INTEGRATED RECONFIGURABLE CONTROL ALLOCATION

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Abstract

This paper presents the development of an integrated reconfigurable control allocation approach. This integrated approach combines frequency-apportioned control allocation with actuator failure detection and isolation. Frequency-apportioned control allocation integrates innovative control effectors with conventional aerodynamic controls and considers both the steady-state performance and frequency response of the individual control effectors. The actuator failure detection and isolation algorithm is a model-based approach that uses a model of the actuator to predict actuator behavior and an adaptive decision threshold to achieve acceptable false alarm/missed detection rates. This integrated approach provides control reconfiguration when an aircraft is subjected to actuator failure, thereby improving maneuverability and survivability of the degraded aircraft. This paper also addresses system implementation issues. This method is demonstrated on a Lockheed-Martin Innovative Control Effector simulation that has been modified to include a new control effector based on passive porosity. Desktop and real-time piloted simulation results demonstrate the performance of this integrated reconfigurable control allocation approach.

Introduction

Future aircraft are being proposed with many more control effectors than the traditional elevator, aileron, and rudder. Optimal use of this large number of effectors will be challenging, but the potential control power and redundancy offers the flight controls designer freedom to maximize mission performance and enhance survivability. In particular, reconfigurable control approaches seek to take advantage of this control redundancy to mitigate the deleterious effects of control effector failure or battle damage [Buffington 1998, Brinker 1999, Tallant 1999]. A key element in these approaches is reconfigurable control allocation.

Integrated Reconfigurable Control Allocation

The reconfigurable control allocation is an integrated approach that combines two main elements: frequency-apportioned control allocation and actuator failure detection and isolation. These elements are discussed in more detail in the following sections.

Control Allocation

The linear control allocation problem can be stated as follows. Given the system

\[ m_d = B \delta \]

where \( m_d \) = desired moment (or angular acceleration) vector, \( B \) = the control effectiveness matrix, and \( \delta \) = the control vector; determine \( \delta \) to yield a desired \( m_d \). The dimension of \( \delta \) is assumed to be greater than the dimension of \( m_d \) and \( \delta \) is constrained by \( \delta_{\text{min}} \leq \delta \leq \delta_{\text{max}} \).

Weighted Pseudo-Inverse. One solution is given by a weighted pseudo-inverse. The weighted pseudo-inverse is a computationally efficient, closed-form solution that accommodates redundant and/or zero effective controls and allows removing controls from the solution by zeroing the weight associated with that control. The weighted pseudo-inverse solution is obtained by minimizing

\[ J = \frac{1}{2} \delta^T W \delta + \lambda^T (m_d - B \delta) \]
where $W$ is a diagonal positive definite weighting matrix. Taking partials of $J$ with respect to $\delta$ and $\lambda$, setting these equal to zero and solving for $\delta$ yields

$$\delta = WB^T (BWB^T)^{-1}m_d = B^*m_d$$

A common approach is to choose the weighting matrix $W$ to be a diagonal matrix of control position limits squared. This results in a solution that emphasizes highly effective controls while minimizing deflections of controls with reduced effectiveness. One of two approaches can be used when controls exceed a constraint: 1) the individual controls can be clipped at the constraint or 2) the entire control vector can be scaled such that no constraints are violated. The scaling approach results in a solution that preserves the direction of the desired moment. In general, a weighted pseudo-inverse solution does not result in a solution that preserves the direction of the desired moment. In general, a weighted pseudo-inverse solution does not result in a solution that preserves the direction of the desired moment. In general, a solution that preserves the direction of the desired moment.

Frequency-Apportioned Control Allocation. Control position weighted pseudo-inverse allocators consider only the moments produced by the individual control effectors at their maximum deflections. A limitation of the approach occurs when commands are large and changing rapidly. This can occur for aggressive pilot inputs during rapidly maneuvering flight. When slow-moving controls saturate at their rate limits, errors and time lags are introduced into the flight control system that can significantly degrade system performance. This shortcoming is addressed in this paper by an extension to the weighted pseudo-inverse approach that accounts for actuator rate limits. This method is referred to here as frequency-apportioned control allocation (FACA). This approach distributes high frequency commands to the controls with higher rate limits and low frequency commands to the highly effective controls. A diagram of the approach is given in figure 2. In this development $m_d = (pitch \ moment, \ roll \ moment, \ yaw \ moment)^T$. Desired moment commands are partitioned into high and low frequency components using a low-pass filter matrix.

$$m_j = L(s)m_d$$

$$m_h = [1-L(s)]m_d$$

where

$$L(s) = \text{diag}\left(\frac{1}{T_m s + 1}, \frac{1}{T_r s + 1}, \frac{1}{T_y s + 1}\right)$$

where $M = \text{pitch moment}$, $L = \text{roll moment}$, and $N = \text{yaw moment}$.

A weighted pseudo-inverse is used for allocating the high and low frequency components according to the individual control effector rate and position limits.

$$\delta_j = B^*_p m_j = B^*_r L(s)m_d$$

$$\delta_h = B^*_p m_h = B^*_r [1-L(s)]m_d$$

where $B^*_p$ and $B^*_r$ are position limit and rate limit weighted pseudo-inverses, respectively, given by

$$B^*_p = W_p B^T (BW_p B^T)^{-1}$$

$$B^*_r = W_r B^T (BW_r B^T)^{-1}$$

where $W_p = \text{diagonal matrix of control position limits squared}$ and $W_r = \text{diagonal matrix of control rate limits squared}$.

The control vector is then given by

$$\delta = \delta_j + \delta_h = \left[ B^*_p L + B^*_r [1-L] \right]m_d$$

A key element in this approach is selection of low-pass filter time constants $T_M$, $T_r$, and $T_y$. The time constant determines the frequency at which commands are passed to the position-weighted versus the rate-weighted pseudo-inverse solutions. One method for choosing the time constants is to determine position and rate limit boundaries for each control for a sinusoidal input and choose the time constant that yields the least restrictive boundaries. Boundaries are defined as a function of input amplitude and frequency. The position and rate limit boundaries are determined using a reciprocal Bode analysis as follows.

Transfer functions are determined from desired moment to control position and rates for the allocator/actuator system (figure 3).

$$\frac{\delta_j}{m_d} = H_{p,j}(s); \quad \frac{\delta_h}{m_d} = H_{r,j}(s) = sH_{p,j}(s)$$

for $i=1$ to $m$, for a given desired moment $j$ where $j=1$ to 3. The inverse of the position and rate transfer functions are multiplied by the individual control effector position and rate limits, respectively,

$$P_{\lim,i} = \left| \delta_{\lim,i} \right| / H_{p,j}(s)$$

$$r_{\lim,i} = \left| \delta_{\lim,i} \right| / H_{r,j}(s) = \left| \delta_{\lim,i} \right| / sH_{p,j}(s)$$

for $i=1$ to $m$, for a given desired moment $j$ where $j=1$ to 3.

These functions define the individual control position and rate limit boundaries for a sinusoidal input as a function of input amplitude and frequency. The minimum of all the individual control limit boundaries
defines the rate/position limit boundary of the system as a function of amplitude versus frequency. For a sinusoidal input with amplitude and frequency in the region below this rate/position limit boundary, no control is in a rate or position limit. This region will be referred to as the “limit-free” region (figure 4). By determining the rate/position limit boundaries for a range of time constants, one can determine the time constants that maximize the area of this “limit-free” region for each axis over a desired control bandwidth.

Although this development has considered employing a weighted pseudo-inverse, the approach can be extended to incorporate a cascaded weighted pseudo-inverse solution to achieve maximum available moments.

**Actuator Failure Detection and Isolation**

Failure Detection and Isolation (FDI) in dynamic systems has been the subject of considerable work for many years [Frank 1990, Patton 1994]. While some approaches employ neural networks, most of the methods developed for FDI involve the use of a model of the system for which failures are being diagnosed, and such is the case with the present approach. In the current application, FDI is used to detect actuator failures.

For this effort it was assumed that the only measurements available from the actuators are the command input and the actuator output, or position. At first thought, it might seem that a failure of the actuator could simply be detected by comparing the measured position with the command, and, if these are different, a failure has occurred. However, because of the dynamic response of the actuator, the output will differ from the command during most transients, and thus false failures will be declared unless the threshold for failure declaration is set unacceptably high. This problem is overcome in a model-based FDI approach by using a model of the actuator in the FDI system to predict actuator behavior as in figure 5, and by comparing the model output with the measured actuator position. If the model is perfect, the no-failure residual will be zero. Thus, a failure is declared when the residual is not zero. Nominal measurement errors are accommodated by using a non-zero decision threshold for comparison with the residual. However, if model errors are significant, residuals can be quite different from zero. In fact, they can be so large that a constant threshold must be set so high to minimize false alarms that the missed detection rate is unacceptable. In this case, acceptable false alarm/missed detection rates can often be achieved by use of an adaptive decision threshold. If the actuator and its model are linear, the residual caused by model error is a linear function of the input amplitude, and the adaptive threshold can vary linearly with the amplitude of the input. For actuators which are nonlinear due to limiting, generating an adaptive threshold as a function of a composite signal, which at each sample is the maximum of the real-time and delayed versions of the command provides much improved false alarm/missed detection performance.

An example of the adaptive threshold behavior can be seen in figures 6 through 8. These data were generated in the stand-alone desktop simulation of an actuator. Figure 6 shows the actuator position, and the amount of surface activity that is typical of a maneuvering high performance aircraft. Note that the actuator failed at its current position at about 35.8 seconds. Figure 7 is a plot of the adaptive threshold and the absolute value of the residual for this case and shows the increased residual after the failure. Figure 8 is a time-expanded version of figure 7 showing that the no-failure residual near 15 seconds would have produced a false alarm had not the threshold adapted. This increase in residual was caused by a model inaccuracy in the actuator rate limit.

The actuator model used in the FDI system is a discrete second-order model with position and rate limits. The model output is subtracted from the measured actuator position to form the residual. To simulate model errors, values of the actuator parameters were varied to determine their effects on the residuals. It was found that amplitude of the residuals due to model error (no failures) was determined primarily by errors in the position and rate limit models with errors in the natural frequency and damping being secondary. To obtain a quantitative measure of the effect of input amplitude on the amplitude of the no-failure residuals, a Monte Carlo analysis was conducted using a stand-alone MATLAB/Simulink-based simulation of the actuator and the FDI system. Actuator position and rate limits and measurement errors were randomly varied run-to-run as were the amplitudes of the command inputs. The range of variation of the rate limit was chosen based on the rate limit versus hinge-moment model of the actuators in a current fighter aircraft. Analysis of these results were used to determine the parameter values of the current adaptive-threshold actuator FDI design.

**Implementation**

The integrated Control Allocator is organized into five main elements (see Figure 9): Command Interconnect, Effector Aero Model, Control Mixer, Control Distributor, and the Actuator FDI. These elements are discussed in the following.

The Command Interconnect maps stability-axis rotational acceleration commands into desired body-axis moments and provides inertial coupling
compensation. The Effector Aero Model contains linearized control effectiveness coefficients as a function of flight condition. The control mixer contains the control allocation algorithm. Two algorithms are implemented – a position limit weighted pseudo-inverse and the frequency-apportioned control allocation. The Control Distributor maps control commands to the individual control effectors.

Left and right one-sided controls are modeled as a single control in the Aero Model and the Mixer and are mapped into left and right surface commands in the Control Distributor. During nominal operation, the allocator distributes the controls based upon the internal model of the individual control effectiveness as a function of flight condition.

The control allocator accepts inputs from the Actuator Failure Detection element, which continually monitors the health of the control surface actuators. When informed by the FDI that an actuator failure has occurred, the allocator removes the failed control from the set of available controls and redistributes the remaining controls to accommodate the failure.

Displays are under development to inform the pilot when a control failure has occurred and show available control power remaining. The pilot display used in this study, shown in figure 10, is an extension of a concept developed by Honeywell Laboratories under contract to NASA. This figure shows the display signaling a right elevon failure. The display is composed of two parts, a control failure display on the right and a control power display on the left. The control power display consists of roll (top), pitch (middle), and yaw (bottom) control power bar graphs. When a failure occurs, red bars show control moment lost as a percent of nominal. The control surface display shows a diagram of the aircraft. When a failure is detected, the failed control on the display turns red.

**Application to ICE Aircraft**

This integrated allocation method has been implemented in a modified version of the Lockheed-Martin Innovative Control Effector (LM-ICE) simulation [Dorsett 1996]. The LM-ICE aircraft is a 65 degree swept delta-wing, tailless, single-engine, supersonic fighter. This configuration incorporates a large number of redundant conventional and innovative control effectors including elevons, pitch flaps, pitch and yaw thrust vectoring, all-moving wing tips (AMT’s), spoiler-slot deflectors (SSD’s), and outboard leading-edge flaps (OLEF’s). The SSD and OLEF’s were not used in this study (figure 11).

This simulation has been modified to include a new control effector based on passive porosity [Hunter 2001]. Passive Porosity (PassPort), as used in this study, is a control device that changes aerodynamic forces on a vehicle wing by equalizing the pressure gradient on the exterior surface. Actuation is accomplished by opening and closing a minimum depth cavity (plenum) (figure 12a). The plenum is designed with a porous surface conforming to the wing shape. For this study, eight separate devices were installed on each wing (figure 12b). The controller actuates each device discretely to an “on” or “off” position.

All actuators are simulated as second-order systems with rate and position limits except the passive porosity actuator. Dynamic data is currently not available for passive porosity. The actuator was chosen to be modeled by a position and rate-limited first-order system. Actuator dynamics and limits are given in Table 1.

The control law is designed to give conventional responses to three-axis pilot controls. Pitch rate, roll rate and sideslip angle commands are scheduled with the available control power in each axis.

The longitudinal control law is a proportional-plus-integral arrangement with feed-forward that produces a pitch acceleration command for the control allocator. Longitudinal control stick deflections command pitch rate at low speed. The control law transitions to normal acceleration command at high speed. Feedback gains were chosen following the guidance of MIL-STD-1797A for short-period frequency and damping ratio. Attitude angles are used to compensate for gravity. Roll rate and the angle of sideslip are used to compensate for pitch rate sensor offsets that occur when the airplane rolls with sideslip.

Lateral control stick deflections command stability-axis roll rate by means of a single feedback gain on roll rate error. Rudder pedal deflections command the angle of sideslip by means of a proportional-plus-derivative controller. Sideslip error feedback provides static directional stability. Stability-axis yaw rate combined with attitude angles and lateral acceleration to form a synthesized rate-of-change of sideslip that provides yaw damping. Phase margins in both the longitudinal and lateral-directional channels are enhanced by lead filters.

Initial control system gains were obtained using frequency-domain design techniques on a set of continuous models. The models range from Mach 0.225 to Mach 0.9 with altitudes ranging from sea level to 40,000 feet. The control law was discretized and tested for large-amplitude motions on a nonlinear desktop simulation. Additional refinements were made in response to piloted simulation results.

The Effector Aero Model for the allocator contains pitch, roll, and yaw moment effectiveness coefficients for each control as a function of flight condition. The coefficients were calculated for controls at full positive and negative deflections using piece-wise linear fits of the ice database.
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boundaries for FACA with weighted pseudo-inverse solution (13a) and rate limit boundaries for a control position.

MATLAB/Simulink

The desktop simulation is implemented in being conducted to evaluate and refine the approach. The FACA method with pseudo-inverse solution. The FACA method with a pitch command time constant of $T_M=0.3$ results in a position/rate limit boundary that is substantially higher in the 2-to-20 rad/sec frequency range and slightly lower in the 0-to-2 rad/sec range than the boundary with the pseudo-inverse solution. The FACA method with $T_M=0.3$ results in a “limit-free” region that is 49% larger in area than the region from the control position weighted pseudo-inverse solution.

**Desktop and Piloted Simulation Evaluation**

Desktop and piloted simulations are currently being conducted to evaluate and refine the approach. The desktop simulation is implemented in MATLAB/Simulink. Piloted simulations are being conducted in NASA Langley’s Differential Maneuvering Simulator (DMS). The DMS is a fixed-base generic fighter simulator having wide-angle visual displays and is capable of simulating two airplanes as they maneuver relative to each other.

The effect of the FACA is demonstrated by considering the control activity for a pitch stick step input sequence (+5in/-5in/+5in) at Mach=0.3 and Altitude=12300 feet in the desktop simulation. This input produces load factors between 0 and $+2.25$ g’s with angle-of-attack ranging between 0 and 26 degrees. Figure 14 shows RMS position and rate activity for a control position weighted pseudo-inverse solution (CWPSI) and the FACA approach. RMS values are a percent of individual control rate and position limits. With CWPSI, the pitch flap uses 35% of its rate capability while the other controls use 15% or less of their respective rate capabilities (See top of figure 14). With FACA, the rate of the pitch flap is greatly reduced so that the controls are more balanced - all using less than 20% of the rate capabilities. This is accomplished with an increase of eleventh rate and position demands. This implies that the FACA allocator maintains the control actuators in linear operation for much larger commands than would a conventional control position weighted pseudo-inverse allocator.

The response of the actuator FDI system to an eleventh failure at 10 seconds in one of the piloted simulation runs is plotted in figure 15. The FDI system detected the failure in 0.0625 seconds, and the control allocator removed the surface from use on the next computational cycle. This was typical of the FDI performance in the piloted simulations.

Pilot-in-the-loop tracking tasks were conducted to assess the performance of the integrated control allocation approach. Test subjects performed a gunsight tracking task using a pre-recorded maneuvering target projected on the simulator dome. The attack aircraft starts at an initial condition of Mach=0.6, altitude=11700 feet, in straight and level flight. The target aircraft starts at the same initial condition and 500 feet ahead of the attack aircraft. The target performs a series of roll reversals with conditions varying between 300-500 knots-equivalent-airspeed, 9500-12200 feet in altitude, and 1-7 g’s. Pilot tracking performance was measured by target cone angle $\epsilon$, defined as the angle between the attacking aircraft’s x-body axis and a vector from the attacker to the target. (figure 16) [Foster 1998]. Pilot tracking time histories are given in figure 17 for a left elevon failure at 15 sec with FDI On (17a) and FDI Off (17b). Both sets of time histories are plotted against a baseline tracking case with no failures. As can be seen in figure 17a, the FDI On with failure time histories compare very favorably to the baseline both in terms of stick activity and target cone angle. In this case the allocator, advised of the failure by the FDI, compensates by redistributing the commands to the remaining functioning effectors. Pilot comments for this case were: “slightly more oscillatory (than baseline)”, “minor increase in workload”, “good tracking”. Figure 17b shows FDI Off with failure time histories compared to the baseline. In this case the allocator is ignorant of the failure. Time histories show more stick activity and significantly larger target cone angle. Pilot comments for this case were: “major increase in workload (after failure)”, “unable to track target”. The simulation results demonstrate that the integrated control allocator is able to reconfigure after actuator failures to allow the tracking task to be completed.

**Concluding Remarks**

This paper has presented the development of an integrated reconfigurable control allocation approach. The integrated approach combines frequency-apportioned control allocation, with actuator failure detection and isolation. This integrated approach provides control reconfiguration when subjected to actuator failure, thereby improving the degraded

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aircraft’s maneuverability and survivability. This paper also addressed system implementation issues. The method has been demonstrated on a Lockheed-Martin Innovative Control Effector simulation that has been modified to include actuated passive porosity. Desktop and real-time piloted simulation results demonstrate the performance of this integrated reconfigurable control allocation approach.

In the next phase of this work a real-time parameter identification module, currently in development, will be integrated into the system. Also in development are a parity-space-based FDI module for detecting and isolating failures in redundant flight control sensors, a cascaded pseudo-inverse implementation of frequency-apportioned control allocation, and incorporation of additional unconventional control effectors, such as fluidic thrust vectoring and synthetic jets.

References


Actuator Failure Detection / Isolation

Feedback Measurements

Figure 1. Integrated Reconfigurable Control Allocation.

Frequency-Apportioned Control Allocation Approach

Figure 2. Frequency-Apportioned Control Allocation Approach.

Frequency-Apportioned Control Allocation Actuators

Figure 3. Frequency Apportioned Control Allocation/Actuator System.

Position Limit Boundary
Rate Limit Boundary

Figure 4. Position and Rate Limit Boundaries as a Function of Input Amplitude and Frequency.

Actuator Failure Detection and Isolation

Figure 5. Actuator Failure Detection and Isolation.

Failed Actuator Position

Figure 6. Failed Actuator Position.
Figure 7. FDI Threshold and Residual for Failed Actuator.

Figure 8. Expanded View of Threshold and Residual.

Figure 9. Integrated Reconfigurable Control Allocation Implementation.

Figure 10. Control Power/Actuator Failure Pilot Display – Right Elevon Failure.

- Advanced tailless, delta wing configuration
- Low radar signature, high agility
- Aero data for 0.3<M<2.16, -4.0<α<90.0, -30.0<β<30.0
- Simulation includes increments for steady rotations, controls, control interactions, hinge moments
- Innovative Control Effectors (ICE)
  Pitch and yaw TV, elevons, pitch flaps, all-moving wing tips, spoiler-slot deflectors, differential leading edge flaps [Dorsett 1996]
- Nominal configuration modified to include actively controlled passive porosity effectors

Figure 11. Modified Lockheed-Martin Innovative Control Effector (ICE) Configuration. (Aircraft Figure from Dorsett 1996.)

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Figure 12a. Schematic of Passive Porosity Effector.  
(Figure from Wood 1999.)

Figure 12b. Passive Porosity on ICE.

Table 1. Effector Dynamics and Limits.

<table>
<thead>
<tr>
<th>Effector</th>
<th>Dynamics (freq (r/s), damping)</th>
<th>Position Limit (deg)</th>
<th>Rate Limit (deg/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevon</td>
<td>(63.246 , 1.107)</td>
<td>-30 / +30</td>
<td>150</td>
</tr>
<tr>
<td>AMT</td>
<td>(63.246 , 1.107)</td>
<td>0 / 60</td>
<td>150</td>
</tr>
<tr>
<td>Pitch TV</td>
<td>(39.189 , 1.001)</td>
<td>-15 / +15</td>
<td>60</td>
</tr>
<tr>
<td>Yaw TV</td>
<td>(39.142 , 1.001)</td>
<td>-15 / +15</td>
<td>60</td>
</tr>
<tr>
<td>Passive Pososity*</td>
<td>80.0</td>
<td>0 / 8</td>
<td>40</td>
</tr>
<tr>
<td>Pitch Flap</td>
<td>(63.246 , 1.107)</td>
<td>-30 / +30</td>
<td>50</td>
</tr>
</tbody>
</table>

* First order model

Figure 13a. Position and Rate Limit Boundaries from Reciprocal Bode Analysis – Control Position Weighted Pseudo-Inverse.

Figure 13b. Position and Rate Limit Boundaries from Reciprocal Bode Analysis - FACA with $T_M=0.3$.

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Figure 14. Percent RMS Effector Rate and Position Activity for a Pitch Step Sequence
– Control Position Weighted Pseudo-Inverse (CWPSI) and FACA.

Control Order
1: left elevon
2: right elevon
3: left AMT
4: right AMT
5: pitch TV
6: yaw TV
7: left PassPort
8: right PassPort
9: pitch flap

Figure 15. Elevon Failure Detection in Piloted Simulation.

Figure 16. Target cone angle, $\epsilon$.
(Figure from Foster 1998.)
Figure 17. Piloted Target Tracking Time Responses – Left Elevon Failure at 15 sec, FDI On (17a) and FDI Off (17b).