퍼지추론을 이용한 철도·항공시스템에서의 자세제어시스템

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Strapdown Attitude Reference System(SARS) in the Railway and Aviation System using Fuzzy Inference

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Abstract - This paper describes the development of a closed-loop Strapdown Attitude Reference System (SARS) algorithm integrated filtering estimator for determining attitude reference for railway and aviation system using fuzzy inference. The SARS consists of 3 single-axis rate gyros in conjunction with 2 single-axis accelerometers. For optimal values of fuzzy systems, we utilize on-line scheduling method for initial values and then use genetic algorithms for fine tuning. Implementation using experimental test data of unmanned aerial vehicle has been performed in order to verify the estimation. The proposed fuzzy inference based SARS demonstrate that more accurate performance can be achieved in comparison with conventional one. The estimation results were compared with the on-board vertical gyro as the reference standard.

1. Introduction

Research and development in the technologies related to railway and aviation system including Unmanned Aerial Vehicles (UAV) have been interesting topics in military and civil aviation industry for the past decade[1][2]. An attitude measuring system is indispensable for operation and flight control all the time from launch to landing, and it needs to be as accurate as possible. For example, a high altitude UAV, it is required that these measurement should be better than order 1.0 degree and a resolution of 0.5 degrees[3]. A gimbaled or strapdown inertial sensor system is able to meet the requirements for attitude measurements. The current state of the art in the determination of aircraft attitude angles is still primarily by means of the vertical gyroscope(gyro)[4]. The traditional vertical gyro is a spinning wheel in a gimbaled frame, and uses torquers at each gimbal to adjust and correct attitude, but is complex, expensive, bulky, and heavy[5].

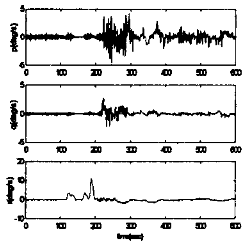
Genetic Algorithms (GAs) were invented by John Holland and developed by him and his students and colleagues[6]. GAs are a stochastic global search method that mimics the metaphor of natural biological evolution. GAs operate on a population of potential solutions by applying the principle of survival of the fittest to produce better and better approximations to a solution.

In this paper, a new closed-loop SARS algorithm based on fuzzy logic for the railway and aviation system using low-cost solid-state inertial sensors will be derived. By recognizing the situation of dynamic condition via fuzzy logic inference process, each parameter of the estimation filter of the existing SARS algorithm is determined online adaptively under varying aircraft dynamics. For this solution scheme, fuzzy rules and reasoning are based on the error signal of the gyro and accelerometer and the magnitude of dynamic motion.

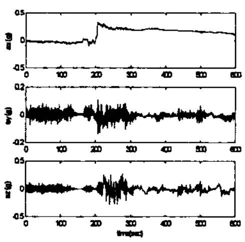
2. Attitude Determination from Inertial Sensors

2.1 Experimental Data

During all the scheme investigation process in this paper, a set of test data from UAV is used. The following figures show parameter time histories of the flight. All parameters of approximately 600 seconds flight duration were sent telemetrically with 10Hz from launching.

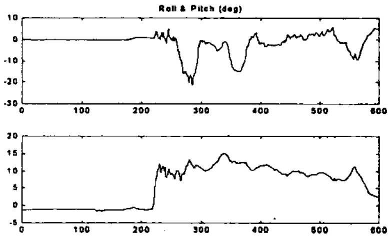


<Fig.1> Test rate gyro measurements



<Fig.2> Test accelerometer measurements

During the test flight, the UAV climbed to cruise altitude at a relatively high rate of climb while maneuvering about the roll axis. The solid-state low cost rate gyro that we adopted is RRS-75 of Inertial Science Inc. (ISI) and we also used CXL04LP3 of Crossbow as an accelerometer. The measurement of angular rates (p, q, and r) and accelerations (a_x,a_y,a_z) from rate gyros and accelerometers are shown in Fig. 1 and 2, respectively. Fig. 3 shows attitude angles obtained from the on-board vertical gyro used as the reference standard or 'truth model'.



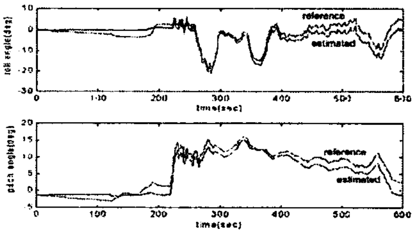
<Fig.3> Attitude angles from the on-board vertical gyro (reference)

2.2 Attitude Determination from Rate Gyros and Accelerometers

Starting with the matrix form of differential equations expressed in terms of Euler angles:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix} \tag{1}$$

It is apparent that solving this equation for a strapdown system using numerical integration will provide attitude angles in terms of Euler angles ψ, θ, and ψ with respect to the chosen reference frame. As a physical instrument, rate gyros also carry some errors such as axis misalignment, fixed bias, drift bias, fixed scale factor errors, asymmetric scale factor error, and so on. The bias drift would be the most serious and deteriorate the accuracy of a SARS. The bias drift, which normally shows nonlinear characteristics, causes the integration result to drift-off from the true attitude as a function of time and rapidly renders the calculation useless.



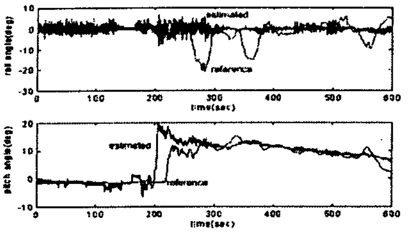
<Fig.4> The Euler angles calculated from rate gyro measurement

Euler angles obtained from open-loop integration of Eq.(1) using first order Euler method of integration are illustrated in Fig. 4 and compared with the reference from the vertical gyros. This result shows ①how the bias errors cause the attitude angles to deviate, and ②the instability of the integration which drifts as a function of time unless corrected.

$$\theta = \sin^{-1}\left(\frac{f_x}{g}\right), \quad \phi = \sin^{-1}\left(\frac{-f_y}{g\cos\theta}\right) \tag{2}$$

It should be noted that the attitude determination using Eq.(2) is true only for specific conditions such as steady level operation and/or flight. If railway and aviation system are circling for an extended period, the accelerometer will not only detect gravitational acceleration, but also centrifugal forces, resulting in incorrect attitude determination. In addition, the change in transient forward acceleration is another possible error source. This means that the attitude calculation from accelerometers is not valid under all dynamic conditions.

Accelerometer measurements during the test are shown in Fig. 2, and the attitudes obtained from simple calculation using Eq.(2) are illustrated in Fig. 5 where it is compared with the reference from the vertical gyros. These results show that the attitude from accelerometers tend to follow the vertical gyro output approximately in steady state, but large errors and poor reliability result in transient and high dynamics.

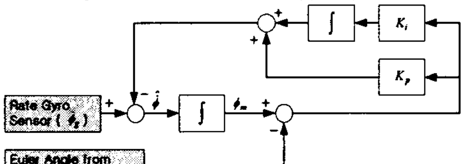


<Fig.5> The Euler angles calculated from accelerometer measurements

3. Fuzzy Attitude Estimator from Inertial Sensors

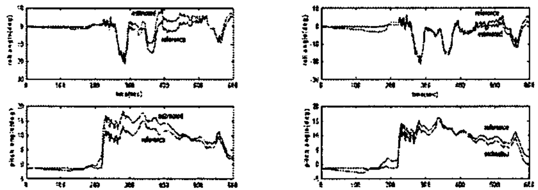
3.1 Conventional Attitude Estimator

To observe and compensate for gyro drift, a process called augmentation is used, utilizing other system states to compensate for gyro errors. One of the conventional approaches is called the accelerometer aided mixing algorithm of SARS. This scheme involves a set of 3-axis rate gyros that provide the required attitude information from integration in combination with a 2-axis accelerometer. The basic concept of this scheme is that proper combination (filtering) of gyro and accelerometer measurements could make precise attitude information available. The gyros are responsible for measuring the transient dynamic part of aircraft motion, while the accelerometers give precise absolute measurement of attitude over a longer period. In this section, the theoretical approach to conventional attitude estimation is provided and reveals some typical problems and drawbacks.



<Fig.6> Conventional closed loop SARS block diagram for roll axis channel

Variation in the estimator's cut-off frequency (natural frequency) had been exercised at 0.01 rad/s and 0.001 rad/s. The estimation results are compared with the vertical gyro outputs in Fig. 7. When cut-off frequency is 0.01 rad/s (a relatively high frequency), the estimation angles converge well at the steady state, but not during high dynamic motion. Reducing the cut-off frequency is set to 0.001 rad/s does not improve the situation. This is because as a cut-off frequency goes lower, the high frequency dynamic characteristics of the filter improve, but the low frequency characteristics become worse. Therefore, the cut-off frequency needs to be optimized to improve the performance of the estimation filter over a wide range of dynamic conditions. However, it is difficult to achieve acceptable performance in all dynamic conditions using this fixed gains filtering structure, especially when using low-cost (high bias drift) solid-state sensors. To overcome these problems, it is necessary to expand the current SARS algorithm to have an adaptive function under varying dynamics.



(a) cut-off frequency=0.01 rad/s (b) cut-off frequency=0.001 rad/s

<Fig.7> Effects of estimation filter cut-off frequency on estimated attitude angles

3.2 Fuzzy Attitude Estimator

Fig. 8 shows a fuzzy logic based attitude filtering estimator. The approach taken here is to exploit fuzzy rules and reasoning to generate parameters of the filtering estimator. The parameters are determined only by the cut-off frequency. Using simulation study results, the nominal cut-off frequency (ω_0) is set at 0.02(rad/s). In the proposed scheme, the cut-off frequency is adaptively determined based on the magnitude of the current error e(k) and the current dynamic motion m(k)as shown in Fig.8. Here the magnitude of the dynamic motion m(k) is defined as:

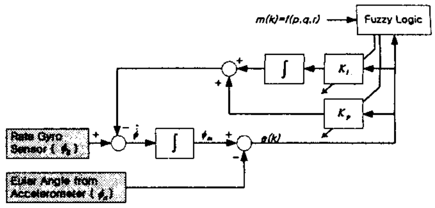
$$m(k) = \sqrt{p(k)^2 + q(k)^2 + r(k)^2} \tag{3}$$

The parameters of the estimation filter is thus obtained by

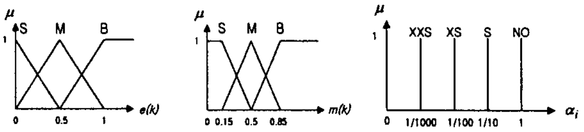
$$k_i = (\alpha\omega_0)^2 \quad \text{and} \quad K_p = \sqrt{2}\,\omega_0 \tag{4}$$

where α is determined by a set of fuzzy rules of the form.

$$IF\ \ e(k)\ is\ A_i \text{ and } m(k)\ is\ B_i\ ,\ then\ \alpha = \alpha_i \tag{5}$$



<Fig.8> Fuzzy closed loop SARS block diagram for roll axis channel



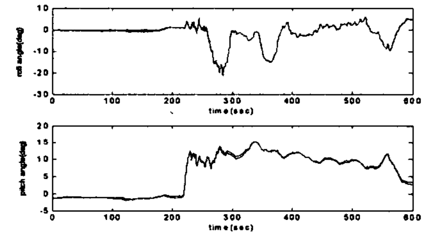
<Fig.9> Membership functions for e(k) and m(k), and singleton membership functions for α

Here, $A_i$and B_i are fuzzy sets of the corresponding supporting sets; α_i is a constant. The membership functions (MF) of the fuzzy sets for e(k) and m(k) are shown in Fig. 9. The fuzzy rule in Eq.(5) was extracted experimentally based on the characteristics of gyros and accelerometers. The either case when the magnitudes of the current error e(k) or the current dynamic motion m(k) is relatively big, the fuzzy inference engine judges that the attitude calculation from accelerometer is inaccurate. To assign more weighting to gyros, the crossover frequency should be decreased. Thus the constant α can be represented by a fuzzy set XXS. Thus a set of rules, as shown in Table 1, may be used to adapt α for the parameters of estimator, K_p and K_i.

Table 1. Fuzzy Tuning Rules for α

		e(k)		
		B	M	S
m(k)	B	XXS	XXS	XS
	M	XXS	XS	S
	S	XS	S	NO

We try to design enhanced fuzzy system having optimized parameters in closed loop SARS and specify fuzzy parameters using GAs. For the fuzzy system, there are ten optimizing parameters in fuzzy I/O membership function in roll channel and pitch channel respectively. The parameter optimization of the fuzzy based closed loop SARS developed after 110 generations in GAs optimizing procedure.



<Fig.10> Responses of the optimized SARS using GAs

4. Conclusion

The proposed closed loop SARS scheme uses fuzzy reasoning and GAs to determine and optimize the filtering estimator parameters by adjusting cutoff frequency. The proposed scheme has shown a good damping characteristic for drift errors form gyro measurement as well as accelerometer measurement noise corruption in all dynamic conditions. The performance improved SARS by GAs fine-tuning gave on accuracy of better than 0.12 deg in roll and 0.10 deg in pitch compared to a 'truth model' vertical gyro reading. This performance is very encouraging and indicates that high accuracy SARS should be possible with low-cost, low-performance inertial.

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