A novel framework of building operation algorithm for the block of technical diagnostics of aircraft's automatic control system

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ABSTRACT

This article presents the problem of designing an automatic control system that is stable against errors and failures of sensors on aircraft. The sensor system has a technical diagnostic block that ensures diagnosis and eliminates typical errors and failures. Based on the determination of the error vector, damage can occur by adding measurement elements corresponding to the measurement parameters to the control system. When there are errors or failures of the sensor elements, the state vector of the system changes and is determined by measurements. The difference between the measured vector components when there are errors, failures and when working normally is the basis of the working algorithm of the failure diagnosis block. The results demonstrate encouraging prospects for practical implementations.

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1. INTRODUCTION

Research on the design and construction of algorithms for the automatic control system (ACS) of aircraft, in addition to ensuring stability and controllability, must also ensure the ability to diagnose technical status before errors occur. Destabilising effects on the system [1], [2]. Considering the aircraft as a control object, the control signal is properly calculated depending on the diagnosis of abnormal events such as damage or excessive error in a certain component of the system [3], [4]. Thus, the diagnostic block, in addition to the task of finding failures and determining the location, type, and form of failures, must also calculate and fix the failures [5]-[8]. If the failure is identified and corrected, the system is stable before failure [9]-[11]. To stabilise before failure, it is necessary to determine in the following order: i) identify abnormal phenomena of system instability; ii) analyze and identify unusual phenomena; and iii) restore the ability to work according to the requirements of the control object.

For simplicity in research, consider an abnormal impact as a failure or excessive error of one of the elements of the control system and collectively call it a failure. Thus, damage can occur to any element of the system. However, in aircraft's ACS in general, failures and errors often occur in sensor system elements [12], [13]. Then it is necessary to determine the failure parameters and methods to fix the failure of the sensor system. The status of other components of the ACS is determined similarly [14].

Conventional diagnostic methods use signal limits or test signals to determine whether a malfunction has occurred [15], [16]. In case of the failure of one of the system elements, it is usually just disconnected from the system and replaced with a spare element. To effectively improve stability against failures in aircraft control systems, people often use the two-out-of-three principle (two good elements can evaluate the state of the third backup element). Of course, the more redundant elements, the better the system is guaranteed to work, but it is not necessary to have redundancy for the entire system, but only to ensure redundancy for elements related to flight safety or for other important components or the expensive equipment’s [17], [18].

In fact, if the ACS has a large number of elements, applying the two-out-of three method is very difficult to detect, evaluate, and handle failures, even when using modern computing technology. Modern diagnostic algorithms today reduce the number of redundant system elements while ensuring improved stability against failures. Mathematical models of system elements and failure modes form the basis of the diagnostic algorithm. The failure diagnosis algorithm must ensure that when a failure occurs, it must automatically handle the identification of the damaged element and restore normal operation without the need to use external devices to evaluate the external status.

In this paper, a technique is presented to identify failures of the aircraft control system. The working algorithm of the diagnostic block structure is built to determine failure vector components to restore the system's workability. We formulate the problems and analyze the system at every point. We build experimental results corresponding to mathematical models. As a result, using the stages of spotting damage or faults in the system, identifying the damaged element, and recovering it, the study apparatus enables surveying all the common sensor element failures on aircrafts.

The remaining sections of the paper are structured in the following manner. Section 2 shows how to identify failures in aircraft control systems. Section 3 provides the ability to work on the systems and restore it. In section 4, experimental models are built after the analysis of mathematical models. Finally, conclusions are provided in section 5.

2. DETERMINE AIRCRAFT CONTROL SYSTEM FAILURES

2.1. System overview

Determining failures in aircraft control systems is similar by channel, so we can take the tilt channel as an example. The equation describing the aircraft's motion according to the angle of inclination is expressed according to the input-output equation as (1) [1], [5], [19]:

$$W_{\gamma}^{\delta_э}(s) = \frac{\gamma(s)}{\delta_э(s)} = \frac{-a_e}{s(s+a_{22})} = \frac{-K_e}{s(T_e s+1)} \tag{1}$$

where a_{22}, a_e are constants corresponding to the kinematic characteristics of the aircraft according to the angle of inclination and the impact coefficient on the angle control mechanism (rudder).

$$\delta_э(s) = -K_{\gamma}[\gamma(s) - \gamma_{ct}(s)] + K_{\dot{\gamma}} s \gamma(s) \tag{2}$$

Figure 1 presents the structural diagram of the tilt angle control channel.

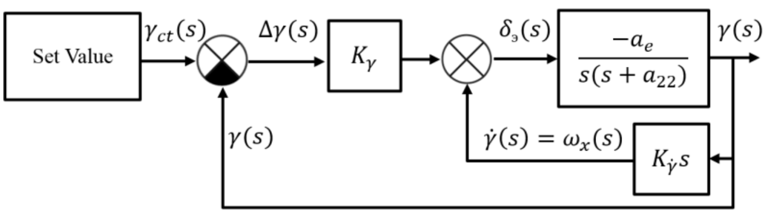


Figure 1. Structure diagram of tilt channel control

After resolving (1) in light of (2), we obtain:

$$(s^2 + a_1 s + a_2)\gamma(s) = a_2 \gamma_{ct}(s) \tag{3}$$

where $a_1 = a_{22} + a_e K_{\dot{\gamma}}$; $a_2 = -a_e K_{\gamma}$. In (3) can be rewritten as (4):

$$\ddot{\gamma} + a_1 \dot{\gamma} + a_2 \gamma = a_2 \gamma_{ct} \tag{4}$$

Or in the form:

$$\ddot{\gamma} = -a_1\dot{\gamma} - a_2\gamma + U \tag{5}$$

where $U = a_2\gamma_{ct}$ is a predetermined value.
This is a quadratic system that may be expressed as two state vector variables $\bar{X} = [X_1, X_2]^T$ with:

$$\begin{cases} X_1 = \gamma \\ X_2 = \dot{\gamma} = \omega_x \end{cases} \tag{6}$$

where γ and ω_x represent the tilt angle and angular speed, respectively, which are utilized to determine the tilt angle velocity.
The output signal and state equation then take the following form:

$$\begin{cases} Y_1 = X_1 \\ Y_2 = X_2 \end{cases} \tag{7}$$

$$\begin{cases} \dot{X}_1 = X_2 \\ \dot{X}_2 = -a_2X_1 - a_1X_2 + U \end{cases} \tag{8}$$

When a failure occurs, the system of (7) and (8) is reformulated:

$$\begin{matrix} \dot{X}_1 = X_2 + f_1 \\ \dot{X}_2 = -a_2X_1 - a_1X_2 + U + f_2 \end{matrix} \tag{9}$$

$$\begin{cases} Y_1 = X_1 + f_3 \\ Y_2 = X_2 + f_4 \end{cases} \tag{10}$$

where $\bar{f} = [f_1, f_2, f_3, f_4]^T$ represent vector failure; f_1 is failure to modify the static properties of the angle sensor; f_2 is modify the output characteristic of the angular speed sensor; f_3 is full fault of the angle sensor; and f_4 is full fault of the angular velocity sensor (ASS).
Differentiating both sides of (10) and putting the result into (9), we have:

$$\begin{cases} Y_1 = X_1 + f_3 \\ Y_2 = X_2 + f_4 \\ \dot{Y}_1 = X_2 + f_1 + \dot{f}_3 \\ \dot{Y}_2 = -a_2X_1 - a_1X_2 + U + f_2 + \dot{f}_4 \end{cases} \tag{11}$$

In (11) can be expressed in the absence of failure as (12):

$$\begin{cases} Y_{10} = X_1 \\ Y_{20} = X_2 \\ \dot{Y}_{10} = X_2 \\ \dot{Y}_{20} = -a_2X_1 - a_1X_2 + U \end{cases} \tag{12}$$

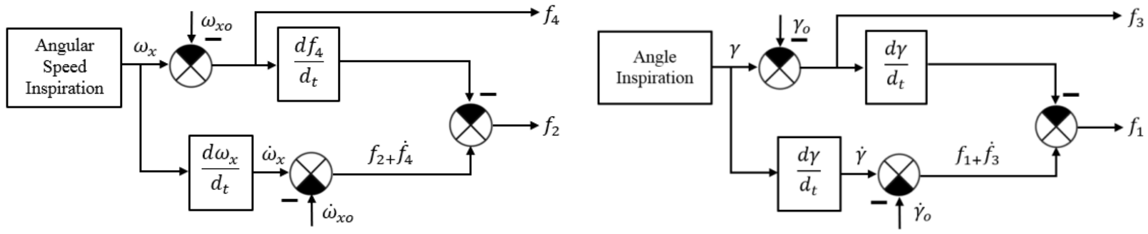
Then the failure vector will be calculated as (13):

$$\Delta Y = \begin{pmatrix} Y_1 - Y_{10} \\ Y_2 - Y_{20} \\ \dot{Y}_1 - \dot{Y}_{10} \\ \dot{Y}_2 - \dot{Y}_{20} \end{pmatrix} = \begin{pmatrix} f_3 \\ f_4 \\ f_1 + \dot{f}_3 \\ f_2 + \dot{f}_4 \end{pmatrix} \tag{13}$$

On the other hand, when measurement tools are present (in this case, angular speed sensors and angle sensors), (13) is rewritten as (14).

$$\Delta Y = \begin{pmatrix} \gamma - \gamma_0 \\ \omega_X - \omega_{X0} \\ \dot{\gamma} - \dot{\gamma}_0 \\ \dot{\omega}_X - \dot{\omega}_{X0} \end{pmatrix} = \begin{pmatrix} f_3 \\ f_4 \\ f_1 + \dot{f}_3 \\ f_2 + \dot{f}_4 \end{pmatrix} = \begin{pmatrix} \Delta\gamma \\ \Delta\omega_X \\ \Delta\dot{\gamma} \\ \Delta\dot{\omega}_X \end{pmatrix} \tag{14}$$

As shown in Figure 2, the failure searching diagram (FSD) is created using the diagnostic block (14) working technique for detecting the failure vector component $\bar{f} = [f_1, f_2, f_3, f_4]^T$. In (14) depicts the properties of the failure vector components include angle sensor (Figure 2(a)) and angular speed sensor (Figure 2(b)). The diagnostic block is designed to increase the stability of error or failure across the entire control system.



(a) (b)

Figure 2. Utilizing diagnostic block structure to identify failure vector components; (a) failure searching diagram of angle sensor and (b) failure searching diagram of angular speed sensor

Based on the diagnostic analysis results obtained from the system (14), we can accurately identify the exact time of failure during parameter measurement or calculation. Additionally, we can build a logical function z_i that only accepts binary values of 0 and 1.

$$z_i = S\{|\Delta U_i|\} = \begin{cases} 1, if \ |\Delta Y_i(k)| > \delta_i \\ 0, if \ |\Delta Y_i(k)| \le \delta_i \end{cases} \tag{15}$$

where $\Delta Y_i(k)$ represents the discrepancy between the measured value and the reference value of the I parameter, as defined by (14); δ_i represents the permissible amount of deviation; and S is a binary logical function.

The function z_i receives the value "1" when it exceeds the allowable value and there is damage, "0" when it is within the allowable value and there is no damage. Thus, the value in (15) shows that to search for failures in the control system, it is only necessary to determine the deviation value between the sample reference value and the measured value of the measuring device.

3. RESTORE THE WORKABILITY

Restoring workability is the process of bringing a control object from an abnormal state with damage to a normal working state. When determining the characteristics of failure and the time to determine failure, it is possible to build a control system that is proactively stable before failure. That is, the system can recover from damage by either automatically changing the system's structure, automatically changing the working algorithm, or using backup sensors [20], [21]. To restore the system's working ability, signal correction methods, coefficient correction methods or structural change methods are often used. Figure 3 shows the steps for restoring pre-failure stability. The first step is to diagnose a recoverable failure. Then determine failure parameters and recovery options based on the above methods. The next step is damage recovery. To eliminate the signal of damaged or erroneous elements, the structure or algorithm is changed to switch to using the signal of a spare element that is not damaged. Signal correction requires determining the signal corresponding to the signal of well-working elements using a signal correction algorithm without disconnecting the element from the system. Specifically, for sensor elements that measure angle and angular velocity, their failures can be due to drift. As soon as it is determined that the drift value does not exceed the allowable value, the recovery process is performed. The determination of the zero-drift value is as:

$U_j^0 = \widetilde{U}_j(k) - \widehat{U}_j(k)$ - then the recovery signal value would have to be: $\widetilde{U}_j(k)_{kp} = \widetilde{U}_j(k) - U_j^0$.

If a failure mode occurs with a change in the signal factor following the pattern $\Delta K_i = \frac{\widetilde{U}_i(k) - \widehat{U}_i(k)}{\widehat{U}_i(k)}$, the corresponding correction value will be $\widetilde{U}_i(k)_{kp} = \frac{\widetilde{U}_i(k)}{1 + \Delta K_i}$. Here, i and j represent the sequence in which the sensors fail. Therefore, the procedure of recovering damaged sensors is performed in order to guarantee the complete automatic stabilization of the system prior to failure.

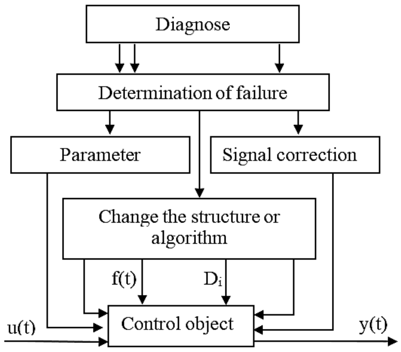


Figure 3. Algorithm for recovering from failures

4. THE SENSOR SYSTEM EQUIPPED WITH AN INTEGRATED TECHNICAL DIAGNOSTIC MODULE

Based on the damage diagnosis and recovery method described above, the authors designed a technical diagnosis block model of the aircraft's sensor system, which included five sensors measuring angle and angular speed as well as a software interface. Figure 4 shows an experimental test.

The IMU sensors are mounted on a pyramid-shaped base block with five faces, as illustrated in Figure 5. The sensors are arranged on the side with a 45-degree slope to the bottom surface for ease of calculation and simulation. The IMU sensor module that we'll be employing is based on an MPU-6050 sensor [22]. The MPU-6050 devices integrate a 3-axis gyroscope and 3-axis accelerometer onto a single silicon chip, along with an integrated digital motion processor™ (DMP™) [23]. The DMP™ handles intricate 6-axis MotionFusion algorithms, measuring angle and acceleration values in three orthogonal directions [24], [25]. Kalman filters are used to remove electrical noise and sensor artifacts from the resulting signal [26]. A microcontroller that blends control algorithms, position stabilization, and technical diagnostic algorithms serves as the core of the flight instrumentation system. The sensor signals were gathered using the I2C protocol on an Arduino Uno platform and transferred to a computer via USB connection, where they were processed and displayed using a graphical interface (C#) at a sample rate of 100 samples per second.

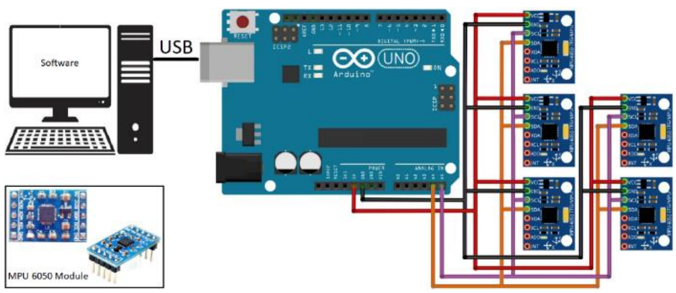


Figure 4. Experimental intrumentation used an arduino UNO to collect the kinematic signals pro-duced by five MPU6050 inertial sensors

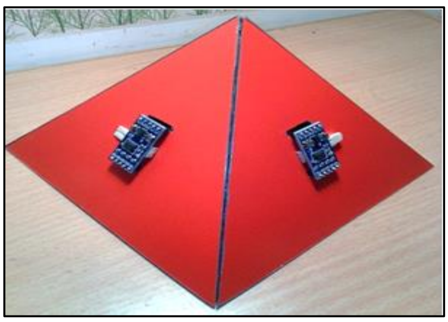


Figure 5. Equipment include five IMU sensors in-stalled on a pyramid-shaped base block

Figure 6 illustrates the connection between the hardware system and a computer with a software interface. This interface allows for the creation of a failure simulation to evaluate the results of the system diagnostic algorithm survey. The sliders provide operational buttons (Fault A1 to Fault A5) that can be used to simulate damage based on the specific failure attributes of each sensor. Users have the option to activate or deactivate individual sensors by using checkboxes labeled K1 to K5. The sensor generates signals which are then received and shown on the interface in the form of an integrated graph.

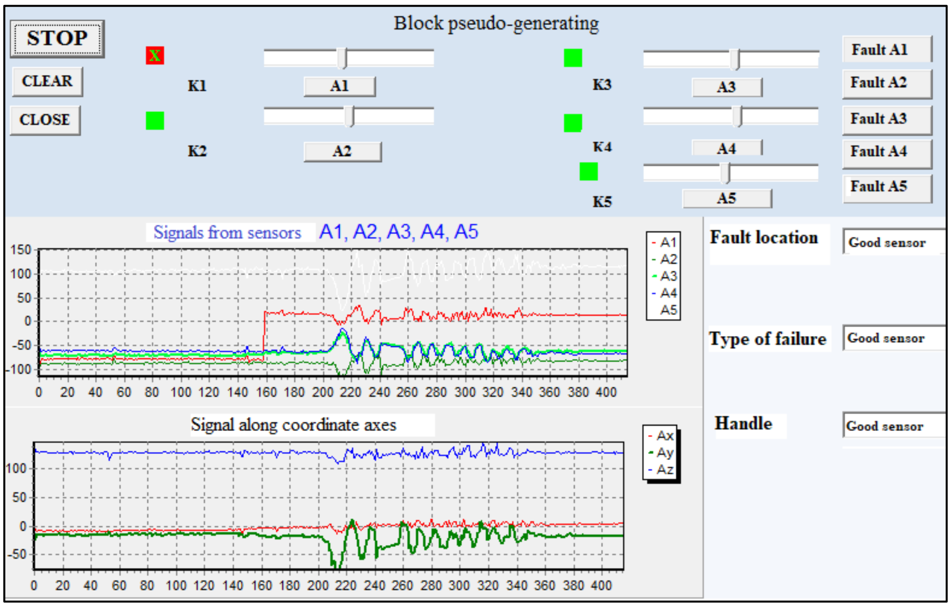


Figure 6. Graphical user interface for software applications

Figure 7 depicts the assessment graph of the diagnostic block, illustrating the process from failure to recovery of the angular speed sensor. The time to commence a failure in the system is referred to as tph (time of failure initiation). The time taken to identify the failure is denoted as tc (time of failure detection), while the process of recovering from the damage is initiated at tc and referred to as damage recovery. The time taken for the restoration process to be completed is represented by tkp (time of restoration completion).

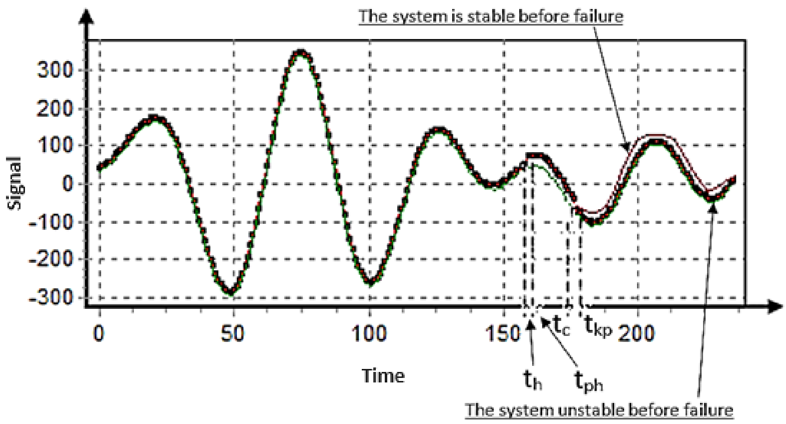


Figure 7. Explain the process of diagnosing and recuperating from angular speed sensor overdrift

The research equipment enables the comprehensive examination of common malfunctions in the aircraft's sensor elements by following a systematic process of identifying damage or mistakes in the system, locating the specific faulty element, and restoring it.

5. CONCLUSION

The research results show that the diagnostic block's working algorithm ensures the system's ability to work in failure conditions, that is, stability before failure. The design can be done by analyzing the failure patterns of each type of sensor and determining their measurement values in measurements with and without failures. On the basis of determining the deviation of those parameters, it is possible to evaluate the working ability of the sensor as well as other elements of the control system. Determining failure characteristics also allows for determining system failure recovery methods. Based on signal correction, parameter adjustment and system structure changes, the algorithm ensures the system works stably before failure.

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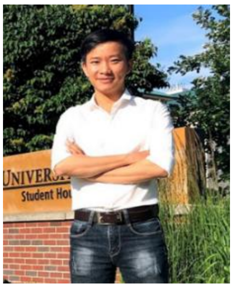

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