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Fuzzy Gain Scheduling of Complementary Filters

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Abstract: This study presents the development of a fuzzy gain scheduling scheme of complementary filters for attitude estimation of six degrees of freedom floating objects. Fuzzy rules and reasoning are utilized on-line to determine the time scale parameter (alpha) based on the gyroscope and accelerometer values commensurate with their full scale ranges. This adaptive filter combines accelerometer output for low frequency attitude estimation with integrated gyroscope output for high frequency estimation. The raw accelerometer output includes a component for the airframe acceleration that occurs predominantly in the object's maneuvers. The validity of gyroscope or accelerometer measurements varies according to the intensity of its movements. In stable conditions, accelerometers can have better estimation on the attitude, though in maneuvers they are misleading due to the linear accelerations on the other hand gyroscopes behave contrarily. Larger time scale trusts the integrated gyro signal for longer and shorter time scale merges the accelerometer signal in faster. Experimental results show better performance since the filter is customizable corresponding different applications.

Key words: Fuzzy, complementary filter, low-cost IMU, gain scheduling, Iran

INTRODUCTION

One of the most urgent tasks is to determine the status of control of the drone. With the increasing use of drones and increasing need to build low-cost and reliable the researchers have particular tendency to develop simple and reliable drones methods that by using them to flying condition can be estimated (Baerveldt and Klang, 1997; Jun *et al*., 1999). Many articles have been done on the subject of technical methods for filtering the State estimation data. For example, according to the study of Markley *et al*. (2005), we can acquaintance with lots of them. More advanced techniques (such as particle filter etc.) are computationally expensive and cannot be used for small processors that are usually on drones, so there are two general methods that are commonly used more than others, EKF: Extended Kalman Filter and some of the specified methods of determining constant efficiency. Method of determining the constant efficiency, often with a complementary filter is implemented. The filter, implemented filtering efficiency with respect to frequency intervals in linear method.

Extended Kalman filter method have been studied in several applications in aerospace science studues (Jun *et al*., 1999; Markley *et al*., 2005; Egziabher *et al*., 2004). This has been proved that this filter to be reliable for applications is faced with many problems in implementation, so in many practical applications from simple single-input-single-output filter are used (Corke, 2004). In recent years a number of researchers have studied the complementary filters and nonlinear single input-single output (Bonnabel *et al*., 2006; Mahony *et al*., 2005; Maithripala *et al*., 2004; Thienel and Sanner, 2003; Vik and Fossen, 2001; Salcudean, 1991). To implement the plan onto the UAV data inertial measurement unit of the output of accelerometers is used to estimate for the acceleration of gravity. The recent researchers activities (Hamel and Mahony, 2006; Mahony *et al*., 2005) possible estimation of flying position with a fixed error in the heading the provided only by using the accelerometer and gyroscope output data.

But the output of this filter in state estimation method may be failed. It is only when the fly was so large that the output dynamic accelerometers is not enough to provide an accurate estimate of the acceleration due to gravity. This happens especially at a time when the fly wants a fixed-wing mode and in a limited space, its rotation maneuver and repeat several times.

This study presents a comparative method to determine the complementary filter. This method uses fuzzy logic and output data accelerometer and uses gyroscope to determine the complementary filter. In this study, a method is provided to determine efficiency of

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manner complementary filter by advanced method. Due to the low-pass and high-pass output data accelerometer and gyroscope output of data the filter should be determined with the help of fuzzy rules so that when the situation changes quickly, according to data more gyroscopes and vice versa at times the birds, gradual change in that situation the biggest focus is on the accelerometer output data. In this manner the input and output membership functions and fuzzy system to follow the rules that determine the proposed method is quite understandable.

Complementary filter: The Gyro sensor structure is such that it shows output changes very faster than and much better than a gradual change. In other words, if the speed is very slowly revolved in a gyroscope and its output is integrated as it switches to gain some underestimated the situation would be changed.

The opposite is true in the case of an accelerometer sensor. This means that if the sensor with high frequency and low amplitude swing constantly in positive and negative direction, the resulting output indicative of swing status will not be true thus, a method is required to combine the two outputs of sensors to achieve the desired output. Therefore, the performance performance of complementary filter in state estimates a low-pass filter on the low-pass estimation of the state that obtained from the accelerometer and a high-pass filter on the high-pass estimation resulting from the integration of the gyro output will be applied. Then the two estimates are combined together to give an overestimate. If the variable angle screw and roll of fly, modeled individually, a single-input single-output filter can be designed use for any signal to the output of the angle between the connected device's accelerometer and gyroscope separate body axis as a reference and output status as the reference speed in a classic linear complementary filter (Buskey *et al*., 2003). According to the presented, a block diagram one of the simplest forms of complementary filter will be as Fig. 1. In this way, complementary filter the filter is to combine, low-pass data accelerometer θ_{accel} to high-pass data of the gyroscope's θ_{gyro}. This combining is done by the following relationship:

$$\theta = \alpha.\theta_{gyro} + (1-\alpha).\theta_{accel} \quad (1)$$

Thus, the considered all over output will be provided. In this regard the value of the parameter α which between zero and one must be determined in such a way that combination of both the sensor data; provide the best

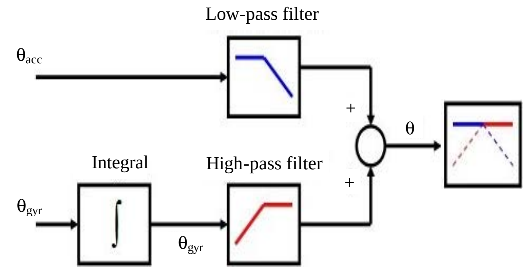

Fig. 1: The block diagram of complementary filter

estimate about changing target positions. In simplest form the variables can be assumed as constant. In some ways this parameter is determined by the help of different equations.

Euston *et al.* (2008) have introduced explicit complementary filter which performs by quaternion matrix and PID control. But in this phase these parameters will be determined by a method that is described as.

MATERIALS AND METHODS

State estimation by Inertial Measurement Unit (IMU): A Six-axis inertial measurement unit can measure the speed and angular acceleration. Common measurement units provide a measurement of the magnetic field but it is not useful signal in UAV applications because the magnetic field is affected by other electronic equipment. Gyroscope measurements are modeled by the following Eq. 2:

$$\bar{\Omega} = \Omega + b + \eta \quad (2)$$

Where:

Ω = The actual value
b = Bias value with time slow changes and
η = A noise process with mean zero

In this regard, the $\bar{\Omega}$ is a vector included of both the variable roll rate φ and screws θ. An angular rate can be used to estimate UAV state but noise and bias value cause the deviation of the actual amount estimation over time. Accelerometer measure "Specific Acceleration" in the body of the device:

$$f^b = a^b - g^b \quad (3)$$

Where:

a^b = UAV accelerometer of inertia machine that is expressed in the body device
g^b = The acceleration of gravity on the body

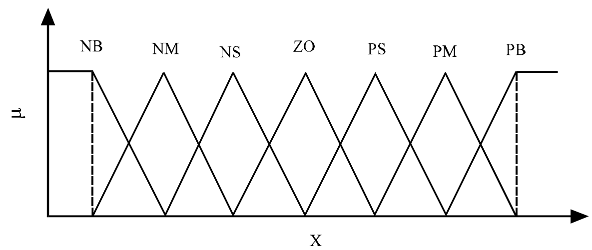

Fig. 2: The input membership function

At the time of flying a^b is considered to be zero. So as to estimate the gravitational acceleration $\hat{g}_b = -f^b$ can be used as a complementary filter input. The initial estimate of the roll angle φ and θ can be screwed directly be obtained as follows:

$$\hat{\phi}_f = A\tan 2\left(-f_y - \sqrt{fx^2 + fz^2}\right) \quad (4)$$

$$\hat{\theta}_f = A\tan 2(fx\sqrt{fy^2 + fz^2})$$

In which Atan2 inverse tangent function with two arguments that the output angle of the signal input arguments will be calculated at all angles. This single-input-single-output estimates used directly in the implementation of complementary filters (Corke, 2004). It is essential to note that when the flying is maneuvering and above relationships are not valid.

Efficiency determining system the fuzzy logic: Figure 2 shows efficiency determining system by fuzzy logic. In fact this system, the parameter α in Eq. 1 is determined with the help of fuzzy logic. In the beginning, it should be noted that single input-single output will cause the system to be screwed amount of each of the variables θ and φ roll individually but determined by quite similar ways. In this regard the value of the parameter α, efficiency gyro sensor and accelerometer efficiency in determining the amount of 1-α in determining output.

The relationship between the parameter α is closer to zero, status output, less dependent on gyro sensor and accelerometer sensor is more dependent on. But contrary to what this parameter to a close affiliation increased output gyroscope and accelerometer decreases. Therefore, the researching principles of this system is that the parameter α should change when the speed is down to zero and when speed change is more it should be closer to one.

According to the block diagram the data input fuzzy system to detect speed changes will be Ω and f^b. In this way-input data changes ranges assumed into two values between +FSR and FSR, therefore without loss of generality the input data divided into FSR value to their ranges between 1 and -1.

Table 1: Fuzzy rules

Variables	NB	NM	NS	ZO	PS	PM	PB
NB	S	S	S	S	S	S	S
NM	B	B	S	S	S	B	B
NS	B	B	B	S	B	B	B
ZO	B	B	B	B	B	B	B
PS	B	B	B	S	B	B	B
PM	B	B	S	S	S	B	B
PB	S	S	S	S	S	S	S

After determining the range of input data should the membership function of the input be determined. Input membership function determined that how much each input according to its value belongs to each group of NB, NM, NS, ZO, PS, PM and PB. The amount allocated to each group to each entry can be a number between 0 and 1. Input membership function diagram is according to Fig. 2 where x can be one of the variables Ω or f^b.

After determining the input membership function, fuzzy logic rules that we want to build it out. The rules presented in Table 1. Columns allocated to Ω input and rows of the table allocated to input f^b, respectively. To check this (Table 1), we should first check name means of input groups. N in this category means negative and P means positive. The letters S, M and B respectively means small, medium and large. ZO also means zero point. In addition to the output of the fuzzy rules table, the B and S means big and small. To check out this chart, we can examine one of the table cells. For example, the output row with the beginning of NS and a column with beginning of ZO is the letter S. This means that if the input Ω belong to the membership function NS input and input f^b belong to the membership function of ZO input the output fuzzy system should be determined by the membership function output S which means small. Output membership function for groups B and S is determined in accordance with the following equation:

$$X_s(\mu) = e^{-4\mu} \quad (5)$$

$$X_B(\mu) = 1 - e^{-4\mu} \quad (6)$$

These relationships graph have been drawn in Fig. 3. Another, point that should be noted about fuzzy rules is rules of composition. Since, an input may belong to more than one group, the output may also be produced by >1 of the points table. The outputs must AND together to result in the final output. In this method for the AND, multiplication must be used. Finally, to determine the output average gravity should be used:

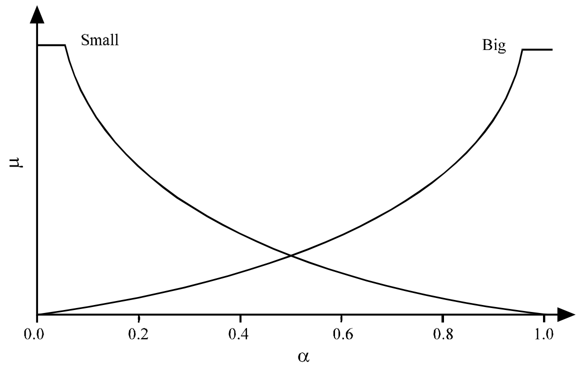

Fig. 3: Membership function graph output for big and small inputs

$$\alpha = \frac{\sum_i \mu_i x \mu_i}{\sum_i \mu_i} = \sum_i \mu_i \, x\mu_i \quad (7)$$

Stability and convergence: Designed system may be Non-convergent due to unstable source of input data. The project consists of two gyro sensor and accelerometer is used. If the output of each of the sensors be constant, designed system must be sustainable. For a limited amount of output sensors, then multiplied by the value of the parameter α which number is <1 is still limited. But there are cases that may actually input the output of each sensor system is designed, unlimited or is invalid. To obtain variable angles, gyroscope output must be integrated. If a gyro output data drifts the integration of it will cause output instability. So, make designed system outputs unstable. But, we can say that the method to determine the phase of each of these sensors will reduce the possibility of instability. When the device is almost constant, gyro sensor output value is close to zero, so the output of the sensor noise level will be lower and this will invalidate the dates. But, the system design phase system reduces the risk of instability and invalid output. Because the rules of the system is in such way that when changing is low, reduced the efficiency of the gyro sensor to determine the efficiency and increases the validity of system output.

The opposite is also true in the case of an accelerometer during maneuvers. To check this, it should be noted that usually the lack of credit and guarantees in the amount of output accelerometers, angular arise in times of rapid change. The fuzzy rules determining efficiency system have been set in such way that specified at the time of drastic changes such maneuvers, reduces the efficiency of the accelerometer, so the possibility of instability of output reduced. Of course, prove this issue needs to be more exact mathematical investigation that given the complexities of mathematical modeling fuzzy systems can have its own difficulties.

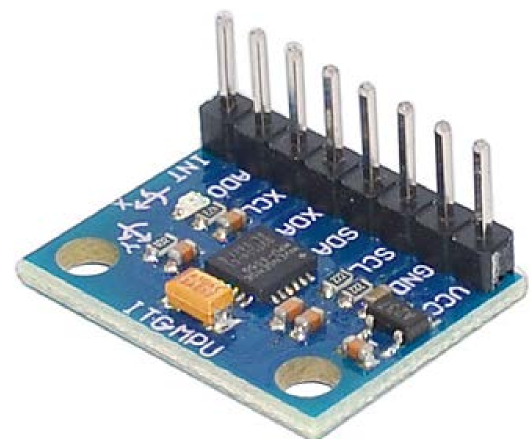

Fig. 4: MPU6050

Test equipment: First, for designed system implementation accelerometer and gyroscope sensors are required. Secondly, a microcontroller for receiving and reading sensor data, implementation of fuzzy rules and create complementary filter is required. The sensors used in this section are examined and then the microcontroller and its range will be discussed.

The sensors used MEMS: Micro-electromechanical and both accelerometers and gyro sensor placed in an IC. This IC has three gyro sensor and three sensors are accelerometers in three axes. In addition, in all cases a thermometer and some of them are also equipped with three Compasses in three directions.

To check the results, the three sensors are used. The first sensor is named MPU6050 and produced by Invensense. The sensor is one of the world's fastest motion detection tools that is designed for applications with power and low price and have good performance in smart phones, tablets and wearable sensors. The image of IC is shown in Fig. 4.

The second sensor is product of the same company, named MPU9250. The IC consists of the accelerometer, gyroscope and compass thermometer. The IC features compared to MPU6050 index is being smaller and less power consumption. It has two features that reduce the accuracy of its outputs. The image of this IC board is shown in Fig. 5. Since, this board is also used for MPU6500 sensor, MPU92/65 is also written on it. The next sensor which is used in the testing is named BMX055 and is product of Bosch Company. Accelerometer sensor

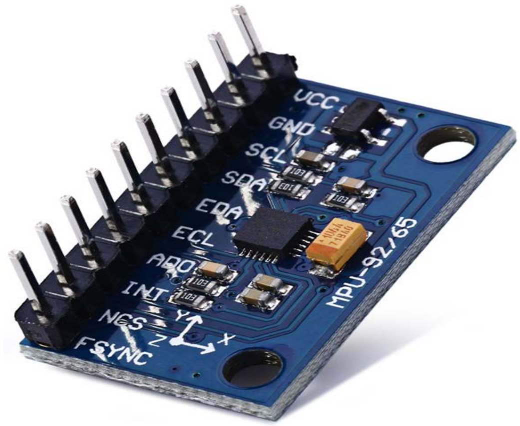

Fig. 5: MPU9250

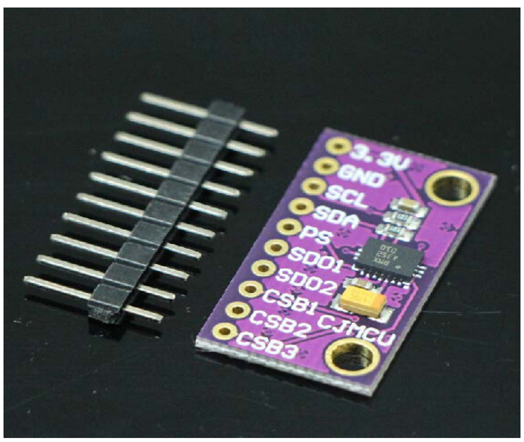

Fig. 6: BMX055

output is 12-bit Gyroscope sensors output are 16-bit. This IC is used in navigation indoors, virtual reality devices and the image of this IC board is shown in Fig. 5 and 6.

After reviewing the used sensors the microcontroller will be examined. In this study, a microcontroller with ARM central processor is used. This microcontroller that is named STM32F405RG is the product of ST's company. The central processor ARM Cortex-M4 microcontroller is a core digital signal processor and is equipped with floating-point computing unit. The 32-bit processor clocked at 168 MHz speed has high capacity computing. The microcontroller has 1 MB of flash memory and works with input voltage in the range of 1.8-3.6 V. But in this project, all boards research with 3.3V voltage. The IC sensor with is done a microcontroller via I2C protocol. The microcontroller important features such as timers, counters and well that given that the project is not intended to be addressed.

To use this microcontroller first a trial board is designed which consists only of microcontroller which provides the basic foundations to the user to use them and other electronic components to establish the connection between the sensor and microcontroller and by receiving the sensor output data and using fuzzy system implementation on the microcontroller, calculate the final estimate of the status. Figure 7 shows the image of the board.

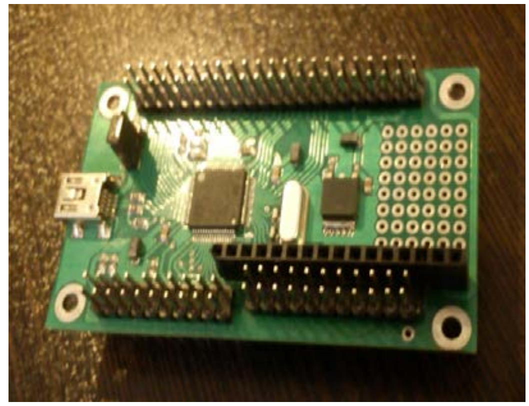

Fig. 7: Following examples microcontroller board

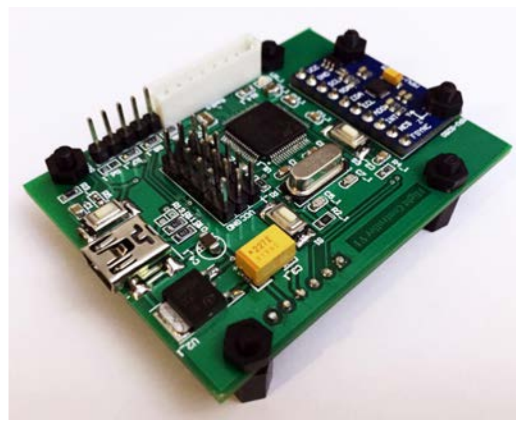

Fig. 8: The final sample microcontroller board

As can be seen, no electronic device except the essentials basic set up and programmed microcontroller is not on the board. After the board was tested and was read using the sensor output, another example of the board along with Bluetooth module for the reliable transmission line and power was built. The board also has features that IC board sensor is on it and with an integrated board on it a reliable hardware would be produced. The board image is shown in Fig. 8. It should be noted that the Bluetooth module is located under the board.

RESULTS AND DISCUSSION

For analyzing the results in the method three different sensors are used. The sensors were tested in the previous

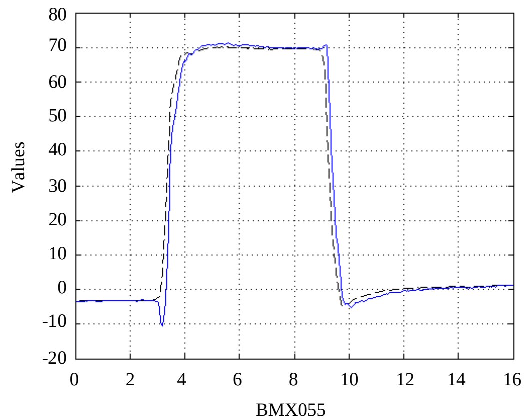

Fig. 9: Output roll angle sensor system is provided using BMX055

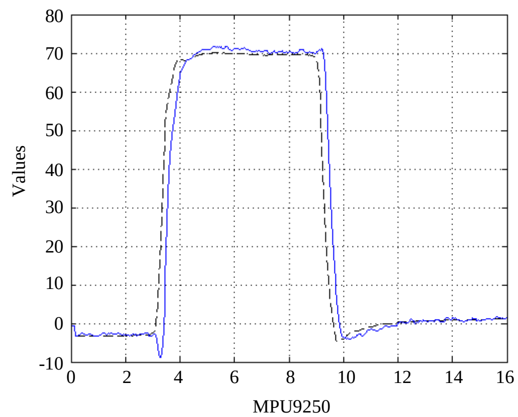

Fig. 10: The output graph roll angle system by using MPU9250 sensor

study. The experiment by giving a positive step and a negative step as much as 70° to the roll variable is done. The obtained results were compared with the output of the Kalman filter. Kalman filter is provided is used as reference since it is the best method to estimate state by using the accelerometer and gyro sensor. Figure 8 shows fuzzy system designed roll angle output graph depicts BMX055 using sensors.

Figure 9 as can be seen, the output of this sensor can accurately calculate the output of the Kalman filter. But, undershoot is a weaknesses of it. In addition, Fig. 10 and 11 charts show the same output using sensors and MPU6050 MPU9250. As can be seen the sensor output BMX055 compared with MPU9250 sensors and MPU6050, respectively has lower noise and higher accuracy. This is because of more accuracy of BMX055 sensor.

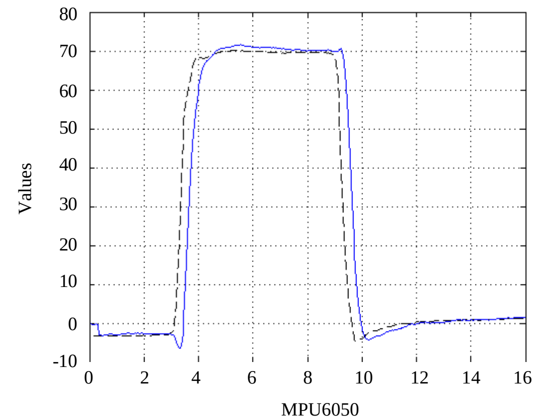

Fig. 11: The system roll angle output graph by using sensor MPU6050

CONCLUSION

The presented fuzzy efficiency determining system of membership functions and fuzzy rules is used to determine the efficiency of complementary filter. The proposed method in different experiments includes the use of several sensors to determine the law has been effective. The proposed method in different tests including the use of different sensors and mechanical different periods have been studied and tested and has achieved satisfactory results. In these experiments the results Kalman filter output which is the most complete method is used as a reference to determine the status and the results of the survey have shown the software and hardware implementation which is less complex approach could estimate Kalman filter output as well.

In addition, analysis of the stability and convergence of the system has been provided and indicate if the system inputs be limited/valid the output will be limit/valid. Moreover, the use of this method makes the system output to be stable and reliable in the invalid accelerometer output in fast movements or even in invalid and unlimited integral gyro output in steady state or slow movements.

SUGGESTIONS

The research and experiments which have been investigated on the use of fuzzy methods to determine the complementary filter so far, indicates that by research on the rules tables and conducting experiments we can study whether the rules given in this article are optimal at all conditions or not. For example, this table is perfectly symmetrical and studies the two inputs accelerometers and gyroscopes is absolutely the same. Also in this project as being simple and fast algorithm performance after the implementation the microcontrollers is very important, linear membership functions have been used. In addition, mathematical analysis, integration and sustainability of the system using valid measures can help researchers in the future. The other issue which has been concerned by researchers today is to estimate quaternion by using low-cost and low-power accelerometer and gyroscope sensors the providers of this article now on this theme uses complementary filter and use the efficiency determining system. This method also can be used to evaluate and determine a nonlinear method. That is by setting different rules and membership functions can determine acceptable behavior as an output of estimator and for which design a more dynamic transfer function that is more efficient in terms of volume calculations.

REFERENCES

Baerveldt, A.J. and R. Klang, 1997. A low-cost and low-weight attitude estimation system for an autonomous helicopter. Proceedings of the IEEE International Conference on Intelligent Engineering Systems INES'97, September 17-17, 1997, IEEE, Halmstad, Sweden, ISBN:0-7803-3627-5, pp: 391-395.

Bonnabel, S., P. Martin and P. Rouchon, 2006. A non-linear symmetry-preserving observer for velocity-aided inertial navigation. Proceedings of the Conference on American Control, June 14-16, 2006, IEEE, Paris, France, ISBN:1-4244-0209-3, pp: 5-5.

Buskey, G., J. Roberts, P. Corke, P. Ridley and G. Wyeth, 2003. Sensing and control for a small-size helicopter. Exp. Rob., 8: 476-486.

Corke, P., 2004. An inertial and visual sensing system for a small autonomous helicopter. J. Rob. Syst., 21: 43-51.

Egziabher, D.G., R.C. Hayward and J.D. Powell, 2004. Design of multi-sensor attitude determination systems. IEEE. Trans. Aerosp. Electron. Syst., 40: 627-649.

Euston, M., P. Coote, R. Mahony, J. Kim and T. Hamel, 2008. A complementary filter for attitude estimation of a fixed-wing UAV. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS, September 22-26, 2008, IEEE, Australia, ISBN:978-1-4244-2057-5, pp: 340-345.

Hamel, T. and R. Mahony, 2006. Attitude estimation on SO [3] based on direct inertial measurements. Proceedings of the IEEE International Conference on Robotics and Automation ICRA, May 15-19, 2006, IEEE, New York, USA., ISBN:0-7803-9505-0, pp: 2170-2175.

Jun, M., S.I. Roumeliotis and G.S. Sukhatme, 1999. State estimation of an autonomous helicopter using Kalman filtering. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS'99, October 17-21, 1999, IEEE, Los Angeles, California, ISBN: 0-7803-5184-3, pp: 1346-1353.

Mahony, R., T. Hamel and J.M. Pflimlin, 2005. Complementary filter design on the special orthogonal group SO (3). Proceedings of the 44th IEEE Conference on Decision and Control, European Control Conference CDC-ECC'05, December 15-15, 2005, IEEE, Canberra, Australia, ISBN:0-7803-9567-0, pp: 1477-1484.

Maithripala, D.H.S., J.M. Berg and W.P. Dayawansa, 2004. An intrinsic observer for a class of simple mechanical systems on a Lie group. Proceedings of the Conference on American Control, June 30-July 2, 2004, IEEE, Lubbock, Texas, ISBN:0-7803-8335-4, pp: 1546-1551.

Markley, F.L., J. Crassidis and Y. Cheng, 2005. Nonlinear attitude filtering methods. Proceedings of the AIAA Conference on Guidance, Navigation, Control and Exhibit, August 15-18, 2005, AIAA, San Franscisco, California, pp: 1-32.

Salcudean, S., 1991. A globally convergent angular velocity observer for rigid body motion. IEEE. Trans. Autom. Control, 36: 1493-1497.

Thienel, J. and R.M. Sanner, 2003. A coupled nonlinear spacecraft attitude controller and observer with an unknown constant gyro bias and gyro noise. IEEE. Trans. Autom. Control, 48: 2011-2015.

Vik, B. and T.I. Fossen, 2001. A nonlinear observer for GPS and INS integration. Proceedings of the 40th IEEE Conference on Decision and Control, December 4-7, 2001, IEEE, Trondheim, Norway, ISBN: 0-7803-7061-9, pp: 2956-2961.