

# Actuator Fault Compensation for a Helicopter Model

Xiao-Hua Yu

**Abstract**— A fault-tolerant system is the one that can continue its operation without significant impact on performance in the presence of hardware and/or software errors. In this paper, the design of a fault-tolerant flight controller to control UH-60 helicopter is investigated. A 9th-order state space representation of the helicopter model operating at the forward mode with 80 knots is presented; then a fault-tolerant optimal feedback controller is designed and tested.

**Index Terms**— Fault-tolerant control, flight controller, adaptive control.

## I. INTRODUCTION

Autonomous manipulators can be used in a wide range of applications, especially to complete dangerous tasks in remote or hazard environment such as planetary exploration, cleanup of toxic waste, fire fighting, etc. When an error occurs (e.g., a sensor fails to provide correct measurement), it is desirable that the mobile manipulator is capable of compensating this failure without the need of human presence to fix the problem.

A fault-tolerant system is the one that can continue its operation without significant impact on performance in the presence of hardware and/or software errors. The studies of fault-tolerant system started in late 50s, when the first electronic computer was developed. To overcome the low reliability of the electronic parts, some of the early computers had two duplicated Arithmetic Logic Units (ALUs). Since 1970s, research on fault-tolerance systems has led to a variety of applications, including robotics, nuclear power plants, computer architecture and industrial process control.

A fault-tolerant control system must be capable of performing: (a) fault detection; (b) fault identification/diagnosis (i.e., recognition of which components are failed); and (c) controller reconfiguration/recovery, also called fault compensation (i.e., to adjust the control signal in case of a component failure). Fault-tolerant control systems design can be classified into two different schemes, i.e., passive approach and active approach. The passive approach employs robust control techniques such that the overall closed-loop system is "insensitive" to certain faults. The limitation of this method is that it can only "tolerant" some specific type of faults. The active approach generates a new control law to compensate the faulty system so that behaves as the nominal system without faults.

The parallel redundancy approach has been developed

in early researches in the fault-tolerant control area. It employs two or more identical channels and a comparator (voter) [6]. The voter takes the signal from each individual channel and then only chooses one as the nominal (error-free) signal. This approach can easily detect a failure but hard to identify which channel fails; and the voting logic itself (e.g., maximum likelihood estimation) has some probability of making errors.

Using its nonlinear mapping ability, an artificial neural network can be trained for fault detection and identification [5]. A data set which contains the direct measurement from sensors must be obtained; then a set of feature vectors and its corresponding failure indication vectors can be extracted from this data set and provided as the input/output pairs for training neural networks. The difficulty of this approach is how to obtain the original data set. If simulated data is used, it may not match with the real case; however to get measurement data, the system must be operated under failure status till enough data is collected.

In this paper, a fault-cancellation algorithm is applied to design a fault-tolerant flight controller for a NASA UH-60 helicopter with the presence of a single actuator fault on the system. A 9th-order state space representation of the helicopter model operating at the forward mode with 80 knots is presented; then a fault-tolerant optimal feedback controller is designed and tested by simulation.

## II. FAULT-TOLERANT SYSTEM DESIGN FOR A NASA UH-60 HELICOPTER

The continuous-time 6-DOF (degree of freedom) linear model of a NASA UH-60 helicopter (in its forward flight mode at the speed of 80 knots) is obtained from wind-tunnel test data, and can be described as the following dynamical state equations [2] [3]:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t)\end{aligned}\quad (1)$$

The state variable vector  $x$  (with dimension  $n = 9$ ) is defined as:

$$\begin{aligned}x &= [x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6 \ x_7 \ x_8 \ x_9]^T \\ &= [u \ v \ w \ p \ q \ r \ \varphi \ \theta \ \psi]^T\end{aligned}\quad (2)$$

where  $u$ ,  $v$ , and  $w$  represents the longitudinal, lateral, and vertical velocity (ft/sec), respectively;  $p$ ,  $q$ , and  $r$  represents the roll, pitch, and yaw rate (rad/sec), respectively;  $\varphi$  and  $\theta$  represent the roll and pitch attitude (rad); and  $\psi$  is the heading (rad). There are five control inputs ( $m = 5$ ), i.e.,  $u = [u_1 \ u_2 \ u_3 \ u_4 \ u_5]^T$ , where  $u_1$  is the lateral stick (inch),  $u_2$  is the longitudinal stick (inch),  $u_3$  is the collective stick (inch),  $u_4$  is the pedal position (inch), and  $u_5$  is the horizontal tail incidence (degree). This system is then

This work was supported in part by NASA/ASEE summer faculty fellowship program at NASA Ames research center, Moffett field, CA.

Xiao-Hua Yu is with California Polytechnic State University, Department of Electrical Engineering, San Luis Obispo, CA 93407, USA (email: xhyu@ee.calpoly.edu).

sampled with a sampling period of 0.05 second to obtain a discrete-time dynamic model:

$$\begin{aligned} x(k+1) &= A x(k) + B u(k) \\ y(k) &= C x(k) + D u(k) \end{aligned} \quad (3)$$

The eigen-values of this sampled system are: 1.0000, 0.9881+0.0052j, 0.9881-0.0052j, 0.9986+0.0062j, 0.9986-0.0062j, 1.0034, 0.9983, 0.9997+0.0012j and 0.9997-0.0012j. The system is controllable, observable, and unstable. A feedback controller is added to stabilize the system first, then an optimal controller is designed to minimize the following performance index:

$$\begin{aligned} J &= \frac{1}{2} \sum_{k=0}^N [(y_r(k) - y(k))^T Q (y_r(k) - y(k)) \\ &+ u^T(k) R u(k)] \end{aligned} \quad (4)$$

where  $y_r(k)$  is the desired system output,  $y(k)$  is the actual output. Let  $y_1(k) = E_1 x(k)$  represent the vector of outputs ( $y_1 \in R^p$ ,  $p \leq m$ ) that are required to follow the desired trajectory,  $y_r(k)$ . In the case of steady state,

$$y_r(k) - y_1(k) = 0 \quad (5)$$

To achieve this objective, a vector  $z$  is added which must satisfy the following relation:

$$z(k+1) = z(k) + T_s [y_r(k) - E_1 x(k)] \quad (6)$$

where  $T_s$  is the sampling interval. The augmented system now becomes:

$$\begin{aligned} \begin{bmatrix} x(k+1) \\ z(k+1) \end{bmatrix} &= \begin{bmatrix} A & 0 \\ -T_s E_1 & I_p \end{bmatrix} \begin{bmatrix} x(k) \\ z(k) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(k) \\ &+ \begin{bmatrix} 0 \\ T_s I_p \end{bmatrix} y_r(k) \end{aligned} \quad (7)$$

$$y(k) = [C \ 0] \begin{bmatrix} x(k) \\ z(k) \end{bmatrix} \quad (8)$$

In the presence of an actuator fault, the above equation can be rewritten as:

$$\begin{aligned} \begin{bmatrix} x(k+1) \\ z(k+1) \end{bmatrix} &= \begin{bmatrix} A & 0 \\ -T_s E_1 & I_p \end{bmatrix} \begin{bmatrix} x(k) \\ z(k) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(k) \\ &+ \begin{bmatrix} 0 \\ T_s I_p \end{bmatrix} y_r(k) + \begin{bmatrix} F_a \\ 0 \end{bmatrix} f_a(k) \end{aligned} \quad (9)$$

$$y(k) = [I_n \ 0] \begin{bmatrix} x(k) \\ z(k) \end{bmatrix} \quad (10)$$

In the above equation an additional term is added to model the actuator fault, where  $F_a$  corresponds to the  $i$ -th column of matrix  $B$  in the case of the  $i$ -th actuator fault, and  $f_a$  is the magnitude of fault. If a feedback control law  $u_{ad}(k)$  can be chosen such that:

$$\begin{aligned} B u_{ad}(k) + F_a \hat{f}_a &= 0, \text{ i.e.,} \\ u_{ad}(k) &= -B^+ F_a \hat{f}_a(k) \end{aligned} \quad (11)$$

then the actuator fault can be eliminated [1], where  $\hat{f}_a$  is the estimated value of fault,  $B^+$  is the pseudo-inverse of matrix  $B$ :

$$\begin{bmatrix} x(k+1) \\ z(k+1) \end{bmatrix} = \begin{bmatrix} A & 0 \\ -T_s E_1 & I_p \end{bmatrix} \begin{bmatrix} x(k) \\ z(k) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(k)$$

$$+ \begin{bmatrix} 0 \\ T_s I_p \end{bmatrix} y_r(k) + \begin{bmatrix} F_a \\ 0 \end{bmatrix} f_a(k) + \begin{bmatrix} B \\ 0 \end{bmatrix} u_{ad}(k) \quad (12)$$

The following figure shows the computer simulation result on this fault-tolerant controller applied to the UH-60 helicopter. It is assumed that the first actuator is broken at  $k = 2000$  (sec.), i.e., the lateral stick control is lost. Then the fault-cancellation algorithm is called to compensate this error. In the figure, the solid line indicates the state of the fault-free (ideal) system with a nominal optimal controller, while the two different kinds of dotted lines represent the outputs of the faulty-system with/without a fault-tolerant controller, respectively. As an example, only the second state of the system is plotted in the figure. It is shown that by employing the fault-cancellation algorithm, the output follows the desired trajectory even with an actuator fault.

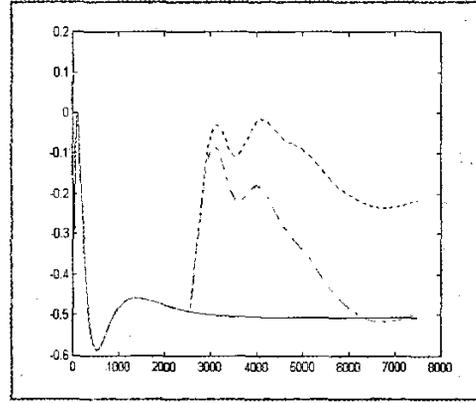


Fig. 1 Comparison on the trajectories of a fault-free system and a faulty-system with/without a fault-tolerant controller).

### III. CONCLUSIONS AND FUTURE WORKS

Fault-tolerance is an important criterion for the design of autonomous vehicles operating in remote environment. In this research, a fault-cancellation algorithm is discussed and its application to a NASA UH-60 helicopter model is presented. Further evaluation and testing on this algorithm will be investigated.

### IV. ACKNOWLEDGEMENT

This research work was supported in part by the NASA/ASEE summer faculty fellowship program at NASA Ames research center, Moffet field, CA. Special thanks to Dr. William Warmbrodt, Mr. Chad R. Frost, and Mr. Larry Young for their helps during the course of this research.

### REFERENCES

- [1] H. Noura, D. Sauter, F. Hamelin, et. al., "Fault tolerant control in dynamic systems: application to a winding machine", *IEEE control systems magazine*, Feb. 2000.
- [2] K. Hilbert, "A mathematical model of the UH-60 helicopter", *NASA technical memorandum 85890*, April 1984.
- [3] J. Fletcher, "A model structure for identification of linear models of the UH-60 helicopter in hover and

- forward flight", *NASA technical memorandum 110362*, Aug. 1985.
- [4] K. N. Groom, A. A. Maciejewski, and V. Balakrishnan, "Real-time failure-tolerant control of kinematically redundant manipulators", *IEEE transactions on robotics and automation*, vol. 15, no. 6, Dec. 1999.
- [5] A. T. Vemuri, M. M. Polycarpou, and S. A. Diakourti, "Neural network based fault detection in robotic manipulators", *IEEE transactions on robotics and automation*, vol. 14, no. 2, April 1998.
- [6] P. A. Lee and T. Anderson, *Fault tolerance: principle and practice*, 2<sup>nd</sup> Ed., Springer-Verlag Wien New York, 1990.