SENSOR/ACTUATOR FAILURE DETECTION FOR TURBOFAN ENGINES

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SUMMARY

The demand for higher performance levels of turbofan engines has resulted in the development of increasingly more sophisticated air breathing engine design configurations. As the performance demands become more restrictive, the number of manipulated inputs increase in correspondence with the increase in the number of controlled outputs. Thus, from a control system design viewpoint, the engine must be treated as a multi-input-multi-output system. The control design may then proceed using modern design methodologies in either the time domain or in the frequency domain.

Inherent to any successful control system design is the requirement to accurately record on-line engine performance and to reliably actuate the control input signals. A failure of any sensor or actuator used by the controller can lead to significantly reduced performance levels. The extent of the performance reduction is determined by the source and type of failure and the dependency of the design methodology on that information.

Traditionally, the problem of sensor/actuator failure has been resolved through the utilization of redundant components. The failed component was then easily detected using standard voting procedures. As turbofan engine designs become more complex, hardware redundancy becomes more impractical. With the introduction of on-board digital computers for flight control (F100 and QCSEE) hardware redundancy may be replaced with analytical redundancy.

For time domain control procedures requiring the full state vector for control actuation the residuals of the Kalman-Bucy filter may be examined for "whiteness." If the statistics associated with the residuals depart from the white noise condition, then a failure is declared. Willsky and Jones [1] use this concept to develop a procedure for sensor/actuator failure detection using a Generalized Liklihood Ratio (GLR) hypothesis test. Since the sensor data is used to generate state estimates which are then used to reconstruct output estimates for detector evaluation, the number of failure modes considered by the detector is large. Thus, detection time increases in direct proportion to the number of failure modes considered.

If the feedback control design does not require an estimate of the state vector, as in the case of the Multivariable Nyquist Array Method (MNA) [2,3], the Kalman filter "model" of the system is no longer required. Thus, the "residuals" can be generated by comparing the sensor outputs with a similar set of outputs generated by an accurate non-linear simulation model. The concept of the GLR can then be retained to provide a reliable evaluation of sensor or actuator operation since sensor outputs are no longer needed to provide data estimates. Figure 1 diagrams the proposed failure detection procedure using a simulation model.

The development of the proposed GLR detector using model residuals utilizes the following assumptions:

A. The physical system may be non-linear with outputs contaminated by zero-mean additive white noise of known intensity.

B. The on-board digital computer is of sufficient size for storage of the noise-free nonlinear simulation of the plant, the detection software and the feedback controller.

C. The residuals are zero mean when no failure exists.

D. Under a failed sensor or actuator the residuals have non-zero mean.

E. It is desirable to estimate which sensors or actuators failed, the form of failure occurring and the time the failure occurred.

F. An observation "window" of finite dimension is to be used for failure detection to reduce storage and computational requirements.

G. The set of failure modes is finite and is known a priori.

Utilizing these requirements a GLR detector was developed for hard-over failure conditions of the following type:

1. Actuator step failures

2. Brief disturbances in actuator output

3. Sensor step failures

For each case a hypothesis test was established for comparison with the null hypothesis (i.e., no failure condition). The GLR was formed, data window widths selected for low probability of false alarms and cross detection. Threshold levels are then established from these requirements.

The performance of the proposed GLR method was evaluated by application to the General Electric QCSEE turbofan engine [4]. Using the non-linear simulation for the under-the-wing model of QCSEE developed by Mihaloew [5] the output sensor measurements PS11, NL, NH, P12, P4, and T3 were corrupted by white noise to represent the physical engine. The actuators considered were those associated with the fuel metering valve position, fan nozzle area position, and the fan pitch mechanism drive motor position. A duplicate software program was used to represent the plant model as indicated in Figure 1.

For the application considered here, the 62.5% of full power condition was used. For the actuator and sensor failure conditions cited above, the GLR detector accurately diagnosed the failure type and identified the failed component correctly in every case. In addition, the GLR detector correctly identified the time at which the failure occurred. A representative plot of the GLR index is presented in Figure 2.

To obtain the data of Figure 2, the GLR index for each actuator and sensor is computed for all assumed failure modes. A comparison of all indices is made and the largest index is selected at each time step and plotted. Prior to the actual induced failure ($K = 10$) the maximum GLR index is non-definitive since no failure has occurred and the index remains below the established threshold ($\varepsilon = 34$). With an induced failure in PS11 (at $K = 10$) the detector correctly identifies the sensor and the failure time. The threshold of $\varepsilon = 34$ is established prior to any test runs and is strictly a function of the data window length, the pre-established probability of a false alarm, and the covariance of the sensor noise.

REFERENCES

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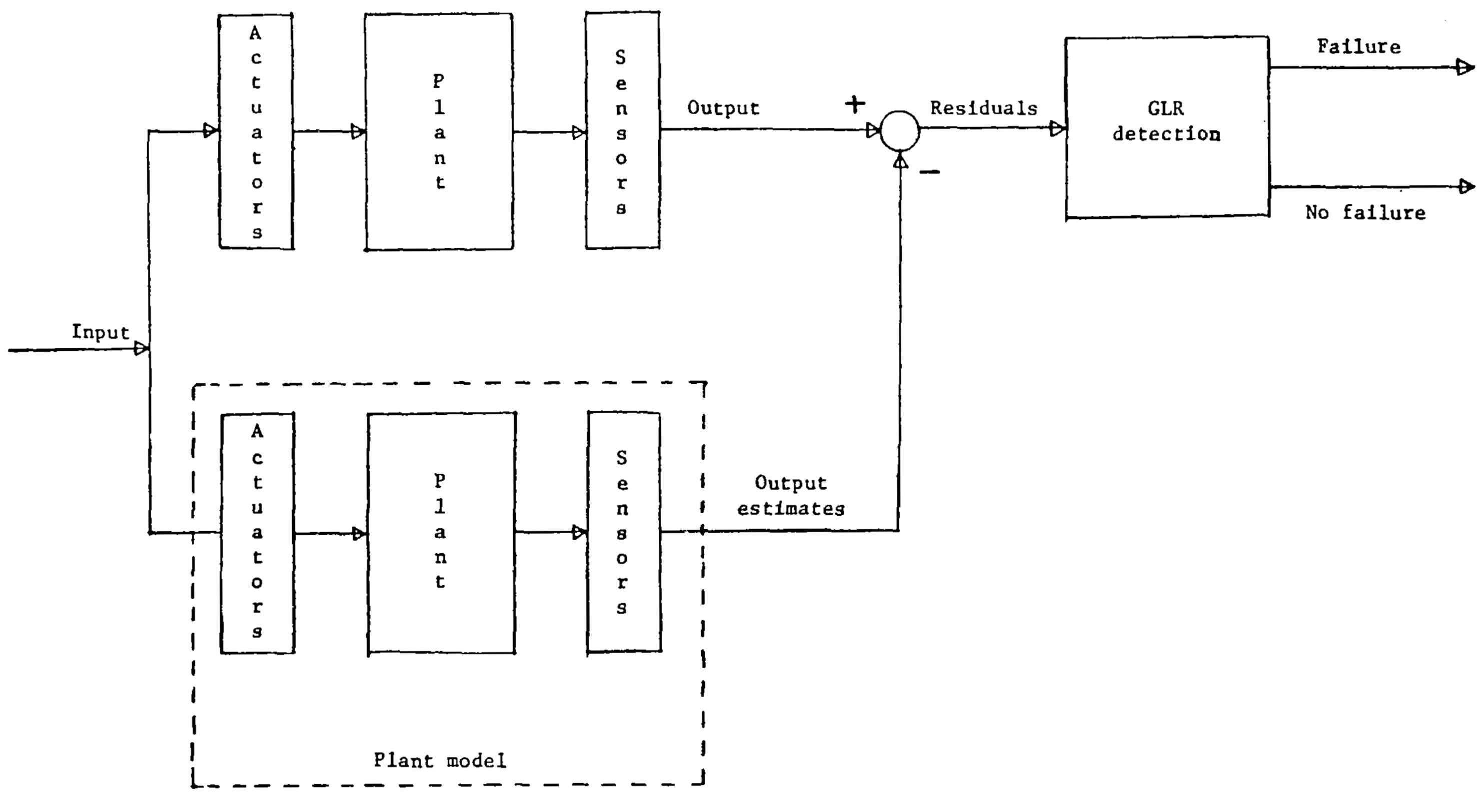

Figure 1. - Failure detection with plant model.

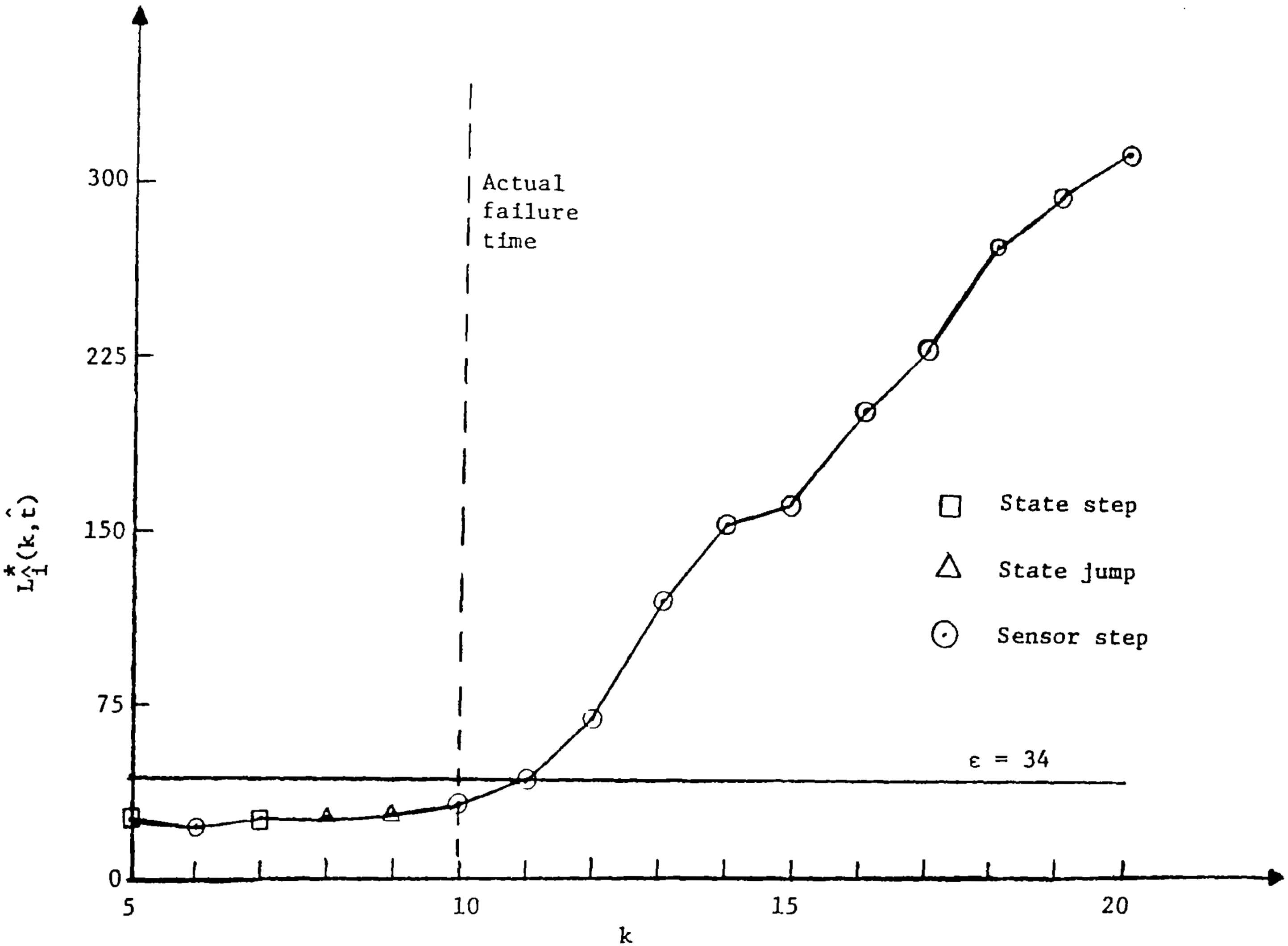

Figure 2. - Maximum GLR index for sensor-step failure in PS11 as function of observation number.