Research on Hybrid Redundancy Voting Algorithm Based on Fuzzy Theory

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Abstract. The hardware redundancy technology is to reduce the basic reliability in exchange for the high reliability and safety of the system, but the failure rate of the system will increase with the increase of the hardware redundancy. Aiming at the disadvantages of hardware redundancy, the article takes the angle of attack (AOA) as the object, and constructs the analytical value of AOA based on the analytical relationship between the sensors of the flight control system; Introduce an equalization algorithm to eliminate the drift error between redundant signals, further proposes a hybrid redundancy voting algorithm based on hardware redundancy and analysis redundancy. The algorithm calculates the weight of the sensor signal based on the difference between the sensor signal and the analytical value, so that the voting value is closer to the true value, thereby improving the safety of the system. At the end of the article, the feasibility of the voting algorithm is verified by simulation; the analytical study of the AOA proves the effectiveness of the hybrid redundancy design scheme and the voting algorithm.

1. Introduction
In order to meet the high safety and reliability of the flight, the fly-by-wire (FBW) flight control system mostly use redundant hardware redundancy[1], equipped with multiple sets of sensors. However, the use of redundant hardware redundancy technology will bring many disadvantages[2-3]. In view of the various deficiencies caused by hardware redundancy, the analysis redundancy is introduced to reduce the hardware redundancy and form a hybrid redundancy structure. According to the proposed hybrid redundancy structure, a monitoring voting algorithm is designed to enable the flight control system to effectively monitor and isolate the fault signal and obtain a voting signal closer to the true value.

This article takes the AOA as the object, combines the flight test data of a certain flight phase of the aircraft, and constructs the analytical value of the AOA according to the analytical relationship of the AOA signal, which is hybrid triple redundancy structure with the signals of two sets of independent AOA sensors installed on the aircraft. A hybrid triple-redundancy AOA monitoring and voting algorithm based on two sets of hardware redundancy and analysis redundancy is further proposed to improve the usability and reliability of the AOA signal.

2. AOA signal analysis
At present, the AOA signal is mostly solved according to the relationship between the airflow coordinate and the airframe coordinate, and the aircraft linear velocity component under the aircraft body shaft system is solved through the aircraft kinematics equation. Further calculate the AOA signal according
to the relationship between the aircraft linear velocity component and the AOA[3,4], and the estimated error of the AOA is ±0.5°.

In a certain flight stage of the aircraft, the sensors installed on the aircraft obtain various flight status signals, and obtain the analysis AOA signal according to the analytical relationship between the flight status signals, as shown in Fig 1.

Fig 1. Angle of attack signal analysis result

The AOA signal analyzed in a certain flight stage can quickly track the AOA signal transmitted by the sensor. The change of the analyzed AOA is smoother and the analytical error is within ±0.3°, which is within an acceptable range. When the aircraft flight status data is correct and valid, the AOA signal obtained by solving the analytical relationship of the AOA signal is correct and valid.

3. Voting algorithm design
In the process of redundant signal voting, firstly, the fault signal is detected and isolated based on the effectiveness monitoring of the signal itself and the comparison monitoring between the signals, and then an optimal signal is obtained according to the voting algorithm.

3.1. Traditional triple redundancy signal monitoring and voting algorithm
The margin signal is compared with the defined threshold value (δ) to determine whether the signal is faulty by pairwise difference, and the fault signal is counted (fault occurs, increase X; no fault, decrease Y). When the count exceeds the defined threshold (Z), then the signal is latched, and then the redundancy signal is fault detected and isolated[5]. The redundancy signal judges the final validity of the signal according to its own validity and comparison monitoring, and selects the final signal value according to the voting algorithm.

At present, the redundant signal voting methods used in the project include the median voting method [6] and the arithmetic average voting method[7]. In the absence of faults, median voting can well eliminate the influence of signal drift; compared to median voting, average voting can only mitigate the effects of signal fault drift[7]. When the failure rate is the same, the fault detection threshold of the average voting method is smaller than that of the median voting method[8].
3.2. Improved hybrid redundancy voting algorithm

Aiming at the obvious problem that the average voting algorithm reacts to the drift error, an equalization algorithm is introduced, and the input signal is equalized according to the validity of the signal and the voting value of the signal, so as to eliminate the influence of the average algorithm on the drift error. Tomlinson[8] proposed a triple redundancy signal equalization algorithm, which uses the method of integrating and equalizing all signals to eliminate the drift error between redundant signals (3.2.1 details).

Aiming at the average voting algorithm ignoring the actual characteristics of the original signal, Zhao Hangzhou[7] proposed a weighted average voting algorithm based on the statistical characteristics of each redundancy signal, which makes the voting value extremely close to the true value. Combining the mixed triple-redundancy signal voting structure composed of two hardware redundancy and analytical redundancy, this paper proposes a voting algorithm based on the difference between the analytical signal and the hardware signal and using fuzzy theory to assign the weight of the hardware signal. The improved hybrid redundancy monitoring voting block diagram is shown in Fig 2.

![Fig 2. Improved hybrid triple redundancy monitoring voting diagram](image)

3.2.1 Equalization algorithm. The specific algorithm is as follows:

\[
\begin{align*}
x_{1eq} &= x_1 - E_{q1} \\
x_{2eq} &= x_2 - E_{q2} \\
x_{3eq} &= x_3 - E_{q3}
\end{align*}
\]  

(1)

Where, \(x_1, x_2, x_3\) is the input signal 1, 2 and 3, \(x_{1eq}, x_{2eq}, x_{3eq}\) is the equalization signal of the input signal 1, 2 and 3, and \(E_{q1}, E_{q2}, E_{q3}\) is the equalization value of the input signal 1, 2 and 3.

The equalization value realizes the input toward the center of the target value according to the rate factor defined by different signal characteristics, as shown in (2).

\[
\begin{align*}
E_{q1_{n+1}} &= \left[K_f(x_{1n} - y_n) - K_c \cdot Centring_n\right] \\
E_{q2_{n+1}} &= \left[K_f(x_{2n} - y_n) - K_c \cdot Centring_n\right] \\
E_{q3_{n+1}} &= \left[K_f(x_{3n} - y_n) - K_c \cdot Centring_n\right]
\end{align*}
\]  

(2)

Where, \(K_f, K_c\) is the rate factor, \(y_n\) is the signal voting value at the previous moment, \(Centring_n\) is the equalization center value at the current moment, and \(E_{q1_{n+1}}, E_{q2_{n+1}}, E_{q3_{n+1}}\) is the equalization value of the input signals 1, 2 and 3 at the next moment. The calculation of \(Centring_n\) is shown in Figure 2.
3.2.2 Voting algorithm based on fuzzy theory. In the redundancy signal voting algorithm, Latifi-Shabgahi [9] uses fuzzy theory to calculate the weight of the triple redundancy signal. In the proposed improved hybrid redundancy voter, the voting signal is obtained according to the value and validity of the input data. If three signals are valid, output the weighted voting value; if two signals are valid, output the average value; if one signal is valid or all three signals are invalid, output the last-minute voting value. The content of fuzzy theory is as follows:

1) Define the difference between the sensor and the analytical value as $\text{abs}_x_1\text{diff}, \text{abs}_x_2\text{diff}$;
2) The fuzzy sets of $\text{abs}_x_1\text{diff}$ and $\text{abs}_x_2\text{diff}$ are {small, medium, large};
3) The fuzzy set of the weight of sensor 1 is {vlow, low, med, high, vhigh};
4) Membership function of input (output) fuzzy sets as shown in Fig 4 (5).
5) Fuzzy rules:
   a) If ($\text{abs}_x_1\text{diff}$ is small) and ($\text{abs}_x_2\text{diff}$ is large) then Weight is vhigh.
   b) If ($\text{abs}_x_1\text{diff}$ is small) and ($\text{abs}_x_2\text{diff}$ is medium) then Weight is high.
   c) If ($\text{abs}_x_1\text{diff}$ is small) and ($\text{abs}_x_2\text{diff}$ is small) then Weight is med.
   d) If ($\text{abs}_x_1\text{diff}$ is medium) and ($\text{abs}_x_2\text{diff}$ is large) then Weight is high.
   e) If ($\text{abs}_x_1\text{diff}$ is medium) and ($\text{abs}_x_2\text{diff}$ is medium) then Weight is med.
   f) If ($\text{abs}_x_1\text{diff}$ is medium) and ($\text{abs}_x_2\text{diff}$ is small) then Weight is low.
   g) If ($\text{abs}_x_1\text{diff}$ is large) and ($\text{abs}_x_2\text{diff}$ is large) then Weight is med.
   h) If ($\text{abs}_x_1\text{diff}$ is large) and ($\text{abs}_x_2\text{diff}$ is medium) then Weight is low.
   i) If ($\text{abs}_x_1\text{diff}$ is large) and ($\text{abs}_x_2\text{diff}$ is small) then Weight is vlow.
   j) If ($\text{abs}_x_1\text{diff}$ is large) or ($\text{abs}_x_2\text{diff}$ is large) then Weight is med.
   k) If ($\text{abs}_x_1\text{diff}$ is medium) or ($\text{abs}_x_2\text{diff}$ is medium) then Weight is med.
   l) If ($\text{abs}_x_1\text{diff}$ is small) or ($\text{abs}_x_2\text{diff}$ is small) then Weight is med.

Fig 3. Flowchart for the calculation of $\text{Centring}_n$
Fig 4. Membership function of input sets  

Fig 5. Membership function of output sets

4. Simulation verification and result analysis

Assume that the two-way AOA sensor signal and the analyzed AOA signal are shown in Fig 6. (assuming that the analyzed AOA signal C is the actual AOA of the aircraft. The AOA signal A and the AOA signal B are superimposed with Gaussian white noise with different variances to test the robustness of the voter and verify the effectiveness of the improved hybrid redundancy voting algorithm; the AOA signal A is in the first and the fourth cycle is injected with a fault signal with an amplitude of 3, the AOA signal B is injected with a fault signal with an amplitude of 3 in the third cycle, and the AOA signal C is injected with a fault signal with an amplitude of -3 in the fourth cycle to test whether the voting device can quickly and effectively identify the fault signal). To further verify the accuracy of the model and the accuracy of the voting algorithm, the AOA signals A, B, and C were set to be invalid in different periods, as shown in Fig 7. The Reset signal of the counter and latch module is shown in Fig 8.

Set the parameters of the counter module, the comparison monitoring module and the equalization module according to the signal characteristics. Based on the amplitude of the AOA signal and the sampling frequency (80 Hz), the simulation parameters are set as shown in Table 1. The results obtained by using the voting model designed in this paper are shown in Fig 9. a) The voting results of the improved hybrid redundancy voting algorithm using signal equalization and unequalization (OutputA, OutputB); b) The voting results of improved hybrid redundancy voting and average voting algorithms using signal equalization (OutputA, OutputC); c) Signal fault latch result graph; d) Output signal validity.

Table 1. Simulation model parameter configuration

| Up & Down Counter | Comparative monitoring | Equalization |
|-------------------|------------------------|--------------|
| X                 | Y                      | Z            |
| 30                | 1                      | 900          |
| δ                 | K_E                    | K_L          |
| 2                 | 0.5                    | 0.5          |
Analyze the results in Fig 9:

a) In the first time period, the three AOA signals are all valid, the AOA signal A fluctuates (the error margin is 3), and the error margin exceeds the threshold range. Therefore, the AOA signal A is processed for failure and the output signal is the average value of the signals B and C, the signal validity output result is 1.

b) In the second time period, the AOA signals A and B are invalid, and the three signals are normal. Therefore, the AOA signal A and B are invalidated. The output signal is the valid value at the previous moment, and the signal validity output result is 0.

c) In the third time period, the AOA signal C fails, the AOA signal B fluctuates (the error margin is 3), and the error margin exceeds the threshold range, so the AOA signal B is faulty and the AOA signal C is invalid, the output signal is the effective value at the last moment, the signal validity output result is 0.

d) In the fourth time period, the three AOA signals are all valid, the AOA signals A and B fluctuate (the error margin is 3), and the error margin exceeds the threshold range. Therefore, the AOA signals A and B are processed for failure. The output signal is the valid value at the last moment, and the signal validity output result is 0.

e) When the AOA signals A, B and C are all valid and there is no fault, the output signal is the weighted average of the AOA signals A and B, and the signal validity output result is 1;

f) Comparing the results of using equalization algorithm and not using equalization algorithm, the output signal value sudden change caused by signal failure can be effectively solved by the equalization algorithm, the output signal value is more stable, and the influence of redundant signal drift error is eliminated;

g) Compare the results of the improved mixing algorithm and the average algorithm. Since the AOA signal A is closer to the true value, the weight is higher, and the voting value is closer to the true value.

h) For signals that continue to fail and exceed the upper limit of counting, they can be latched correctly, and the counter value can be cleared by resetting the signal so that the latched signal can continue to participate in voting.

Fig 9. Monitor & voting output result
5. Conclusion
This paper takes the AOA as the object, and obtains the AOA based on the analysis of the physical relationship between the flight states of a certain aircraft. Based on the hybrid triple redundancy architecture composed of two AOA sensor signals and analytical AOA signals, an equalization algorithm is introduced to eliminate the drift error between redundant signals, and a hybrid triple redundancy voter design scheme based on fuzzy theory is proposed. Through simulation verify the effectiveness of the equalization algorithm and the correctness of the voting device design. This article has guiding significance for the sensor redundancy configuration and voting design of domestic civil aircraft.

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