Self-repairing control for UAVs via quantitative feedback theory and quantum control techniques

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Abstract

In this paper, the problem of self-repairing control for unmanned aerial vehicles (UAVs) is analyzed via quantitative feedback theory and quantum control techniques. For the complex faults of unmanned aerial vehicles, a direct self-repairing control law based on quantitative feedback theory is proposed using quantum control techniques, which can guarantee the UAVs stable and solve the problem of UAVs robust control based on the uncertain parameters. Finally, simulation results are given to illustrate the effectiveness of the self-repairing control developed in our study.

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1. Introduction

UAV is a nonlinear complex system, which makes the nonlinear control to be considered [1]. To solve the original modeling error and linearized modeling error, adaptive control with fuzzy control techniques is proposed [2,3]. Actuator is a unreliable component in UAV control system and may lead to the control system failure. Most of the existing literatures utilize the adaptive control technique to accommodate

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actuator faults of the flight control system [4-6]. But only few results are concerned with the problem of the complex faults.

Quantitative feedback theory (QFT), presented by the Israeli scholar, is a method of robust control system designing based on frequency domain. When the aircraft model’s accuracy is not high, QFT is an ideal method. In recent years, the study of quantum control techniques [7-8] has increasingly been a research hot topic, in which the applied research on quantum evolutionary algorithm is very widely.

In this paper, the direct self-repairing control is proposed via quantitative feedback theory and quantum control techniques to improve self-repairing capability. The simulation results show that this method can enhance the UAV directly self-repairing control’s reliability, robustness under the complex fault case.

2. Self-repairing Control Structure

The UAV’s self-repairing control structure based on quantitative feedback theory and quantum control techniques is illustrated in Fig.1.

\[ |\psi\rangle = \alpha \cdot |0\rangle + \beta \cdot |1\rangle \]

Where, \( \alpha \) and \( \beta \) are a pair of complex, called as the probability amplitude of quantum state, namely, as the measurement result in quantum state \( |\psi\rangle \) collapsing \( |0\rangle \) with a probability of \( |\alpha|^2 \) or collapsing \( |1\rangle \) with a probability of \( |\beta|^2 \), and satisfying
Therefore, quantum state can be also denoted by the probability amplitude of quantum state in the form of \( |\psi\rangle = |\alpha, \beta\rangle \). Obviously, when \( \alpha = 1, \beta = 0 \) in (1), \( |\psi\rangle \) is the basic state \( |0\rangle \), which can be described by \( |\psi\rangle = |0, 0\rangle \). Otherwise, when \( \alpha = 0, \beta = 1 \) in (1), \( |\psi\rangle \) is the basic state \( |1\rangle \), which can be described by \( |\psi\rangle = |0, 1\rangle \). Generally speaking, quantum state is the unit vector of two-dimensional complex vector space.

Due to the collapse of quantum states caused by observation, the quantum bits can be seen a continuous state between \( |0\rangle \) and \( |1\rangle \), until it has been observed. The existence of continuous state qubit and behavior has been confirmed by a large number of experiments. And there are many different physical systems can be used to realize quantum bits.

Similar to the single-qubit state, double-quantum-bit state can be expressed as

\[
|\psi\rangle = \alpha_{00} |00\rangle + \alpha_{01} |01\rangle + \alpha_{10} |10\rangle + \alpha_{11} |11\rangle
\]

with the probability amplitude satisfying

\[
|\alpha_{00}|^2 + |\alpha_{01}|^2 + |\alpha_{10}|^2 + |\alpha_{11}|^2 = 1
\]

2.2. Quantitative Feedback Theory

QFT is a robust control system design method based on the frequency response. It extends the frequency domain design of the classical control theory to the Robust Control Law of uncertainty. Form a boundary map in the Nichols with the uncertainty range of the controlled object and the closed-loop system performance using a quantitative manner, and then design and synthesis the system since the open-loop frequency curve is accord with the boundary condition. LTI / SISO system is the core of the QFT design. Although some scholars extended it to a multiple-input multiple-output (MIMO) and non-linear and time-varying systems design in recent years, but the basic conclusion was still using some mathematical methods and techniques which eventually turn complex systems into LTI / SISO system to redesign it. As to say LTI / SISO systems, QFT has a series of mature theory and design steps. The structure of QFT designed system is shown in Fig.1.

In the control system, \( G(s) \) can be with a large uncertainty, and uncertainty range is known. \( B(s) \) is the QFT controller and it can contain the object of uncertainty. What's more, it can inhibit the noise at the level of satisfaction. Since the main effect of \( B(s) \) is to ensure the robustness, it is necessary to add a pre-filter \( A(s) \). \( A(s) \) can compensate the dynamic performance of the UAV. \( f_1 \) and \( f_2 \) are complex faults. \( r \) and \( y \) are the input and output signals. Closed-loop transfer function of the control system is

\[
\phi_r(s) = \frac{Y(s)}{R(s)} = \frac{A(s)L(s)}{1 + L(s)}
\]

(5)

\( L(s) \) is the open-loop transfer function

\[
L(s) = B(s)G(s)
\]

(6)

The closed-loop transfer function for \( f_1 \) and \( f_2 \) are

\[
\phi_{r1}(s) = \frac{G(s)}{1 + L(s)} \quad \phi_{r2}(s) = \frac{1}{1 + L(s)}
\]
QFT design includes the following steps:
1. Calculate the system’s expected performance.
2. Construct frequency response template. The template indicates the uncertainty of the system.
3. Generates the boundary curve.
4. Design the controller B(s). In the Nichols chart, the open loop frequency response curve is moved and shaped to satisfy the boundary requirement.
5. Design the pre-filter A(s). A(s) is added to get the desired performance.
6. Analyze the QFT results.

3. Simulation

3.1. The UAV Model

The UAV model in Fig.1 is

\[
(s + n_{1a}) \Delta \alpha - s \Delta \theta = -n_{2a} \Delta \delta
\]

\[
(n_{1a}s + n_{1o}) \Delta \delta + (s + n_{2o}) s \Delta \theta = -n_{2a} \Delta \delta
\]

where \( \alpha \) is the angle of attack; \( \theta \) is the pitch angle; \( \delta \) is the rudder deflection angle. Through the derivation of the above equations can be rudder deflection angle to the pitch angle of the transfer function:

\[
\frac{\Delta \theta}{\Delta \delta} = \frac{-[(n_{1a} - n_{2a}n_{1o})s + (n_{2o}n_{1a} - n_{2a}n_{1o})]}{[s(s^2 + n_{1o} + n_{2o} + n_{2o})s + (n_{2o} + n_{2o}n_{1o})]}
\]

The coefficients in Eq.11 are uncertain. These uncertainties can be basically determined by simulation.

3.2. Design and Simulation

The quantum feedforward module in Fig.1 realize the double quantum bits state description and control, the specific description of double quantum bits probability amplitude for UAV quantum feedforward module can be seen in Table.1.

| Probability amplitude | Input \( r \) | Fault \( f \) |
|-----------------------|--------------|-------------|
| \( \alpha_{00} \)    | No           | No          |
| \( \alpha_{01} \)    | No           | Yes         |
| \( \alpha_{10} \)    | Yes          | No          |
| \( \alpha_{11} \)    | Yes          | Yes         |

The upper and lower boundaries for UAV are

\[
G_v = \frac{4(s + 2)}{s(s^2 - 2s + 1)} \quad \quad \quad \quad G_r = \frac{s + 1}{s(4s^2 + 2s + 6.25)}
\]

The QFT controller \( A(s) \) and \( B(s) \) is
When \( r = 10 \text{deg} \), a part of simulation results are shown in Fig. 2. Through the above simulation curves can be found in several groups with designed QFT control system has small overshoot, fast response time, etc.

\[
A(s) = \frac{21}{s^2 + 10s + 20} \quad B(s) = \frac{447440(14s^2 + 2s + 6.25)}{(s + 8.5)(s + 1)(s^2 + 336s + 78400)}
\]

4. Conclusion

In this paper, direct self-repairs for UAVs via quantitative feedback theory and quantum control techniques are investigated. Simulation results are given to illustrate the effectiveness of the self-repairs developed in our study.

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