse information in UAV attitude estimation. It was an optimal estimation method of recursive linear minimum variance. In order to improve the accuracy of UAV attitude estimation, researchers have carried out lots of research on various forms improvement of KF to fuse the data detected by different types of sensors (such as vision sensor, inertial sensor or polarization sensor). In [1] the attitude vector navigation filter based on EKF and Unscented KF (UKF) was designed in the research. The nonlinear degree of navigation system was analyzed and a more suitable navigation filter was designed. The simulation results showed that EKF navigation filter had obviously lower performance than UKF navigation filter due to the highly nonlinear equation of state. In [3] the Multiplication Extension KF that can carry out sequential update was proposed. Unlike MEKF, MEKFSU processed pairs of available vector measurement in a sequential form at each sampling. In [6] the estimate of UAV location and orientation was calculated in the EKF relies on inertial measurements and information extracted from the aerial imagery. In [11] the quaternion differential equation was adopted as the dynamic model to improve EKF, and the improved algorithm integrates data detected by the polarization sensor to improve the positioning accuracy of UAV. In [12] the adaptivity of KF was improved with INS and UWB data in UAV moving were fused to improve positioning accuracy.

D. Attitude Estimation in the Relative Navigation of Multi UAVs

In order to ensure the accurate cooperative mission performance, it is necessary to estimate the relative attitude of a single UAV in the collaborative flight of multi UAVs. In [14], when there was no GPS to assist multi-uav's cooperatively navigation and location, UAV cooperative navigation was completed their relative navigation by using noncommunication Unattended Ground Sensor (UGS) system. As the guidance of relative navigation of multi-uavs, UGS can eliminate the calculation of dead reckonings. Aiming at the relative navigation problem of two uavs, the approximate algorithm was proposed. In the collaborative navigation of three uavs, the existing solution method was converted into a

regular asymmetric TSP optimization algorithm. In [15], the relative autonomous flight location system of micro uavs group was designed based on the airborne vision system and the rapid image processing module applicable to the requirement of aircraft group stability. The micro uavs hardware system was equipped with airborne camera module, IMU data module and commercial PX4Flow2 smart sensor module. All single UAV in the developed group hardware system was equipped with black and white (B/W) mode. In UAVs group flight, if the actual distance between adjacent aircraft was meters, the mutual positioning accuracy can reach centimeters. In [16] the cubature information filter algorithm based on the cubature KF (CKF) and information filter were studied. Distributed information fusion structure to fuse the information from INS, VisNav and GPS was built. The relative position, velocity and attitude were obtained by the INS /GPS /VisNav relative navigation filter. In [17] adaptive Huber-based CKF algorithm with noise estimator was proposed which can estimate accurately the relative position, relative velocity and relative attitude information among UAVs. The Huber technique and the covariance matching method were combined. The residual sequences were used to estimate and tune the statistical characteristics of process noise and measurement noise on line. The received measured data were weighted by using the forgetting weighted parameters. In [18] the UWB/DGPS relative navigation algorithm was proposed in the paper. UAV formation flight measurement equations were built according to the features of pseudorange and UWB measurements. The relative navigation states equation was established based on the close-range formation flight scenario. The relative states were estimated by using EKF.

III. Noteworthy Issues

With the reduction of the UAV use cost, the increase of labor cost and the pressure of environment, more and more autonomous UAVs have been applied to complete flight tasks in various fields. It is very important to estimate UAV attitude accurately for autonomous flight in various applications and purposes. Therefore, there are several issues need note in the further study.

(1) In the case of GNSS-denied conditions, attitude estimation based on visual sensor as main sensor is one of the solutions. However, the low cost vision system is two-dimensional, which is converted by coordinate system in the process of three-dimensional construction. The error accumulation caused by coordinate transformation operation is an important issue affecting the estimation accuracy of this method.

(2) The attitude estimation method based on fusion of other sensors is another main method. However, most of the methods transform the problem into linear one, which will lead to error accumulation. In addition, in the environment where the aircraft usually operates (low altitude and indoor) the local magnetic field sometimes changes suddenly and it is impossible to predict UAV attitude value in the reference coordinate system.

(3) For multi UAVs group system the different task of the group requires different method for the single UAV attitude

estimation. Then it is very important to find the right attitude estimation method for the required mission.

IV. CONCLUSION

The attitude estimation of autonomous UAV is an important basis for its autonomous flight mission. However, traditional estimation methods are challenged when the GNSS signal is not available /reliable. Researchers are constantly developing new technologies and methods to provide more accurate attitude estimation and evaluation. This paper summarizes the research status of attitude estimation based on vision as main sensor or other multi-sensors fusion when GNSS signal cannot be used, and summarizes the improved application of KF in UAV attitude positioning and the attitude estimation of UAV in multi-aircraft cooperative flight. This will contribute to the further research on autonomous UAV navigation technology.

ACKNOWLEDGMENT

REFERENCES

[1] L.Huang, JM.Song, CY.Zhang. Observability analysis and filter design for a vision inertial absolute navigation system for UAV using landmarks, OPTIK. 149 (2017) 455-468.

[2] JH.Yang, A.Dani, SJ.Chung, S.Hutchinson. Vision-based localization and robot-centric mapping in riverine environments. Journal of field robotics. 34 (2017) 429-450.

[3] DA.Santos, PFSM.Goncalves. Attitude determination of multirotor aerial vehicles using camera vector measurements. Joural of intelligent & robotic systems. 86 (2017) 139-149.

[4] A,Masiero, F.Fissore, A.Vettore. A low cost UWB based solution for direct georeferencing UAV photogrammetry. Remote sensing. 9 (2017).

[5] A.Hinas, JM.Roberts, F.Gonzalez. Vision-based target finding and inspection of a ground target using a multirotor UAV system. Sensors. 17 (2017).

[6] A.Volkova, PW.Gibbens. More robust features for adaptive visual navigation of UAVs in mixed environments. Journal of intelligent & robotic systems. 90 (2018) 171-187.

[7] FJ.Perez-Grau, R.Ragel, F.Caballero, A.Viguria, A.Ollero. An architecture for robust UAV navigation in GPS-denied areas . Journal of field robotics. 35 (2018) 121-145.

[8] JQ.Cui, SP.Lai, XX.Dong, BM.Chen. Autonomous navigation of UAV in foliage environment. Joural of intelligent & robotic systems. 84 (2016) 259-276.

[9] GA.Kumar, AK.Patil, R.Patil, SS.Park, YH.Chai. A LiDAR and IMU integrated indoor navigation system for UAVs and its application in real-time pipeline classification. Sensors. 17 (2017).

[10] QH.Zeng, WN.Chen, JY.Liu, HZ.Wang. An improved multi-sensor fusion navigation algorithm based on the factor graph. Sensors. 17 (2017).

[11] W.Zhi, JK.Chu, JS.Li, YL.Wang. A novel attitude determination system aided by polarization sensor. Sensors. 18 (2018).

[12] C.Wang, K.Li, GY.Liang, HY.Chen, S.Huang, XY.Wu. A heterogeneous sensing system-based method for unmanned aerial vehicle indoor positioning. Sensors. 17 (2017).

[13] JA.Paredes, FJ.Alvarez, T.Aguilera, JM.Villadangos. 3D indoor positioning of UAVs with spread spectrum ultrasound and time-of-flight cameras. Sensors. 18 (2018).

[14] SG.Manyam, S.Rathinam, S.Darbha, D.Casbeer, YC.Cao, P.Chandler. GPS denied UAV routing with communication constraints GPS. Joural of intelligent & robotic systems. 84 (2016) 691-703.

[15] M.Saska, T.Baca, J.Thomas,J.Chudoba, L.Preucil, T.Krajnik, J.Faigl, G.Loianno, V.Kumar. System for deployment of groups of unmanned micro aerial vehicles in GPS-denied environments using onboard visual relative localization. Autonomous robots. 41 (2017) 919-944.

[16] HX.Jin, T.Yang, XG.Wang, GF.Zhou, W.Yao. Application of multi-sensor information fusion in UAV relative navigation method. Journal of national university of defense technology. 39 (2017) 90-95.

[17] X.Zhang, NG.Cui, XG.Wang, HT.Cui, WT.Qin. Robust adaptive cubature Kalman Filter and its application in relative navigation. Acta Armamentarii. 39 (2018) 94-100.

[18] J.Xiong, Z.Xiong, YG.Yu, JX.Xu, YS.Wang. Close relative navigation algorithm for unmanned aerial vehicle aided by UWB relative measurement. Journal of Chinese Inertial Technology. 26 (2018) 346-351