An Analysis System for Attitude Angles of Four-rotor Aircrafts

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ABSTRACT
More accurate attitude angles can make the control of four-rotor aircrafts more precise. Various filters have been adopted to get more precise attitude angles. However, so far there is no suitable analysis system to evaluate the performance of filters. In this paper, an analysis system has been designed which can get the realistic attitude angles directly and compare the processing results of filters so as to analyze the performance of filters. The hardware of the analysis system contains the main control module, data acquisition module and wireless communication module. And the software of the system which is designed by LabVIEW mainly includes displaying and saving module, analysis module and the front panel. An extended Kalman filter and an innovation-based extended Kalman filter are compared by the system and results show that the attitude angles got by the innovation-based extended Kalman filter are more accurate than the extended Kalman filter.

General Terms
Data Acquisition

Keywords
Four-rotor aircrafts; Analysis system; LabVIEW; Innovation-based extended Kalman filter

1. INTRODUCTION
With the expanding applications of the four-rotor aircrafts, the control system of four-rotor aircrafts has to be more stability [1, 2]. The accurate attitude angles influence the control of the system. For improving the accuracy of the attitude angles, various filters are used. The filtering effect has obvious differences with the different filters. How to choose appropriate filter is important. So, an analysis system is needed to compare these filters.

In terms of the data processing, filtering technology is used to enhance the accuracy of the attitude angles. There are large of literatures on attitude filtering techniques. A new approach for generalizing the Kalman filter to nonlinear system was described by Julier,S [3]. A set of samples were used to parametrize the mean and covariance of a probability distribution [4]. Cheng,Y estimated attitude through the EKF (Extended Kalman Filter) and UKF (Unscented Kalman Filter) update equation. The result showed that EKF and UKF have better fusion effect than Kalman filter for the nonlinear characteristic [5]. In the paper [6], Kalman filter combines 3-axis gyroscope and computed quaternion to determine pitch and roll angles. This algorithm is adequate for the real-time estimation of the orientation of a quadrotor. A nonlinear complementary filter that combines accelerometer output for low frequency was proposed by Euston [7]. The results were provided with a real-world data set and the performance of the filter was evaluated against the output from a full GPS/INS (Global Position System/ Inertial Navigation System) that was available for the data set. The Four-rotor aircraft system is nonlinear system. At present, the most widely estimator used in the four-rotor aircraft is extended Kalman filter.

In this paper, a simple and practical analysis system is designed of hardware and software. The system implements a hardware platform of real-time data measurement and transmission. The hardware contains the main controller design, the data acquisition module design and the wireless communication module design. The programs of the lower computer are written in the C++ language and the upper computer is designed by LabVIEW [8, 9]. First, the attitude angles are measured by sensor MPU6050, and transmitted through the wireless communication module to the computer. Then these data are estimated accurately by the extended Kalman filter based on innovation and shown by the virtual oscilloscope. The system can provide more real and accurate data for the four-rotor aircrafts' control system and the interface of the system is real-time, high speed and intuitive.

2. SYSTEM STRUCTURE
The quadrotor attitude angles analysis system is composed of the main control module, wireless communication module and PC interface. The flight control module includes sensors and main controller. Wireless communication module as the wireless transceiver module is composed of sender and receiver of NRF24L01. The constitution of system is shown in Fig.1.

The data of quadrotor attitude angles are sent to the wireless receiving module by main controller. Then the data are sent to the PC interface and saved in the spreadsheet. At last, the data are estimate accurately by the extended Kalman filter based on innovation and the waveforms are shown by the virtual oscilloscope.

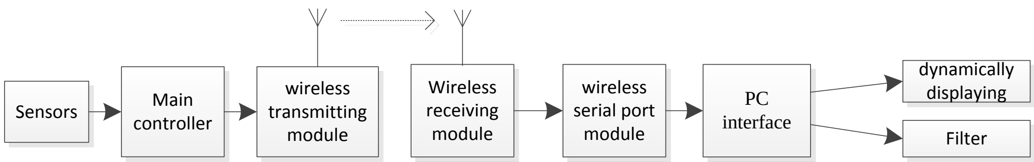

Fig 1: The constitution of system

3. HARDWARE DESIGN

3.1 Main Control Module

STM32F103CBT6 is used to be the main controller of the system. STM32F103CBT6 has 32-bit Coxtex^{TM}-M3 CPU Core. The processing speed is up to 72MHz. It has built-in 128KB Flash, two 12-bit ADCs and 20KB SRAM. The ports of it are two I2Cs and SPIs, three USARTs, an USB and a CAN. The performance can up to 1.25 DMIPS/MHz at 0 wait state memory access, single-cycle multiplication and hardware division. So the rich on-chip resources of STM32F103CBT6 are able to meet the requirements of the analysis system completely. The data of angles detected by the sensors are transmitted to the NRF24L01 wireless transceiver chip through the SPI. The circuit of the STM32F103CBT6 is shown in Fig.2.

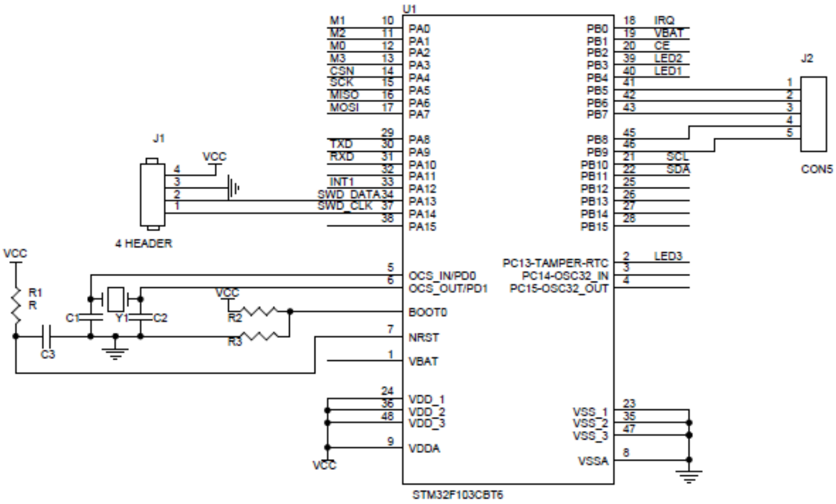

Fig 2: Circuit of the STM32F103CBT6

3.2 Data Acquisition of Attitude angles

The MPU6050 is used to be the data acquisition module. The MPU6050 has a 3-axis MEMS (Micro-electromechanical Systems) gyroscope, a 3-axis MEMS accelerometer, and a digital motion processor. The gyroscope and accelerometer use three 16-bit analog-to-digital converters for digitizing the outputs respectively. The measurable range of the gyroscope are ±250, ±500, ±1000, and ±2000°/sec, and the measurable range of the accelerometer are ±2, ±4, ±8, and ±16g.

In the circuit of the attitude angles acquisition, the PA12, PB10, PB11 pin of the STM32 are connected with the INT, SCL, SDA pin of the MPU6050 respectively. Then the data are transmitted though the I2C communication mode. The circuit of the attitude angles acquisition is shown in Fig.3.

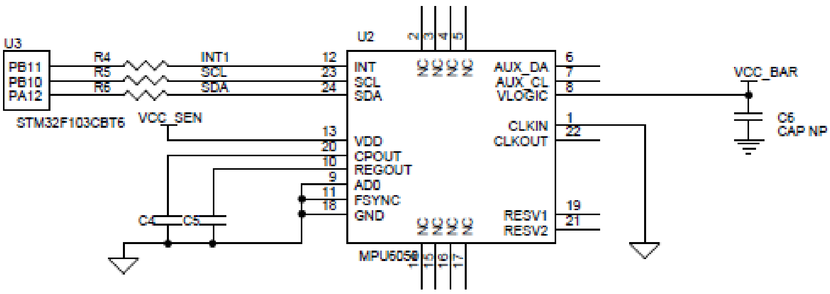

Fig 3: Circuit of the attitude angles acquisition

3.3 Wireless Communication Module

NRF24L01 is used to be the wireless communication module. NRF24L01 is a GFSK (Gaussian frequency-shift keying) single chip radio transceiver, and it works in the 2.4-2.5 GHz band. The rate of wireless can be up to 2Mbps. Combine the NRF24L01, external antenna and power amplifier chip, the transmission distance can reach above 1100m. NRF24L01 consists of a frequency synthesizer, a power amplifier, a crystal oscillator, a demodulator, a modulator and enhanced ShockBurst™ protocol engine. The output power, frequency channels, and protocol setup are easily programmable through the SPI interface. The interface rate of SPI can reach 8Mbps. NRF24L01 has high transmission rate and long transmission distance, but has low current consumption. The current consumption can reach 9.0mA in the TX mode and 12.3mA in RX mode. Built-in power down and standby modes make power saving easily.

The CSN of NRF24L01 provides the signal for chip select which is connected with the PA4 of the STM32.The SCK generate SPI clock signal which is connected with the PA5 of the STM32. The MISO and MOSI are output and input which are connected with the PA6 and PA7. The IRQ is a flag bit of interrupt which is connect with PB0. The CE is connected with the PB2. There are two modes RX or TX. The circuit diagram is shown in Fig.4.

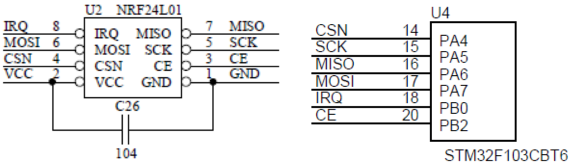

Fig 4: Circuit of the wireless communication module

4. SOFTWARE DESIGN

4.1 Displaying and Saving Module

In this analysis system, the attitude angles have to be displayed and saved, as shown in Fig.5. The file name is defined by module of creating path and the file will be saved as '.txt' format [10]. After the file is created, the data will be written in it.

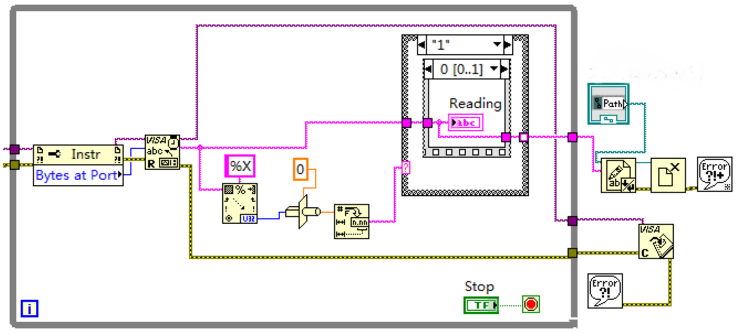

Fig 5: Displaying and saving the attitude angles

4.2 Analysis Module

Any filters can be designed in the analysis module. The filter results will be saved in the virtual oscilloscope, just as shown in the Fig.6.

4.3 The Front Panel

The user interacts with the programs through the front panel. Comparing with the Maltab/Simulink software, the front panel of the LabVIEW is simpler, more intuitive and more scalability. The p saved in the virtual oscilloscope arameters of the wireless serial communication and some options and buttons can be adjusted precisely though the front panel as shown in Fig.7.

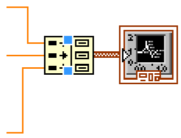

Fig 6: Saved in the virtual oscilloscope

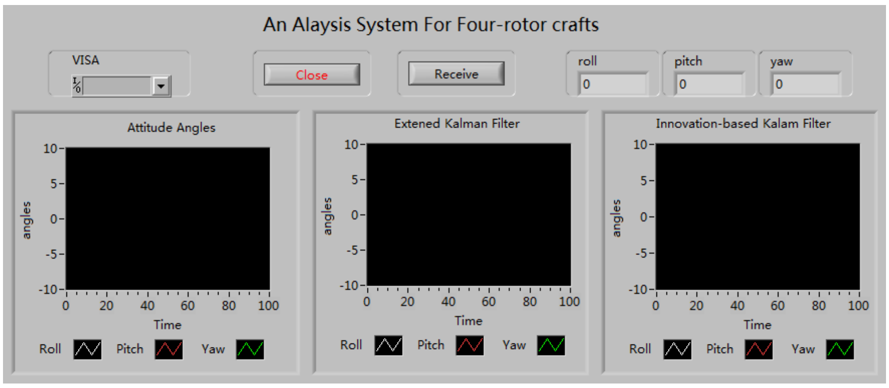

Fig 7: The front panel

5. THE VALIDATION OF SYSTEM

An extended Kalman filter and an innovation-Based extended Kalman filter are compared by the analysis system in the paper.

5.1 The Extended Kalman Filter

Extended Kalman filter apply in nonlinear system. It can convert the nonlinear filtering problem into linear filtering problem and get suboptimal results. The main steps for estimation of attitude angles by extended filter are as follows.

(1) State equation and measurement equation are established as shown in equation (1).

$$\begin{cases} X_0 = [\varphi_r \, \theta_r \, \varnothing_r]^T \\ X_k = f_{k/k-1} X_{k-1} + W_{k-1} \\ Z_k = H_k X_k + V_k \end{cases} \quad (1)$$

In the equation (1), the X_0 is the initial value of the state equation of gyroscope measurements, the X_k is the state estimation value, X_{k-1} is the value of the previous state, $f_{k/k-1}$ is a state transition matrix of the state before and after, W_{k-1} is the process noise, V_k is the measurement noise, Z_k is observation value or accelerometer measurements, H_k is the correlation matrix for measuring.

(2) The initial error covariance matrix P_0 is decided.

(3) The state function is predicted as shown in equation (2).

$$\hat{X}_{k/k-1} = f_{k/k-1}\hat{X}_{k-1} \qquad (2)$$

(4) Mean square error is updated as shown in equation (3).

$$P_{k/k-1} = f_{k/k-1}P_{k-1}f_{k/k-1}^{T} + Q_{k-1} \qquad (3)$$

The Q_{k-1} is the process noise covariance matrix.

(5) The filter gain is updated as shown in equation (4).

$$K_k = P_{k/k-1}H_k^{T} \Big/ H_k P_{k/k-1} H_k^{T} + R_k \qquad (4)$$

The R_k is the measurement noise covariance matrix.

(6) The state function is estimated as shown in equation (5).

$$\hat{X}_k = \hat{X}_{k/k-1} + K_k \qquad (5)$$

(7) The mean square error is updated in equation (6).

$$P_k = (E - K_k H_k)P_{k/k-1}(E - K_k H_k)^{T} + K_k R_k K_k^{T} \qquad (6)$$

Based on the above steps, the extended Kalman filter is designed by LabVIEW, just as shown in Fig.8.

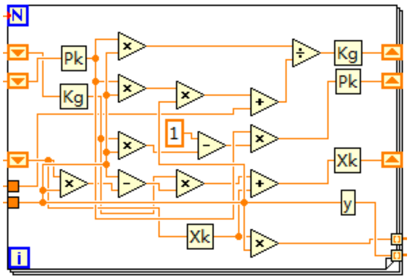

Fig.8: The program diagram of the extended Kalman filter

5.2 The Innovation-Based Extended Kalman Filter

On the basis of the extended Kalman filter, an innovation-Based extended Kalman filter is proposed. The innovation sequence is used in the noise covariance of the process and the measurement estimation. It solves the uncertain problem of the statistic character of noises caused by the strong disturbance environment. The calculate formulas are shown in (7), (8), (9), (10).

Supposed n_k is the innovation state in the time *k*. Z_k is the measured value.

$$n_k = Z_k - H_k \hat{X}_{k-1} \qquad (7)$$

The optimal estimate of the innovation variance is shown in (8). The *r* is the width of the innovation sequence.

$$\overline{nv_k} = \frac{1}{r}\sum_{i=k-r+1}^{k} n_i n_i^{T} \qquad (8)$$

The estimations of the noise covariance are shown in (9) and (10).

$$\hat{Q}_{k-1} = K_{k-1}\overline{nv_k}K_{k-1}^{T} \qquad (9)$$

$$\hat{R}_k = \overline{nv_k} - H_k P_{k/k-1} H_k^{T} \qquad (10)$$

The program diagram of the innovation-based extended Kalman filter is shown in Fig.9.

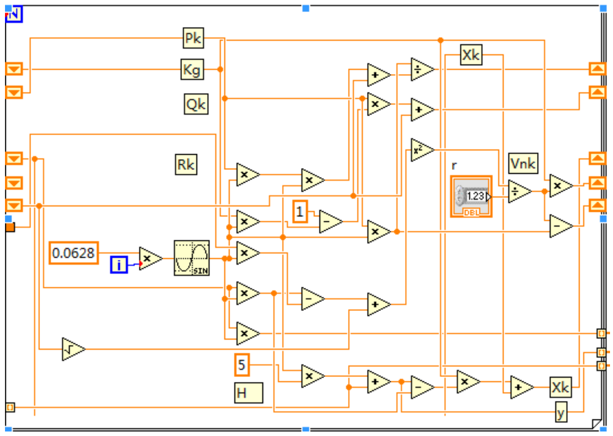

Fig.9: The program diagram of the innovation-based extended Kalman filter

5.3 Comparative Result

The attitude angles estimated through the extended Kalman filter and innovation-based extended Kalman filter can be shown as waveforms, just shown in Fig.10.These waveforms can be used to analyze the accuracy of the attitude angles. xtended Kalman filter apply in nonlinear system. It can convert the nonlinear filtering problem into linear filtering

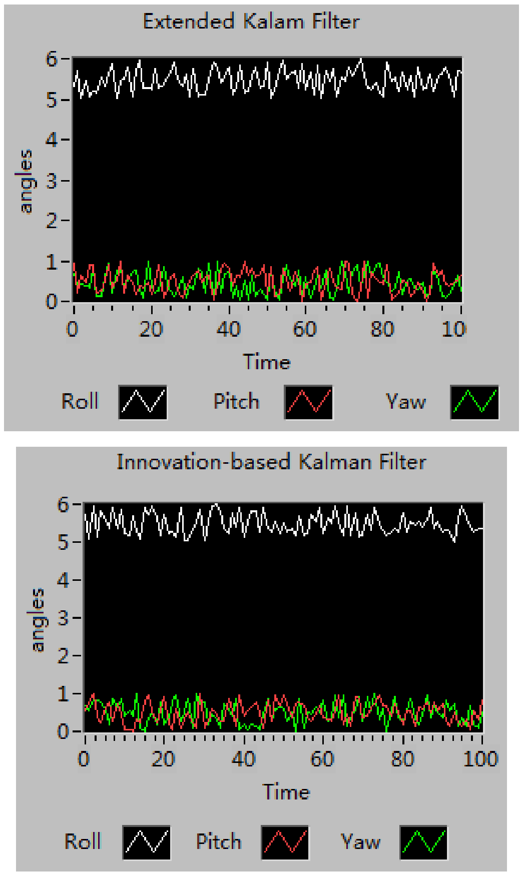

Fig.10: Displaying of the attitude angles

In the Fig.11, the deviations of the extended Kalman filter and the innovation-based extended Kalman filter are compared. It can be seen that the average deviation of the innovation-based Kalman filter is smaller than the average deviation of the innovation-based extended Kalman filter. So, the innovation-based extended Kalman filter can reduce the estimating error of the attitude angles and make the accuracy of the attitude angles estimation higher.

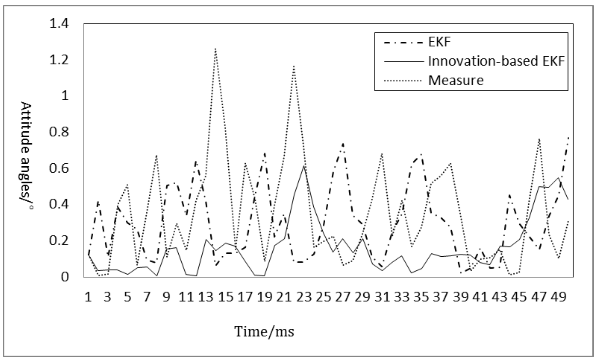

Fig.11: The deviation of the angles

6. CONCLUSIONS

An analysis system for attitude angles of four-rotor aircrafts was designed successfully. By means of the system, the accurate attitude angles can be shown as waveforms by the extended Kalman filter and the innovation-based extended Kalman filter separately. These waveforms were compared and judged which filter has better filtering effect.

The whole design of the system includes the hardware design and the software design. On the hardware side, the STM32F103CBT6 has been used to be the main controller, the MPU6050 has been used to be the Data Acquisition module and the NRF24L01 has been used to be the Wireless Communication Module. On the software side, the upper computer has been designed by the LabVIEW. First, the real attitude angles have been read and saved in the spreadsheet. Then, the extended Kalman filter and the innovation-based extended Kalman filter have been designed. The innovation sequence is used in the noise covariance of the process and the measurement estimation.

The results of designed analysis system are given. The accurate attitude angles are shown by the extended Kalman filter and the innovation-based extended Kalman filter directly. The filtering effect can be compared through the deviation of the angles. The analysis system works well.

7. REFERENCES

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