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# COOPERATIVE VARIABLE BANDWIDTH ACTUATORS FOR AEROSPACE APPLICATIONS

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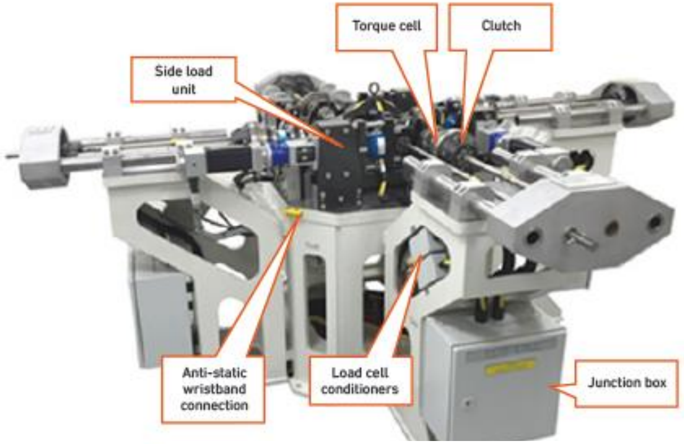
# COOPERATIVE VARIABLE BANDWIDTH ACTUATORS FOR AEROSPACE APPLICATIONS

Abstract: Control surface actuators are a critical component of the control system design for any aerospace vehicle. Typical applications include fins, canards, ailerons, stabilizers, and rudder actuator controllers on aircraft, missiles, or guided projectiles. Many different configurations exist in which combinations of two, three, four, or more control surfaces are used collectively or differentially to control roll, pitch and yaw motions of the air vehicle. When each actuator is controlled independently and driven by position and/or speed commands from the external autopilot, it is difficult to control desired airframe response in pitch, roll and yaw precisely. Due to parameter variations and different aerodynamic loading on each surface, unwanted perturbations airframe response may occur. Another issue is that actuators designed for a fixed bandwidth to meet worst case loading response characteristics, may be inefficient in use of energy and susceptible to noise in less stressing regions of flight. The proposed solution alleviates both problems by combining cooperative control methods with extended high gain observers in the design of Cooperative Variable Bandwidth Electric Motor Actuator Controllers. This presentation describes the design of a cooperative controller that receives roll, pitch and yaw commands from the autopilot, motor position and current feedbacks from each of the multiple actuators, and then provides optimum motor voltage commands to drive each of the actuators. Embedded high gain observers are able to estimate both the loading torque and torque disturbances on each motor, and compensate to eliminate unwanted airframe perturbations. This approach allows for the bandwidth (or response time) of each axis (pitch, roll, yaw) to be controlled independently, and even to be modified during flight by commands from the external autopilot to achieve energy efficiency. Simulation results under hypothetical conditions will be presented to demonstrate these advantages.

# ADVANCES IN ELECTRIC ACTUATION CONTROLLERS

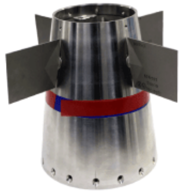
## Electric Actuation is an Important Business at Collins Aerospace

We make actuators for Military and Commercial Aircraft, Helicopters, Missiles, Rockets and Projectiles




Rocket canard CAS

Long-range control CAS



High-accuracy CAS

Guided munition CAS

GLMRS CAS

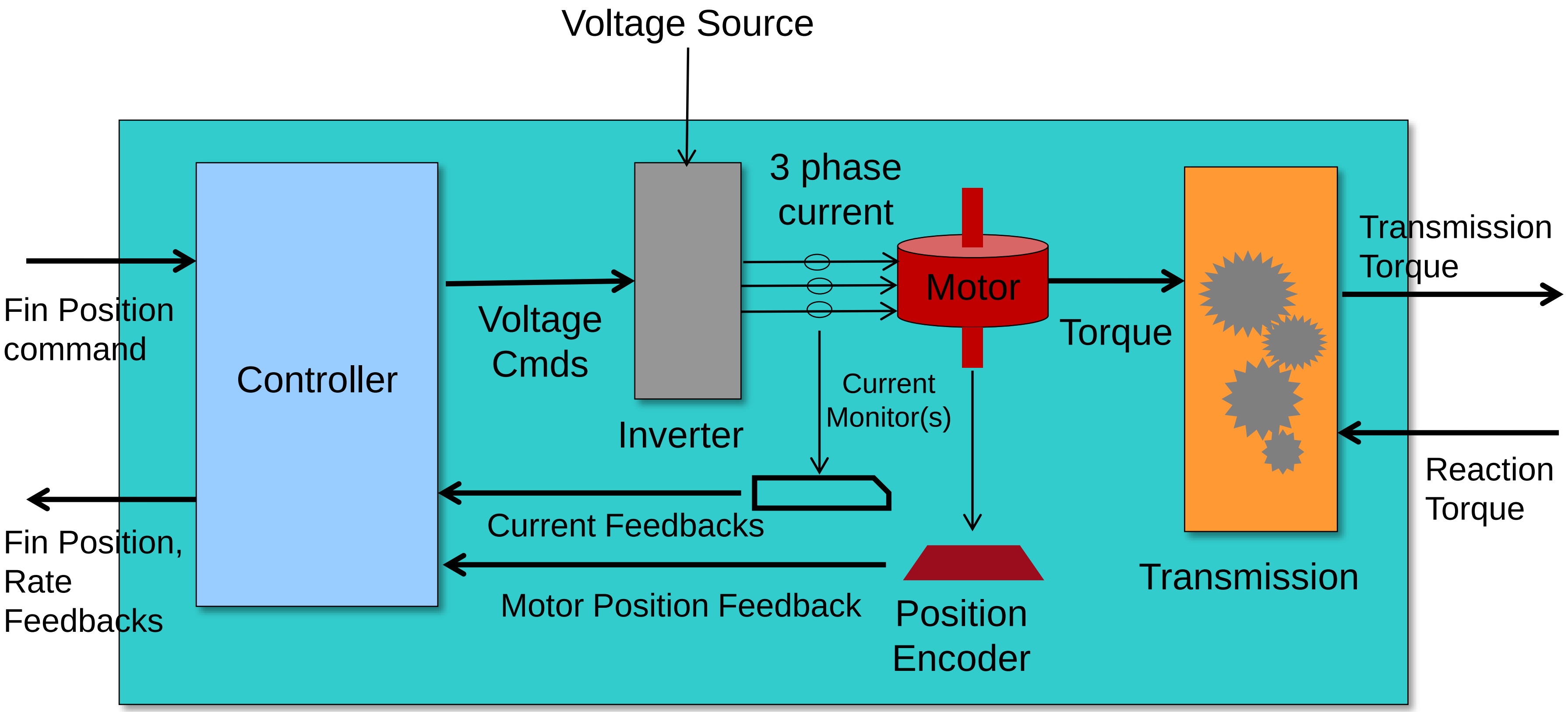
Air launched CAS

Thrust vector actuator

SM CAS

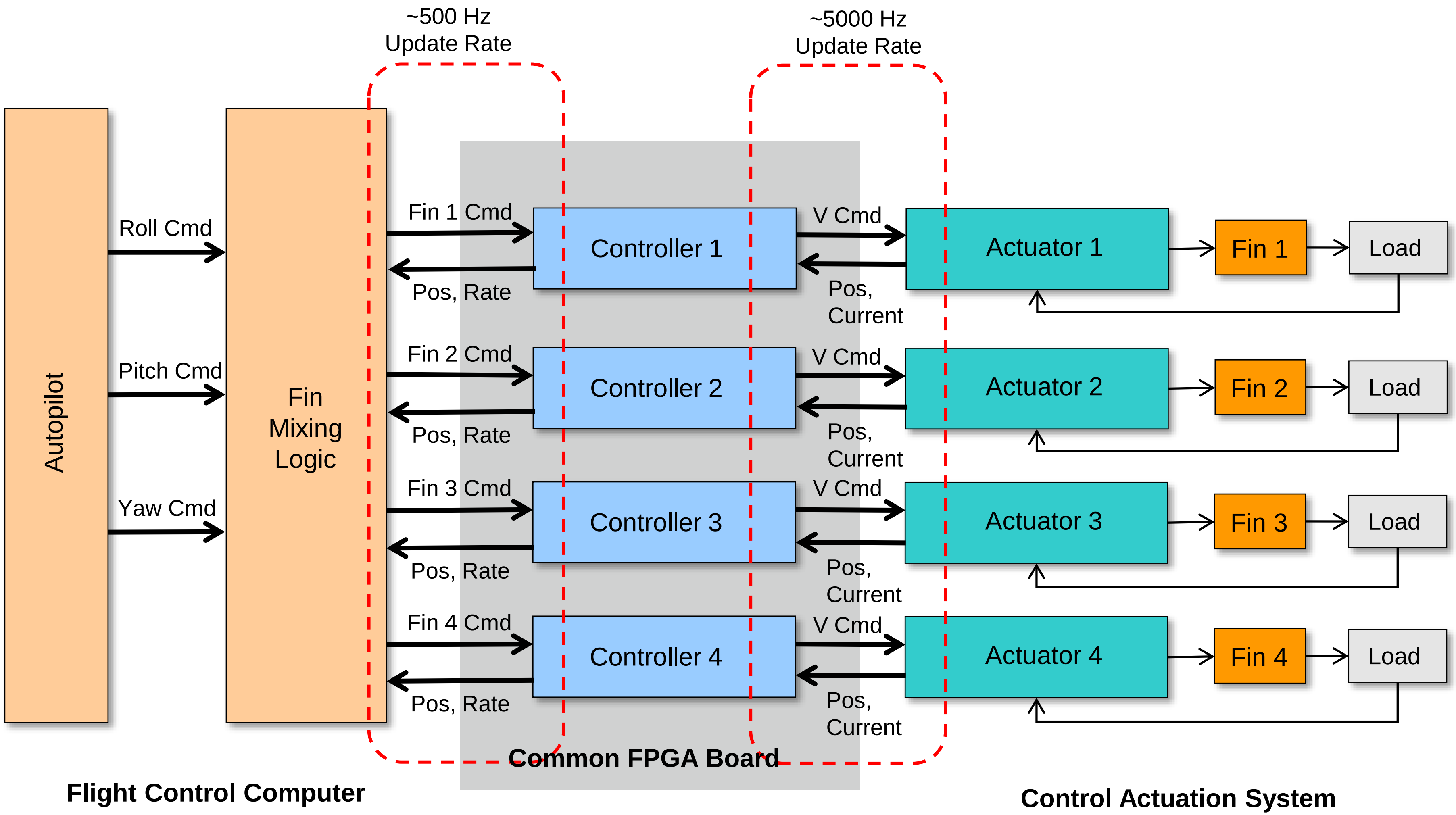
**Advances in Electric Actuation Controller Critical for Electrified Aircraft of the Future**

# CLASSICAL ELECTRIC ACTUATOR CONTROLLER



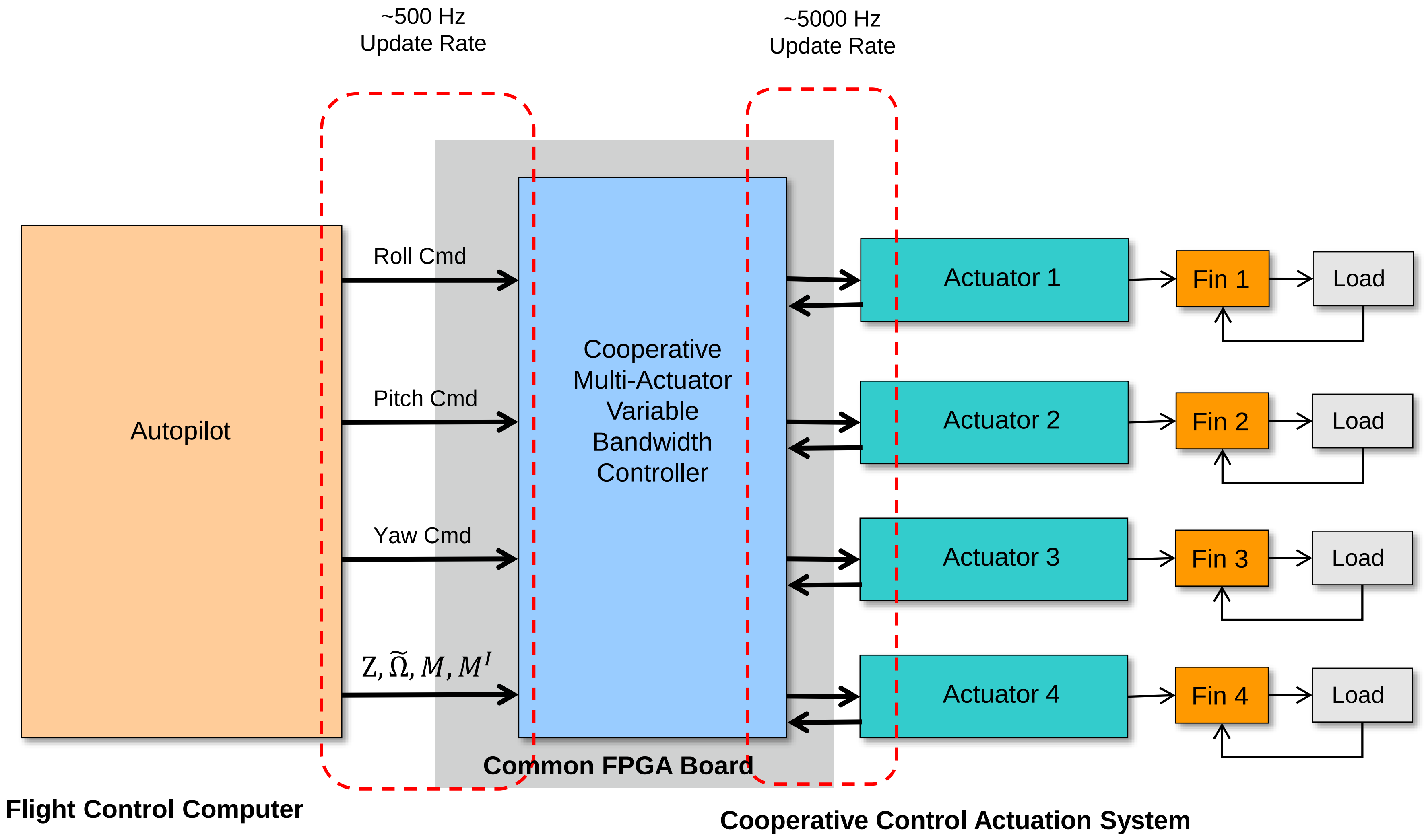

**Note: Hall Sensor Brushless DC Motors being replaced by Permanent Magnet Synchronous Motors**

# TYPICAL MULTI-ACTUATOR APPLICATION




**4 Actuators with 4 Independent Controllers Used to Control 3 Effects (Pitch, Roll, Yaw)**

# COOPERATIVE VARIABLE BANDWIDTH ACTUATORS FOR AEROSPACE APPLICATIONS




**Cooperative Controller Architecture Controls Desired Effects (i.e. Pitch, Roll, Yaw)**

# ADVANCES IN ELECTRIC ACTUATION CONTROLLER DESIGN

## Disturbance Compensating Electric Actuator Position and Speed Controller

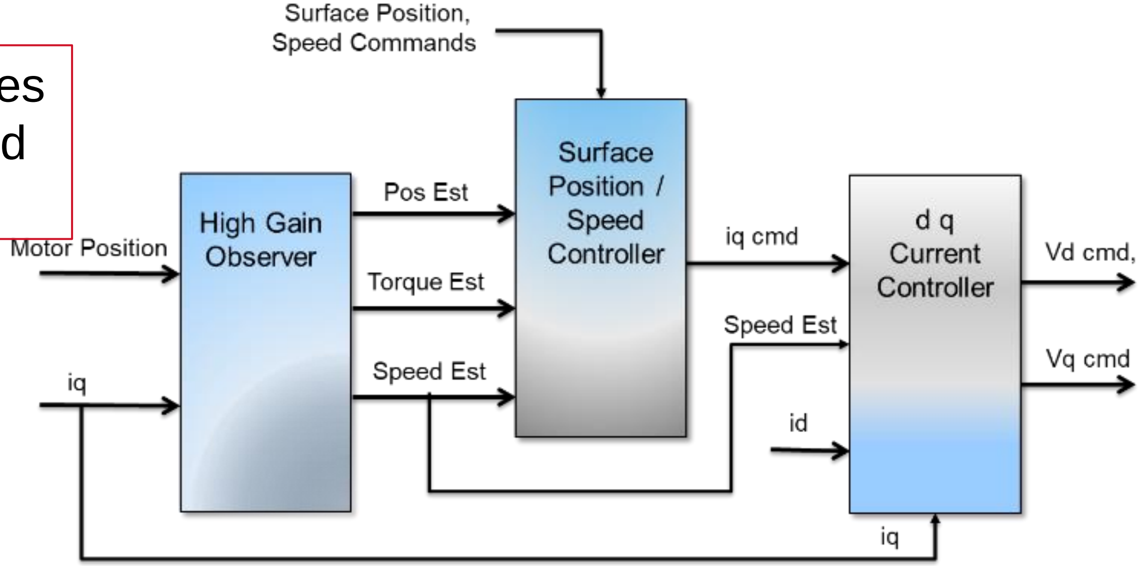
Collins Aerospace Patent Application Filed – April 20, 2023

High Gain Observer provides accurate estimates of speed and total reaction torque

Allows system to adapt to changing load torques and disturbances

Works for Position Control or Speed Control

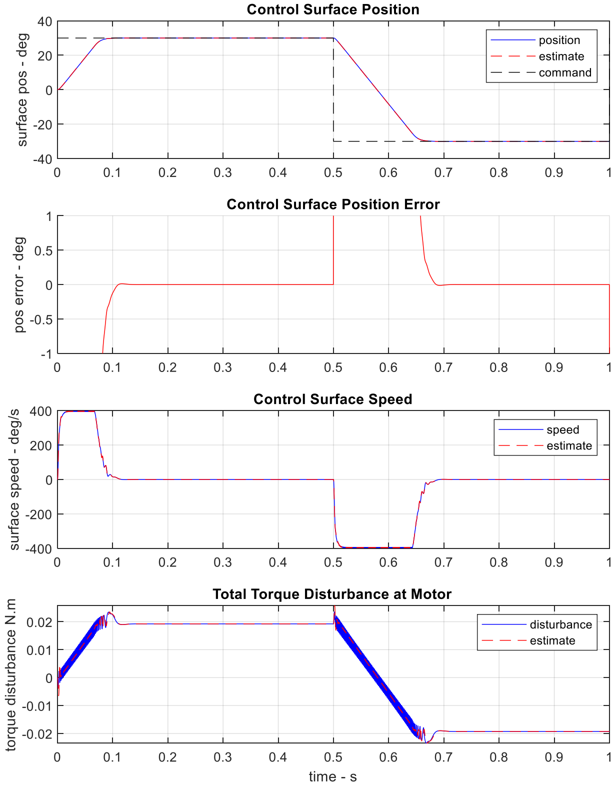
Unique Design Features




Sensor Processing and PWM Modulation

HDL Auto-coder for FPGA Implementation

High Gain Observer design compensates for cogging torque and torque ripple disturbances:



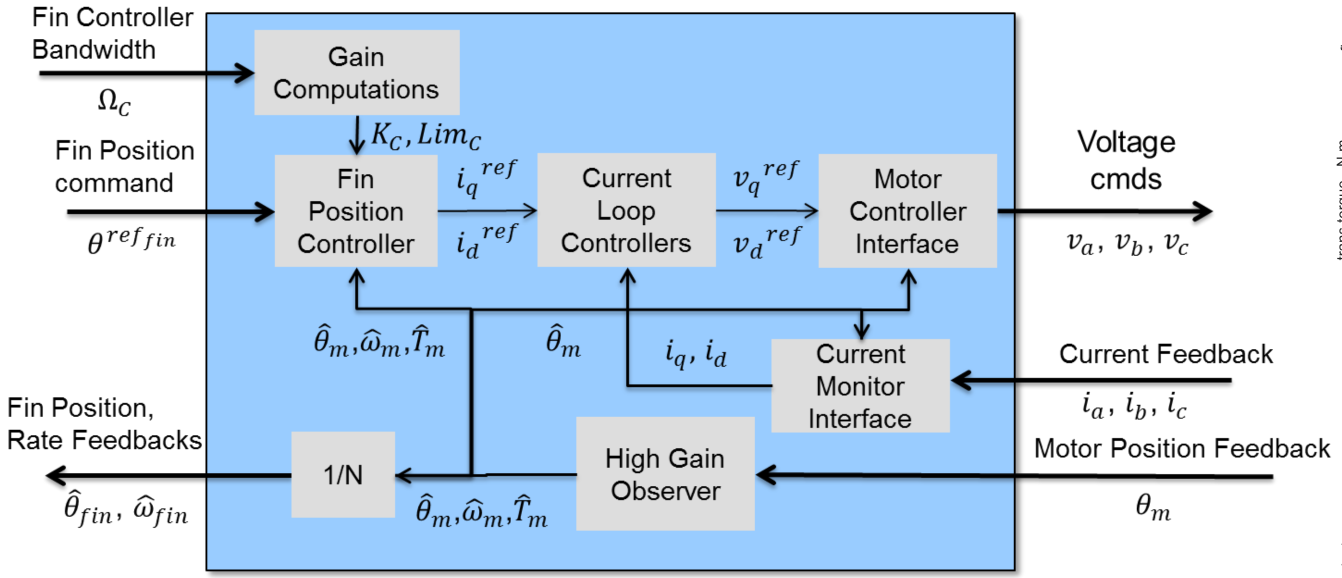

**Provides Robust Performance and Rejection of Non-linear Unmodelled Disturbances**

## Variable Bandwidth Actuator Controller Design

US Patent Application Publication: US 2021/0072708 A1, March 11, 2021

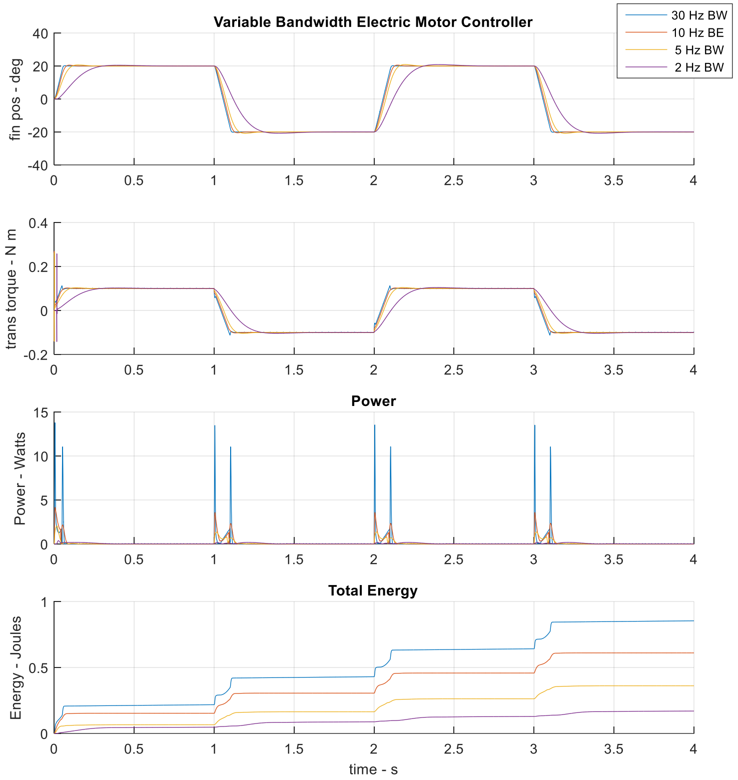
Bandwidth can be changed by external input to vary with flight conditions

High Gains not Required to Overcome Load Torques




Variable Bandwidth Controller Architecture

Energy Consumption is a Function of Actuator Bandwidth




**User Can Dynamically Change Actuator Bandwidth to Save Energy**

# COOPERATIVE VARIABLE BANDWIDTH ACTUATORS FOR AEROSPACE APPLICATIONS

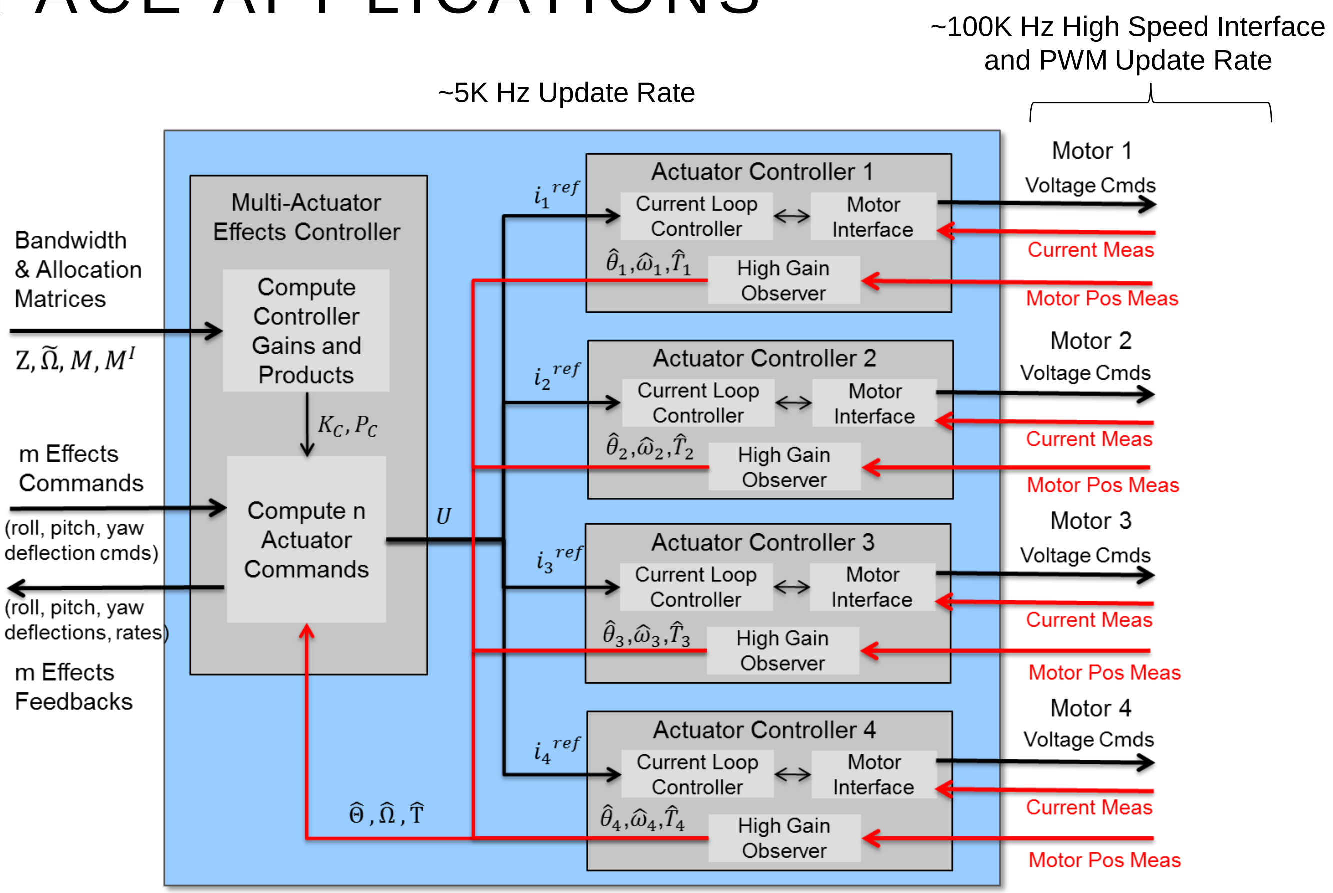
**User (Flight Control Computer) Specifies Bandwidths and Damping of Pitch, Roll, Yaw commands, and Control Allocation Mixing and Inverse Mixing Matrices**

**Synchronization of Control Effects**

**Compensates for Asymmetric Loading and Non-linear Disturbances**

**Potential for Significant Energy Savings**

**Potential Applications in Redundancy Management**




Cooperative Multi-Actuator Variable Bandwidth Controller

US Patent Granted: US 11,609,540 B2, March 21, 2023

**The Cooperative Multi-Actuator Architecture Allocates Commands and Controls BW of Effects**

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

Starting with the simplified mechanical equations for an electric motor driven actuator:

$$\theta = N\delta$$
$$\dot{\theta} = \omega$$
$$\dot{\omega} = -\left(\frac{B}{J}\right)\omega + \left(\frac{T}{J}\right) + \left(\frac{k_m}{J}\right)\mathrm{u}$$

$\delta$ = actuator angular position

N = gear ratio between actuator position and electric motor drive shaft

θ = motor rotor angular position

ω = motor rotational speed

B = electric motor “back emf” damping factor

T = external load torque at motor shaft

$k_m$ = electric motor torque constant (torque/current input)

J = motor rotational inertia

u = control input (motor current)

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

We then write these equations representing a multi-actuator system in matrix form:

$$\Theta = \mathrm{N}\Delta_n$$
$$\dot{\Theta} = \Omega$$
$$\dot{\Omega} = -J^{-1}B\Omega + J^{-1}\mathrm{T} + J^{-1}K_m\mathrm{U}$$

Where:

$$\Delta_n = \text{vector of actuator positions} = [\delta_1 \quad \cdots \quad \delta_n]^T$$

$$\mathrm{N} = \text{diagonal matrix of gear ratios} = \begin{bmatrix} N_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & N_n \end{bmatrix}$$

$$\Theta = \text{vector of motor angular positions} = [\theta_1 \quad \cdots \quad \theta_n]^T$$

$$\Omega = \text{vector of motor rotational speeds} = [\omega_1 \quad \cdots \quad \omega_n]^T$$

$$\mathrm{J} = \text{diagonal matrix of motor rotational inertias} = \begin{bmatrix} J_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & J_n \end{bmatrix}$$

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

continuing:

$$\mathrm{B} = \text{diagonal matrix of “back emf” damping factors} = \begin{bmatrix} B_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & B_n \end{bmatrix}$$

$$\mathrm{T} = \text{diagonal matrix of external load torques} = \begin{bmatrix} T_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & T_n \end{bmatrix}$$

$$K_m = \text{diagonal matrix of electric motor torque constants} = \begin{bmatrix} K_{m_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & K_{m_n} \end{bmatrix}$$

$$\mathrm{U} = \text{vector of motor current control inputs} = [u_1 \quad \cdots \quad u_n]^T$$

Applying the gear ratios, which could be different for each actuator, to the electric motor equations, we get 2n electric motor equations in matrix form:

$$\dot{\Delta}_n = N^{-1}\dot{\Theta} = N^{-1}\Omega \qquad (1)$$
$$\ddot{\Delta}_n = N^{-1}\dot{\Omega} = -N^{-1}J^{-1}B\Omega + N^{-1}J^{-1}\mathrm{T} + N^{-1}J^{-1}K_m\mathrm{U} \qquad (2)$$

# DERIVATION OF
# COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

The **Allocation Matrix** links the dynamics of the multi-actuator system to achieve a set of cooperative behaviors

Example 1: Represents an "X" aerodynamic configuration, where 4 fins are used in different combinations to control roll, pitch and yaw.

$$\underbrace{\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix}}_{\Delta_n} = \underbrace{\begin{bmatrix} 1 & -1 & 1 \\ 1 & -1 & -1 \\ 1 & 1 & -1 \\ 1 & 1 & 1 \end{bmatrix}}_{M} \underbrace{\begin{bmatrix} \delta_p \\ \delta_q \\ \delta_r \end{bmatrix}}_{\Delta_{pqr}}$$

In this case the matrix *M* represents an overdetermined system, with 4 actuators used to control 3 effects.

The reverse transformation for this example is represented by the matrix $M^I$:

$$\underbrace{\begin{bmatrix} \delta_p \\ \delta_q \\ \delta_r \end{bmatrix}}_{\Delta_{pqr}} = \underbrace{\left(\frac{1}{4}\right) \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 \end{bmatrix}}_{M^I} \underbrace{\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix}}_{\Delta_n}$$

Note: we can find $M^I$ from the *pseudo-inverse* of *M:*

$$M^I = M^\# \triangleq [M^T M]^{-1} \, M^T$$

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

The allocation matrix *M* is determined from the physical configuration of control effectors plus control design weighting factors. Some Examples:

$$\underbrace{\begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\\ \delta_4\end{bmatrix}}_{\Delta_n} = \underbrace{\begin{bmatrix}1 & -1 & 0\\ 1 & 0 & -1\\ 1 & 1 & 0\\ 1 & 0 & 1\end{bmatrix}}_{M} \underbrace{\begin{bmatrix}\delta_p\\ \delta_q\\ \delta_r\end{bmatrix}}_{\Delta_{pqr}}$$

Example 2: Represents a “plus” (+) aerodynamic configuration, where 2 fins are dedicated to pitch and 2 are dedicated to yaw.

$$\underbrace{\begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\\ \delta_4\end{bmatrix}}_{\Delta_n} = \underbrace{\begin{bmatrix}.707 & -1 & 1\\ .707 & -1 & -1\\ .707 & 1 & -1\\ .707 & 1 & 1\end{bmatrix}}_{M} \underbrace{\begin{bmatrix}\delta_p\\ \delta_q\\ \delta_r\end{bmatrix}}_{\Delta_{pqr}}$$

Example 3: Represents an “X” (x) aerodynamic configuration, with weighting factors to balance roll aerodynamic effectiveness with pitch and yaw.

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

Additional Examples:

$$\underbrace{\begin{bmatrix}\delta_1\\ \delta_2\end{bmatrix}}_{\Delta_n} = \underbrace{\begin{bmatrix}1 & -1\\ 1 & 1\end{bmatrix}}_{M} \underbrace{\begin{bmatrix}\delta_p\\ \delta_q\end{bmatrix}}_{\Delta_{pq}}$$

Example 4: Represents a system with two fins controlling only roll and pitch.

$$\underbrace{\begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\\ \delta_4\end{bmatrix}}_{\Delta_n} = \underbrace{\begin{bmatrix}1 & -1\\ 1 & 1\\ .5 & 0\\ .5 & 0\end{bmatrix}}_{M} \underbrace{\begin{bmatrix}\delta_p\\ \delta_q\end{bmatrix}}_{\Delta_{pq}}$$

Example 5: Represents a system with two fins to control roll and pitch and two ailerons to assist with roll control

$$\underbrace{\begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\\ \delta_4\\ \delta_5\end{bmatrix}}_{\Delta_n} = \underbrace{\begin{bmatrix}0 & 1 & 0\\ 1 & 0 & 0\\ 1 & 0 & 0\\ 0 & 0 & .707\\ 0 & 0 & .707\end{bmatrix}}_{M} \underbrace{\begin{bmatrix}\delta_p\\ \delta_q\\ \delta_r\end{bmatrix}}_{\Delta_{pqr}}$$

Example 6: Represents an aircraft system with one stabilizer to control pitch, two ailerons to control roll, and two rudders to control yaw.

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

Generalize the relationship between n control actuators and m control effects:

$$\Delta_n = M\Delta_m \qquad\qquad \Delta_m = M^I\Delta_n$$

Develop a cooperative control law that will utilize the n actuators to achieve the desired dynamic response of the $\Delta_m$ states and track the m reference signals $\Delta_m^{ref}$:

$$\ddot{\Delta}_m + \mathrm{K}_1\left(\dot{\Delta}_m - \dot{\Delta}_m^{ref}\right) + \mathrm{K}_2\left(\Delta_m - \Delta_m^{ref}\right) = 0 \qquad \text{(effects dynamics design equation)} \quad (3)$$

$\mathrm{K}_1$ and $\mathrm{K}_2$ are gain matrices selected to map the system to desirable second order system.

$\Delta_m^{ref}$ and $\dot{\Delta}_m^{ref}$ are the desired reference signals and their derivatives (if known).

The gains allow the flexibility to design different response times (or bandwidths) for each of the m states.

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

Using the fin-controlled missile from Example 1, for instance, we can design the gains to impose a well damped second order response with independent natural frequencies (bandwidths), $\varpi$, and damping ratios, $\zeta$, in each of the m states (roll, pitch and yaw).

Second order response shaping parameters for roll, pitch, yaw example:

$$\widetilde{\Omega} = \begin{bmatrix} \varpi_p & 0 & 0 \\ 0 & \varpi_q & 0 \\ 0 & 0 & \varpi_r \end{bmatrix} \quad , \mathrm{Z} = \begin{bmatrix} \zeta_p & 0 & 0 \\ 0 & \zeta_q & 0 \\ 0 & 0 & \zeta_r \end{bmatrix}$$

Then design the gain matrices are chosen:

$$\mathrm{K}_1 = 2\mathrm{Z}\widetilde{\Omega} \quad , \qquad \mathrm{K}_2 = \widetilde{\Omega}^2$$

Note that for the general case, the design parameters and gain matrices $\mathrm{K}_1$ and $\mathrm{K}_2$ are m x m diagonal matrices.

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

Since the reverse allocation matrix $M^I$ is constant:

$$\Delta_m = M^I \Delta_n \qquad \dot{\Delta}_m = M^I \dot{\Delta}_n \qquad \ddot{\Delta}_m = M^I \ddot{\Delta}_n$$

Substituting these into the effects dynamics design equation (3), we relate the n actuator dynamic equations to the m dynamic effects:

$$M^I \ddot{\Delta}_n + \mathrm{K}_1\left(M^I \dot{\Delta}_n - \dot{\Delta}_m^{ref}\right) + \mathrm{K}_2\left(M^I \Delta_n - \Delta_m^{ref}\right) = 0$$

Using the properties of the pseudoinverse, since $(M^I)^{\#} = M$

$$\ddot{\Delta}_n = -M\mathrm{K}_1\left(M^I \dot{\Delta}_n - \dot{\Delta}_m^{ref}\right) - M\mathrm{K}_2\left(M^I \Delta_n - \Delta_m^{ref}\right)$$

Then equating to the motor equations derived for $\ddot{\Delta}_n$, $\dot{\Delta}_n$:

$$-N^{-1}J^{-1}B\Omega + N^{-1}J^{-1}\mathrm{T} + N^{-1}J^{-1}K_m\mathrm{U} = -M\mathrm{K}_1\left(M^I N^{-1}\Omega - \dot{\Delta}_m^{ref}\right) - M\mathrm{K}_2\left(M^I \Delta_n - \Delta_m^{ref}\right)$$

And solving for the required motor input currents $\mathrm{U}$ :

$$N^{-1}J^{-1}K_m\mathrm{U} = N^{-1}J^{-1}B\Omega - N^{-1}J^{-1}\mathrm{T} - M\mathrm{K}_1\left(M^I N^{-1}\Omega - \dot{\Delta}_m^{ref}\right) - M\mathrm{K}_2\left(M^I \Delta_n - \Delta_m^{ref}\right)$$

# DERIVATION OF COOPERATIVE VARIABLE BANDWIDTH CONTROLLER

We derive the n motor input currents required to track the desired cooperative effects:

$$\mathrm{U} = {K_m}^{-1}B\Omega - {K_m}^{-1}\mathrm{T} - {K_m}^{-1}JNM\mathrm{K}_1\left(M^I N^{-1}\Omega - \dot{\Delta}_m{}^{ref}\right) - {K_m}^{-1}JNM\mathrm{K}_2\left(M^I N^{-1}\Theta - \Delta_m^{ref}\right) \qquad (4)$$

Assuming the n motor feedback positions, $\Theta$, rates, $\Omega$, and external torques, $\mathrm{T}$, are available from either measurements or estimated (from the high gain observer).

For ease of implementation we can re-write Equation (4):

$$\mathrm{U} = P_1\Omega - P_2\mathrm{T} - P_3\mathrm{K}_1\left(P_4\Omega - \dot{\Delta}_m{}^{ref}\right) - P_3\mathrm{K}_2\left(P_4\Theta - \Delta_m^{ref}\right)$$

Where the products may be pre-computed:

$$P_1 = {K_m}^{-1}B, \qquad P_2 = {K_m}^{-1}, \qquad P_3 = {K_m}^{-1}JNM, \qquad P_4 = M^I N^{-1}$$

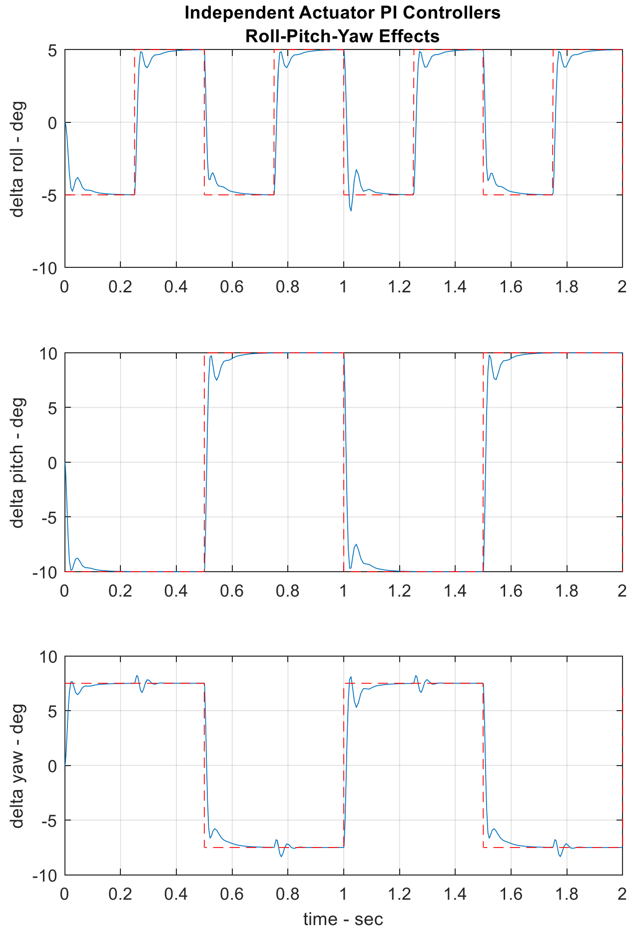
And the gain matrices may be either pre-computed and/or updated in real-time:

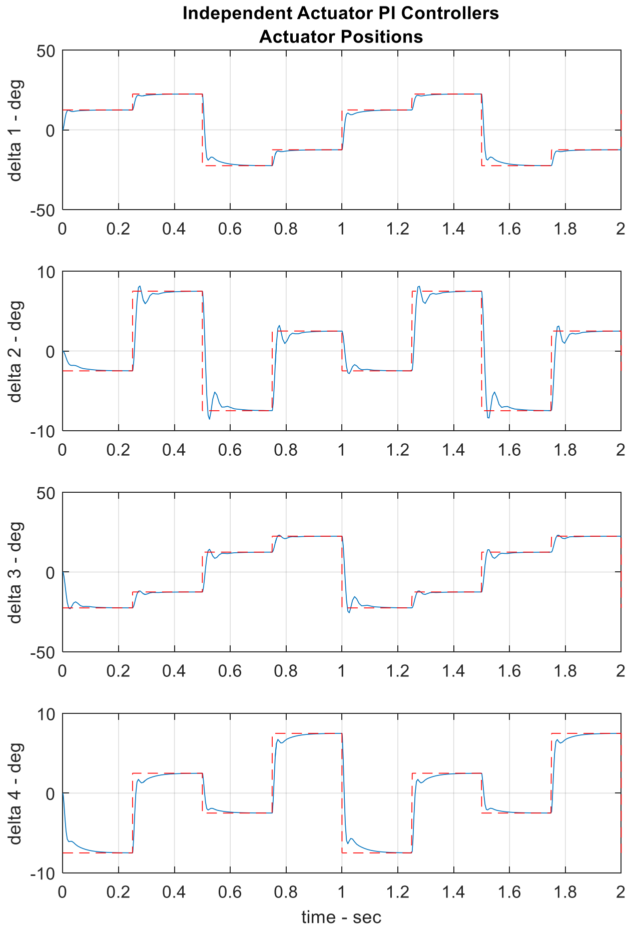
$$\mathrm{K}_1 = 2\mathrm{Z}\widetilde{\Omega} \;, \qquad \mathrm{K}_2 = \widetilde{\Omega}^2$$

if it is desired to change response characteristics of one or more effect.

# SIMULATION RESULTS

## Independent Actuators with PI Controllers

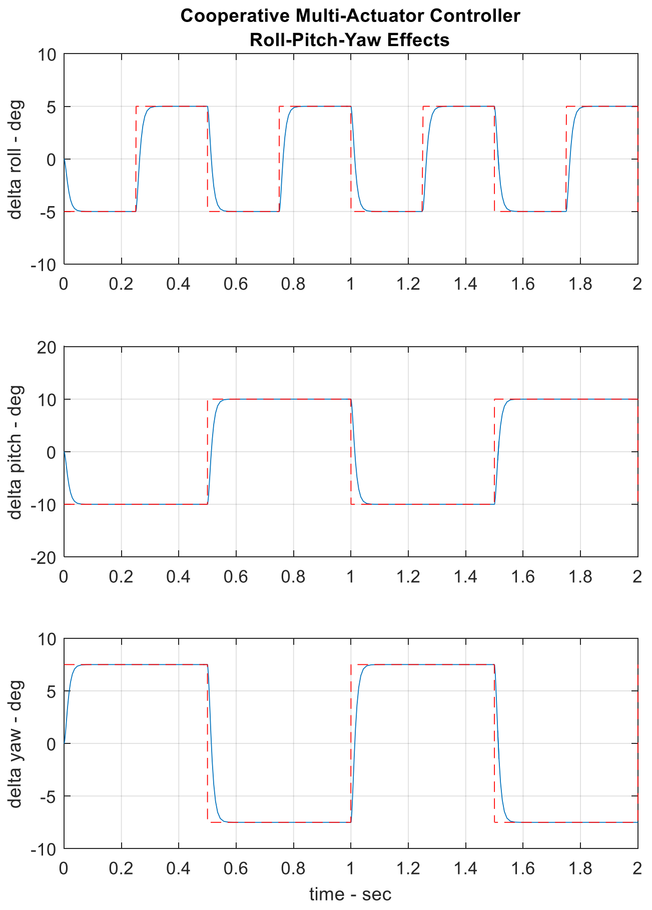


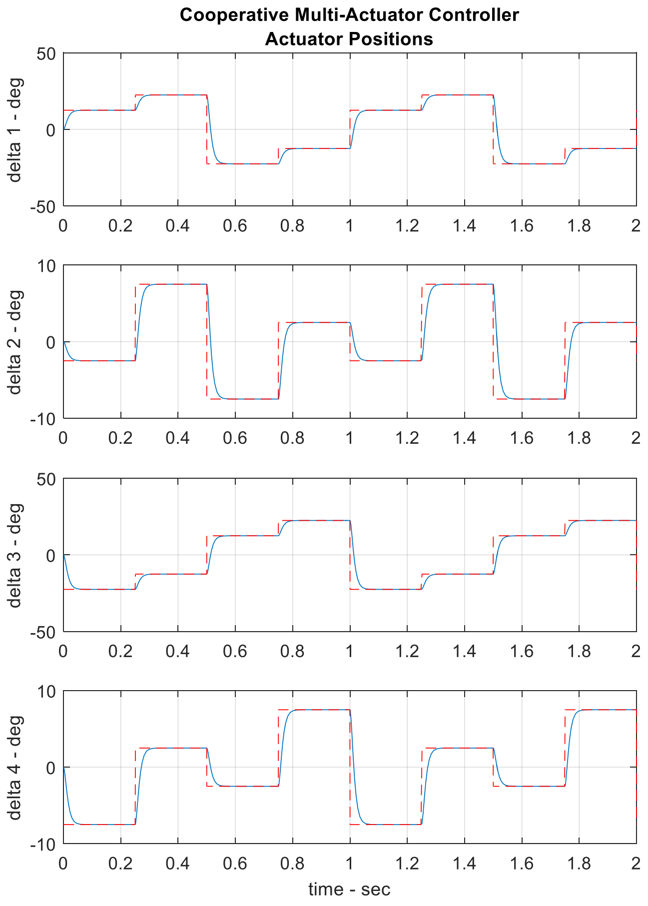




actuators 2 and 3 have twice the rotational inertia of actuators 1 and 2

# SIMULATION RESULTS

## Cooperative Mult-Actuator Variable Bandwidth Controllers
## (with Estimated Torque Feedback)

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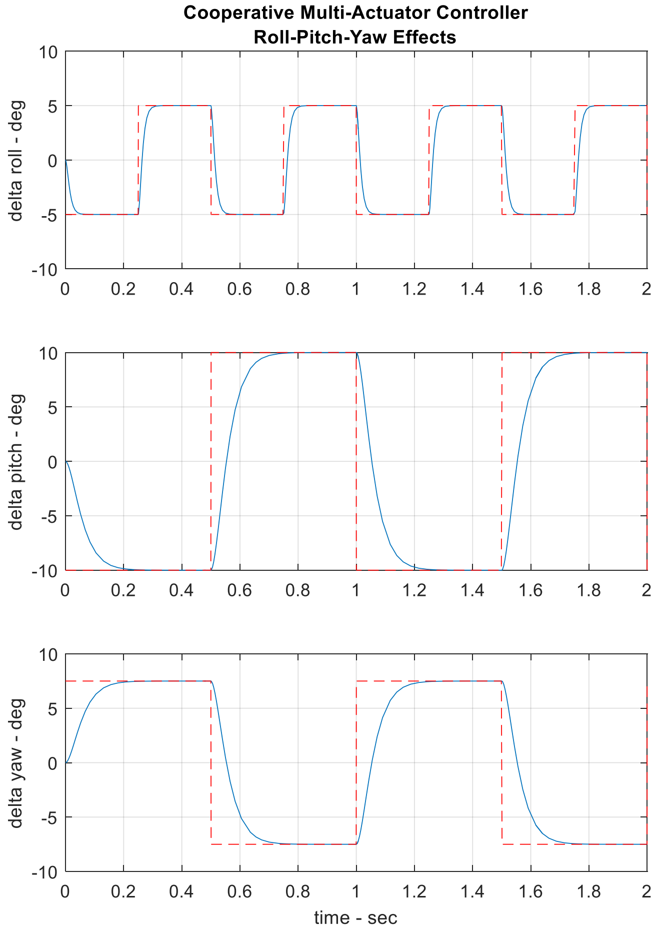
# SIMULATION RESULTS

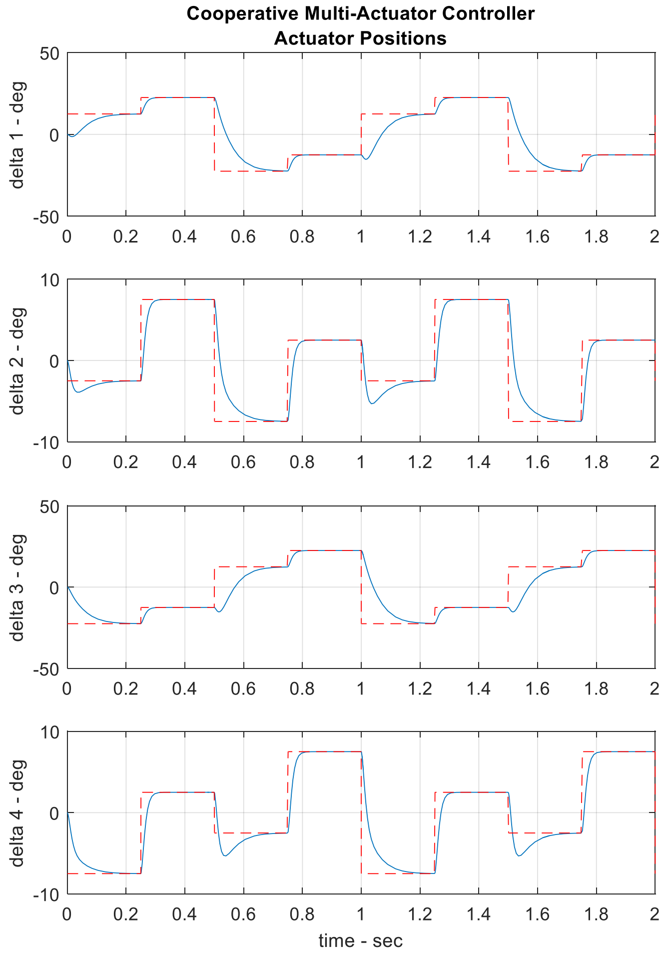
Cooperative Mult-Actuator Variable Bandwidth Controllers
(with Estimated Torque Feedback)




Roll BW = 20 Hz

Pitch BW = 5 Hz

Yaw BW = 5 Hz

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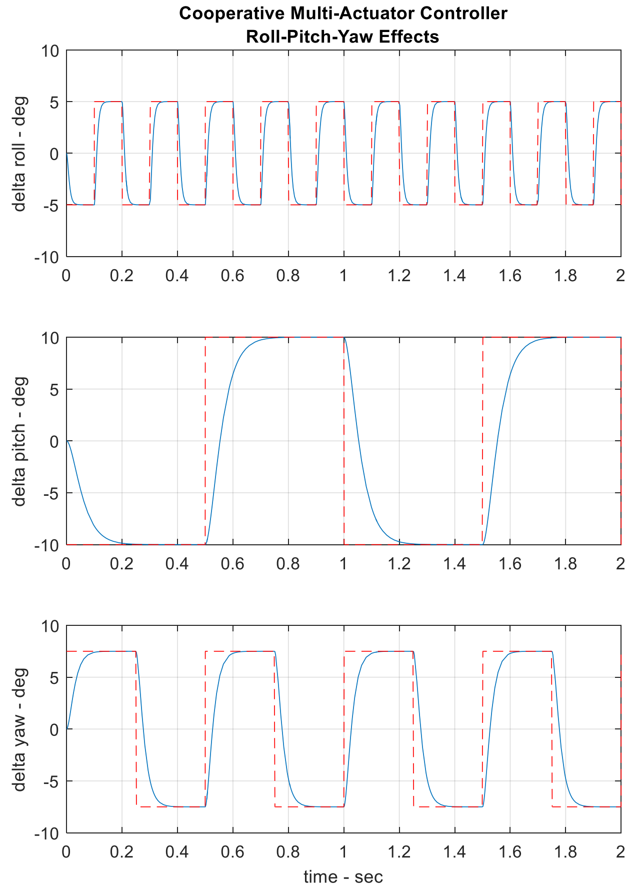
# SIMULATION RESULTS

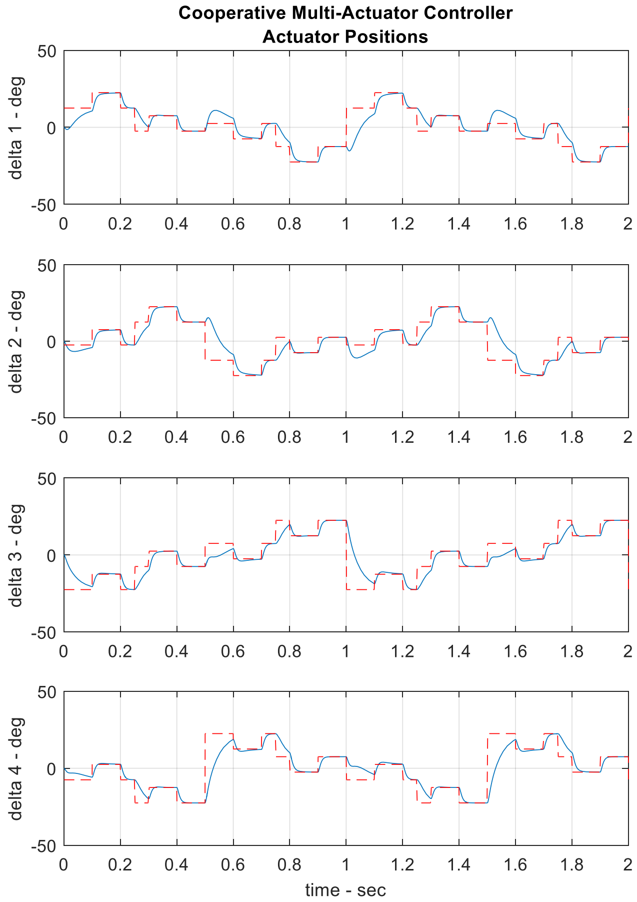
Cooperative Mult-Actuator Variable Bandwidth Controllers
(with Estimated Torque Feedback)




Roll BW = 30 Hz

Pitch BW = 5 Hz

Yaw BW = 10 Hz




actuators 2 and 3 have twice the rotational inertia of actuators 1 and 2

# COOPERATIVE VARIABLE BANDWIDTH ACTUATORS FOR AEROSPACE APPLICATIONS

## Summary

Incorporates Several Advances in Electric Actuator Controller Design

- Non-linear and Multivariable Design of Current and Position Controller Loops
- High Gain Observer to Estimate Load Torques and Improve Disturbance Rejection
- Variable Bandwidth Real-Time Gain Updates to Optimize Power Usage
- Cooperative Control Techniques to Control and Coordinate Group Effects
- MBSE Tools should be used to improve and maintain actuator controller design
  - Model-In-the-Loop and Monte Carlo Testing
  - High Level configuration management of the controller algorithms in Simulink
  - Auto-Coding to C-Code for Floating Point Processors
  - Normalization and Fixed-Point HDL Auto-Coding for FPGA Implementation

# COOPERATIVE VARIABLE BANDWIDTH ACTUATORS FOR AEROSPACE APPLICATIONS

## References


1. "Speed Control of Permanent Magnet Synchronous Motor Using Extended High-Gain Observer," Abdullah A. Alfehaid, Elias G. Strangas, Hassan K. Khalil,Proceedings of the 2016 American Control Conference, July 6-8, 2016.
2. **High-Gain Observers in Nonlinear Feedback Control**, Hassan K. Khalil, SIAM, 2017.
3. **Cooperative Control of Dynamical Systems, Applications to Autonomous Vehicles**, Zhihua Qu, Springer, 2009.
4. **Control System Design, an Introduction to State-Space Methods**, Bernard Friedland, McGraw Hill, 1986.
5. "Variable Bandwidth Actuator Controller", United States Patent Application Publication, US 2021/0072708 A1, Richard Art Hull and Paul Martin Franz, assigned to Simmonds Precision Products, Inc., March 11, 2021.
6. "Cooperative Multi-Actuator Variable Bandwidth Controller", United States Patent No.: US 11,609,540 B2, Richard A. Hull, assigned to Simmonds Precision Products, Inc., March 21, 2023.

# Biography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- Current Role: Senior Technical Fellow with **Raytheon** | An RTX Business , Advanced Technology Group, supporting developments in guidance, navigation, control, actuation and sensors.

- Career Background: Rich has served as a GNC System Engineer in the Aerospace Industry for over 50 years, working for Martin Marietta, McDonnell Douglas, Boeing, AFOSR, Coleman Aerospace, Lockheed Martin, SAIC, Goodrich Aerospace, UTC Aerospace Systems, Collins Aerospace and Raytheon companies. His expertise is in flight controls and dynamics, guidance, navigation, actuation, linear and nonlinear control theory, and Model Based Systems Engineering. He is a Life Senior member of Institute of Electrical and Electronics Engineers (IEEE), a member of the IEEE Control System Society (CSS), former Chair of the IEEE CSS Technical Committee on Aerospace Control (TCAC), and instructor in the Collins Aerospace Technical University (CATU).