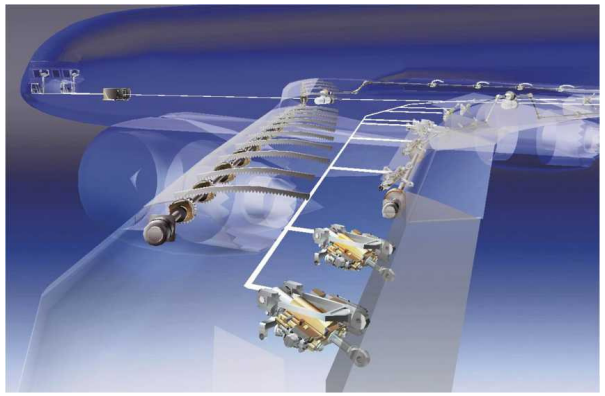
MOOG

SERVO HYDRAULIC TECHNOLOGY IN FLIGHT CONTROL



Workshop on Innovative Engineering for Fluid Power and Vehicular Systems
ABIMAQ - São Paulo
14-15 May 2012

Mario F. Valdo

OVER 55 YEARS OF EXPERIENCE IN MOTION CONTROL

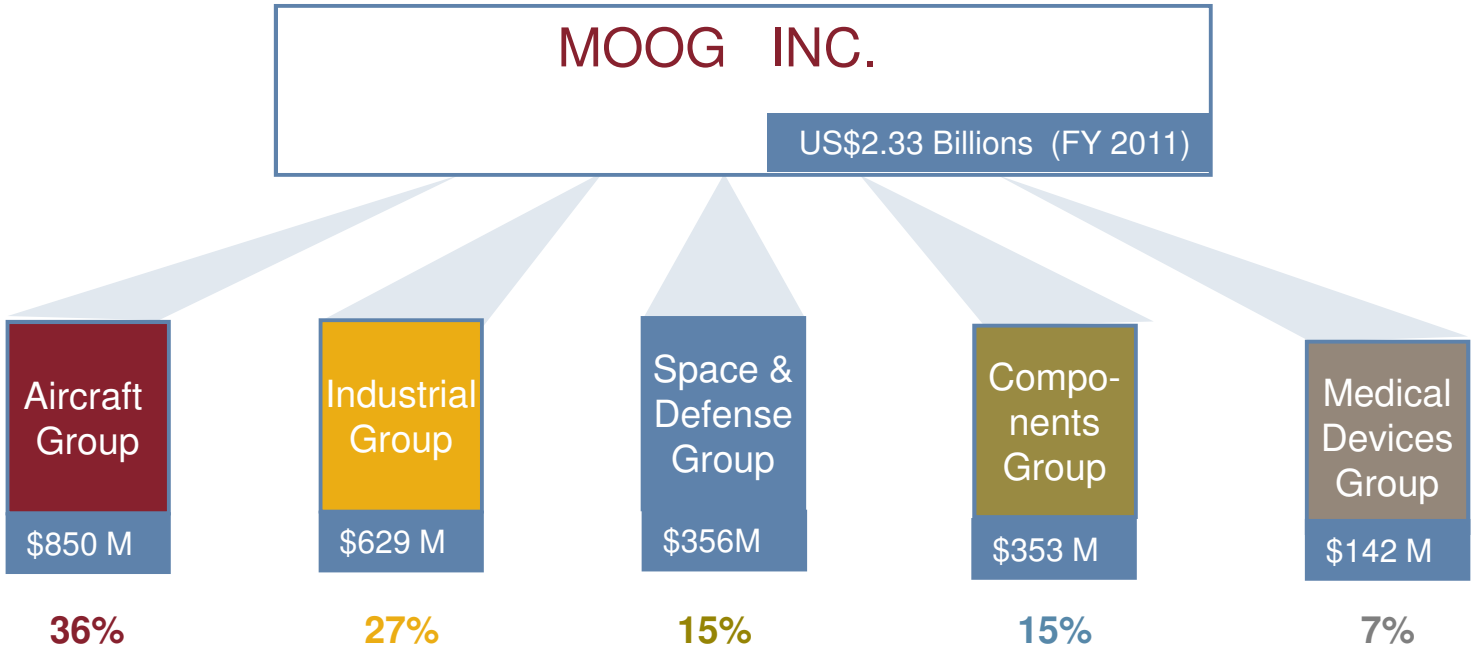
- Founded by Bill Moog, Art Moog and Lou Geyer in 1951 as "Moog Valve Company" – based on the first commercial servo valve

- Founder's culture of innovation and persistence still exist today:
  - Collaborative approach
  - "Can-do" mindset
  - Flexible organization
  - Dedicated solutions

A Global Company

- Argentina
- Australia
- Austria
- Brazil
- Canada
- China
- Costa Rica
- Denmark
- Finland
- France
- Germany
- India
- Ireland
- Italy
- Japan
- Lithuania
- Luxembourg
- Netherlands
- Norway
- Philippines
- Russia
- Singapore
- South Africa
- South Korea
- Spain
- Sweden
- Switzerland
- United Arab Emirates
- United Kingdom
- United States

GROUPS


MOOG INC.
US$2.33 Billions (FY 2011)
Aircraft Group
$850 M
36%
Industrial Group
$629 M
27%
Space & Defense Group
$356M
15%
Compo-nents Group
$353 M
15%
Medical Devices Group
$142 M
7%

HIGH PERFORMANCE MOTION CONTROL

MOOG

Military & Commercial Aircraft

Satellites, Missiles & Launch Vehicles

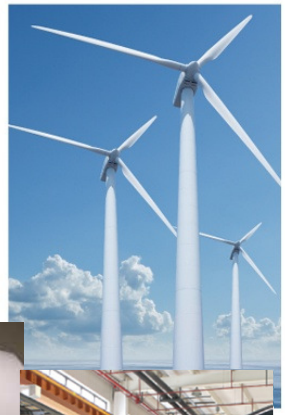
Defense & Surveillance

Industrial Machinery

Test & Simulation

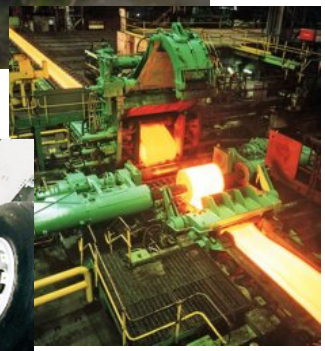
Infusion Pumps (medical)

Components (slip rings, fiber optic joints, air moving, resolvers, encoders)

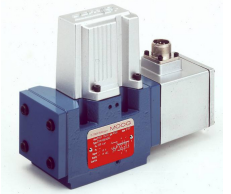













HIGH PERFORMANCE MOTION CONTROL

Closed loop control of physical variables (servocontrol):

- position
- velocity
- aceleration
- force
- pressure

Servocontrols Technology:

Electro-hydraulic: servovalves, servopumps

Electro-mechanical: servomotors

- Electro-pneumatic: proportional pneumatic valves

AIRCRAFT MARKET - OFFERING

MOOG

Integrated Flight Control Systems

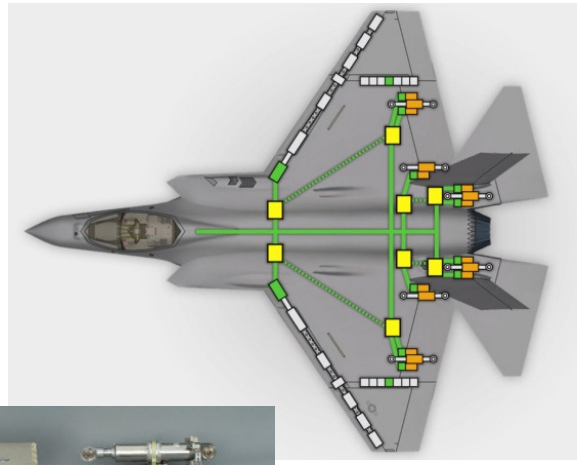
- Primary Flight Control Systems
- High Lift Systems
- Maneuvering Leading Edge Systems

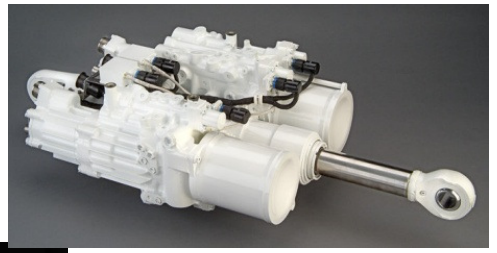
Critical Control Applications

- Engine Controls
- Active Vibration Control
- Weapons Bay Door Drive
- Braking and Steering

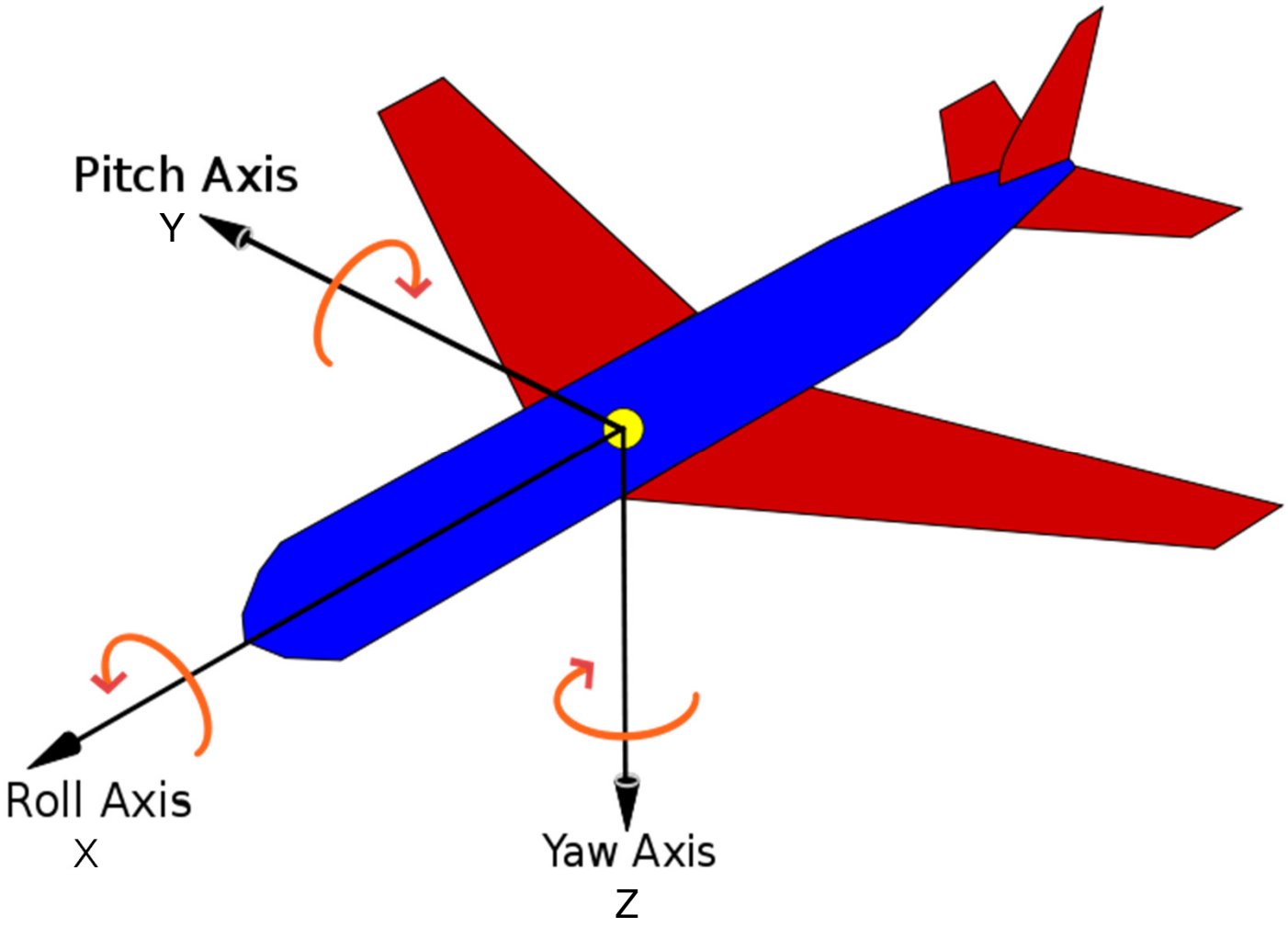
Critical Control Products

- Flight Control Computers & Software
- Cockpit Controls
- Control Electronics & Power Drives
- Actuators – Electrohydraulic, Electromechanical and Electrohydrostatic
- Related Components

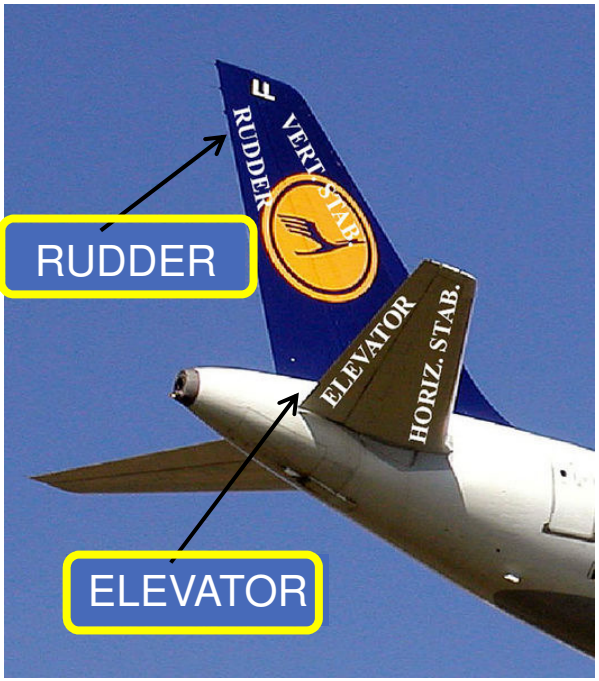


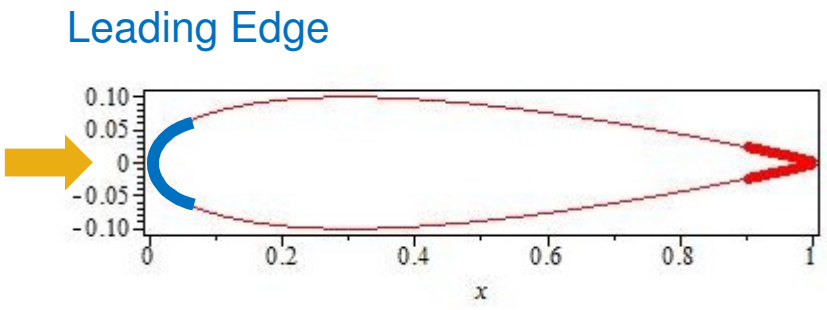


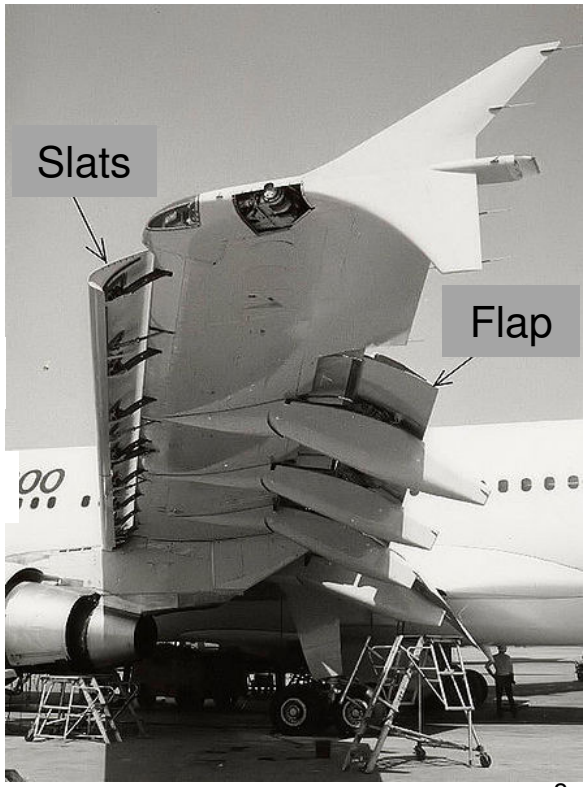
AIRCRAFT AXIS OF MOTION

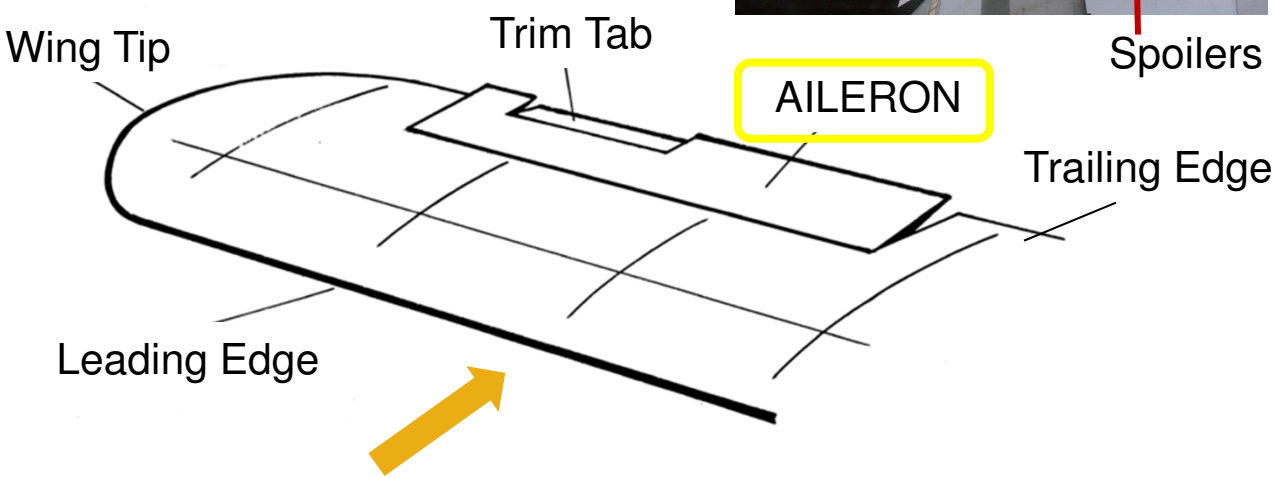


FLY CONTROL SURFACES

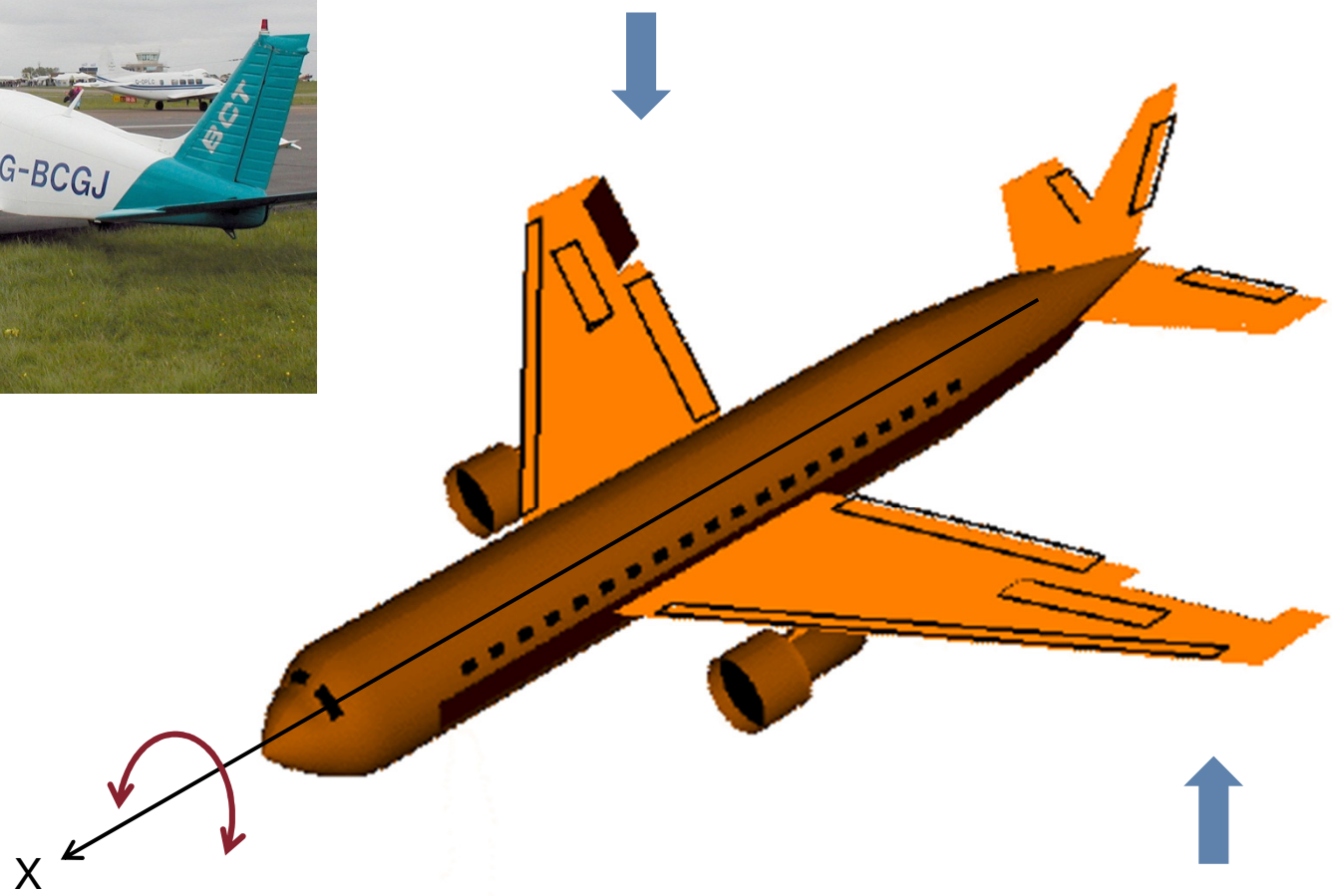






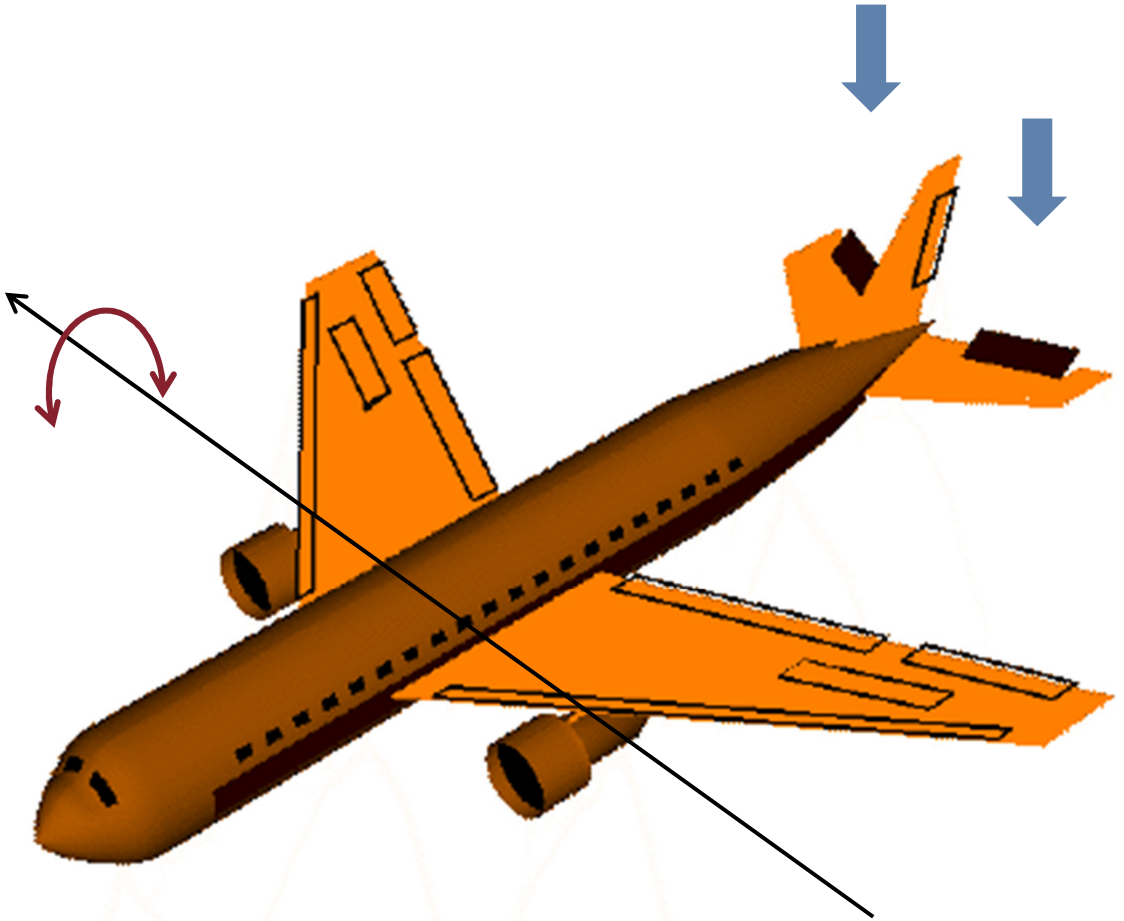


ROLL - AILERONS



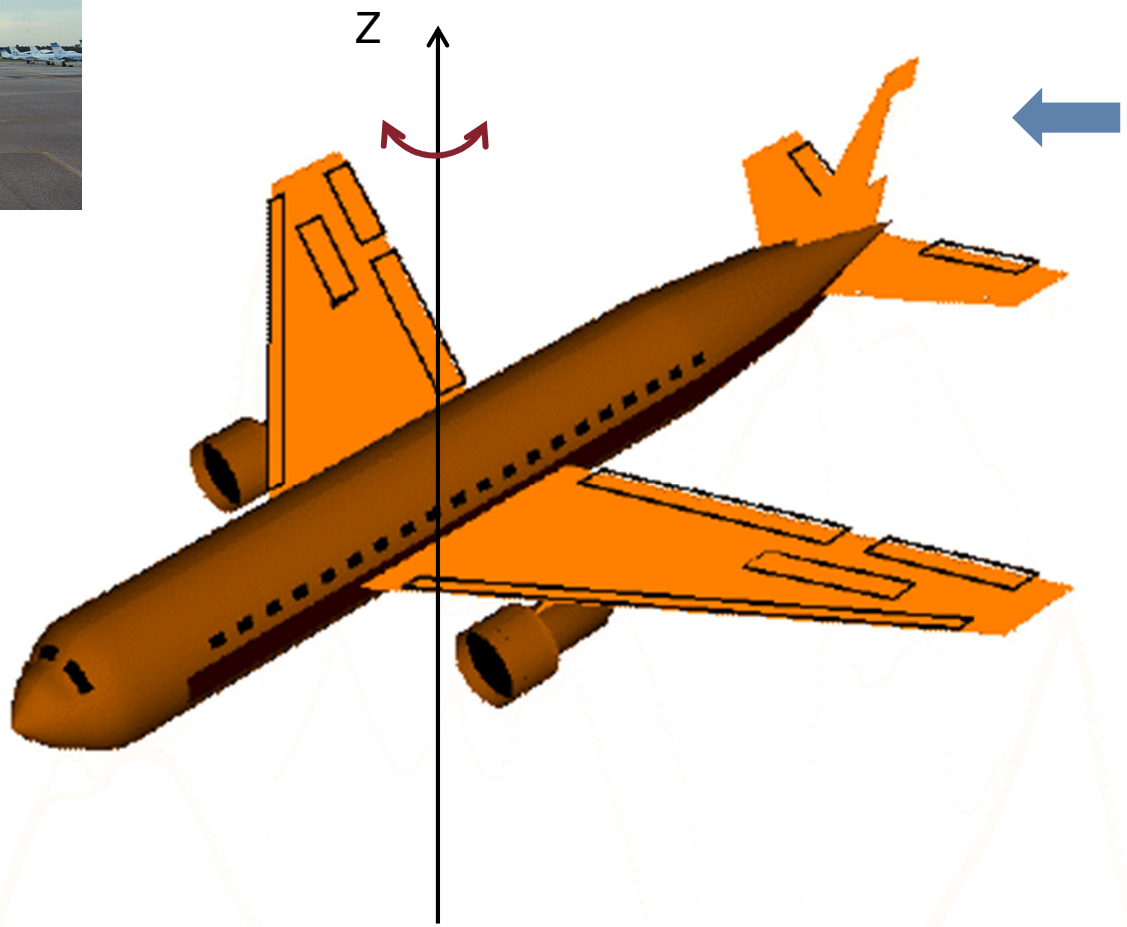
An animation of an airplane rolling via its ailerons

PITCH -ELEVATORS



An animation of an airplane pitching via its elevators

YAW- RUDDER



An animation of an airplane yawing with its rudder

AIRCRAFT FLIGHT CONTROLS

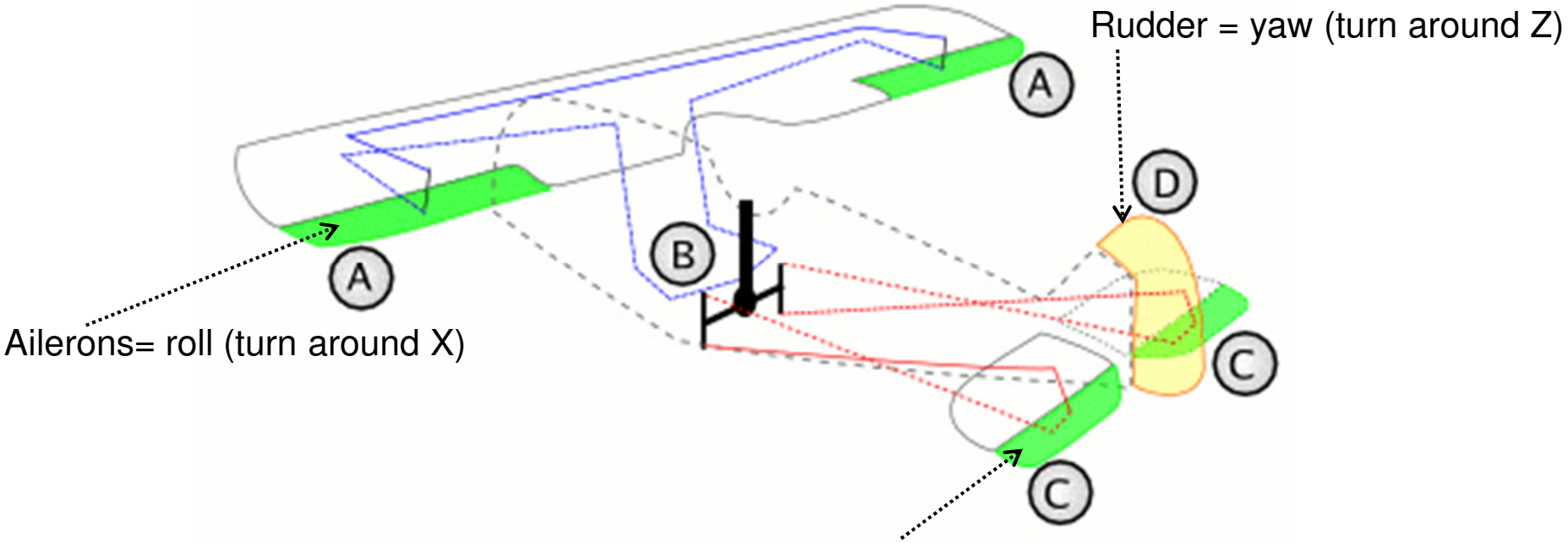
MOOG

In the drawing, a red arrow shows the way the control stick is being tilted. Small green arrows show the swing of the respective control surfaces and indicate the direction of the forces acting on the cable. The bent wires show the generic routing of control cables in the aircraft and connect the controls with the control surfaces.

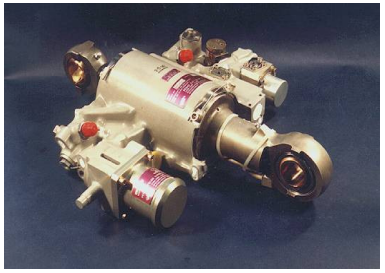
In smaller or older aircraft, the lines represent actual cables that link controls to control surfaces. In more modern aircraft, a computer take of the pilot inputs and send commands electronically to control surface actuators.

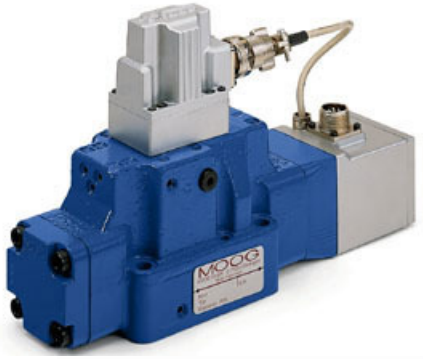
Control surfaces: A) aileron, C) elevator, D) rudder.

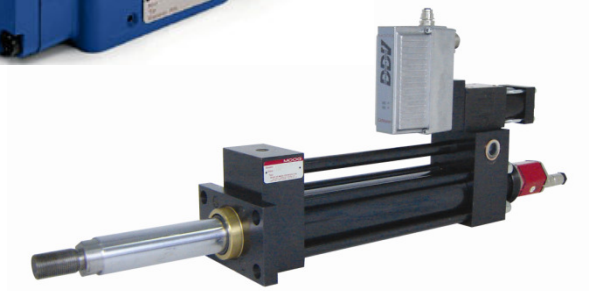
B) control stick



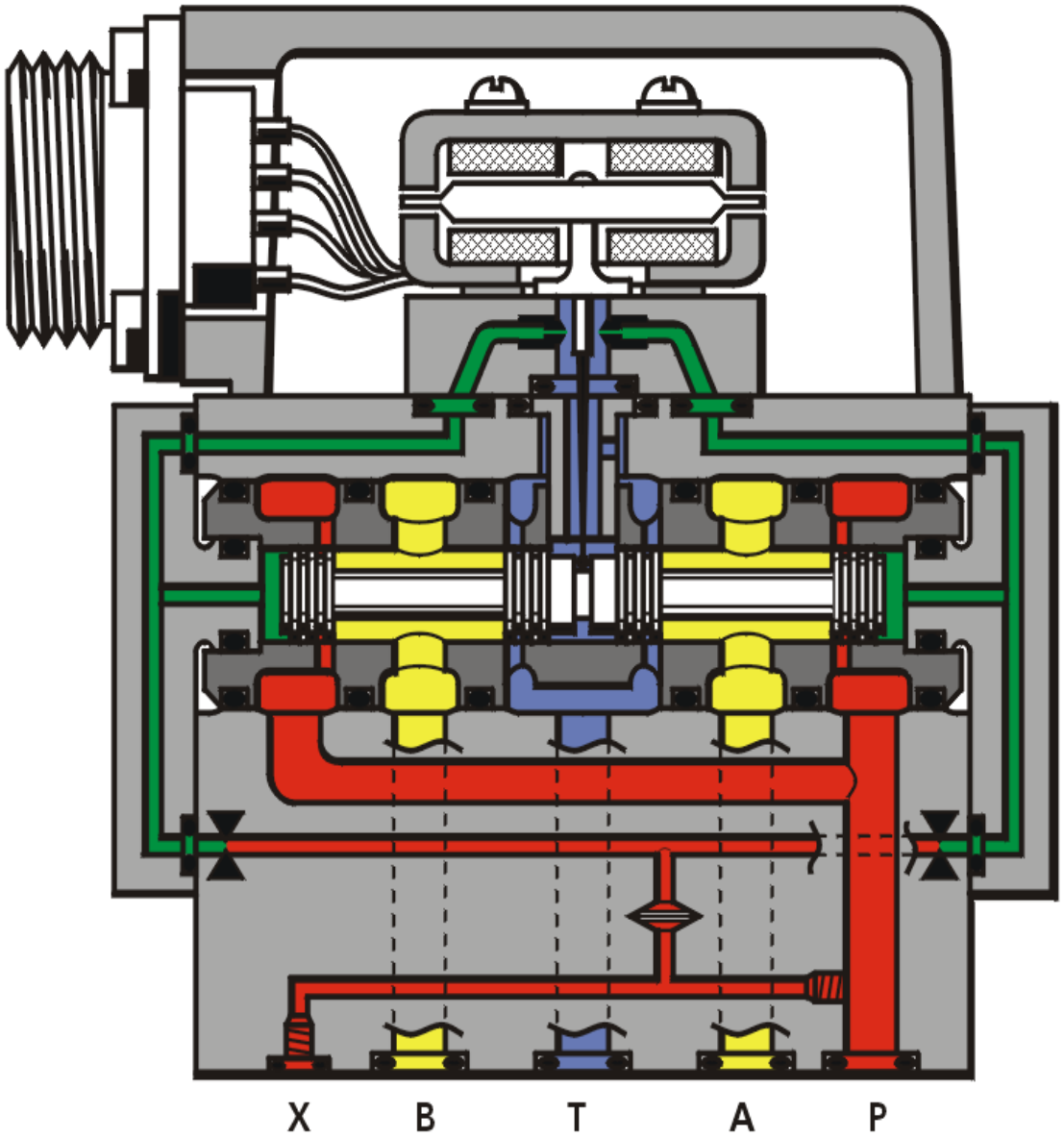
AEROSPACE X INDUSTRIAL COMPONENTS MOOG





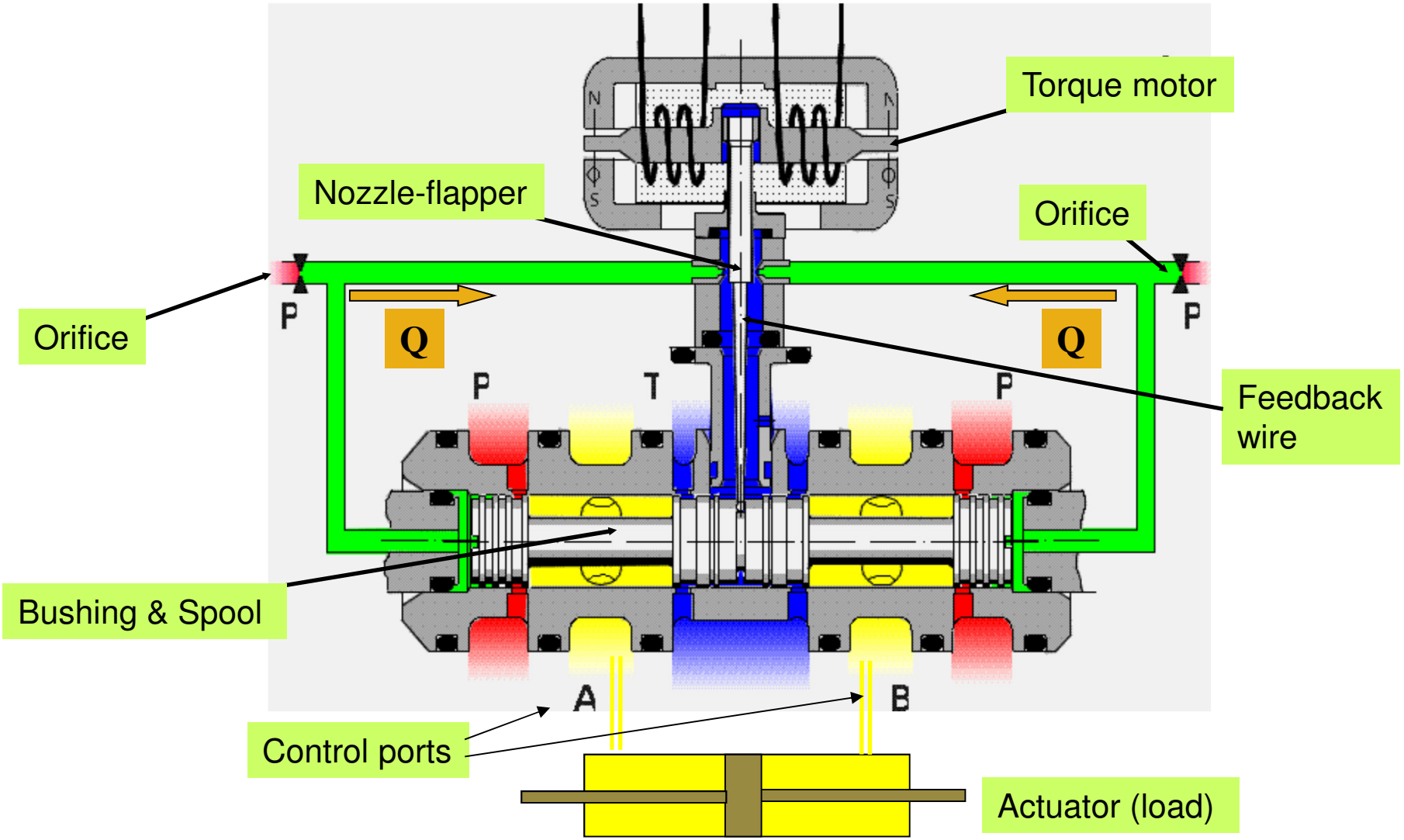


NOZZLE-FLAPPER SERVOVALVE

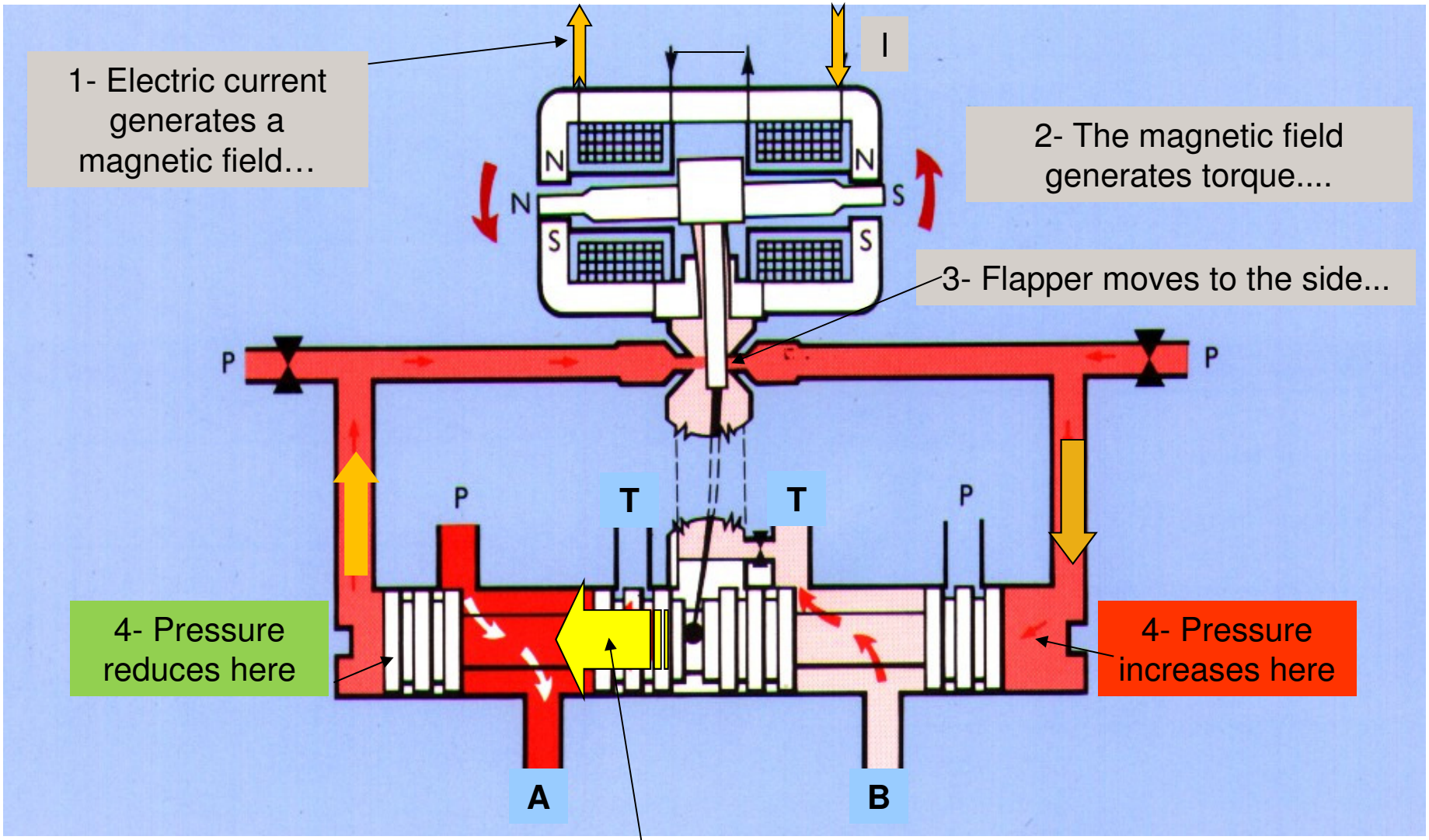


mechanical feedback

NOZZLE-FLAPPER SERVOVALVE – detailed view



APPLYING COMMAND.....

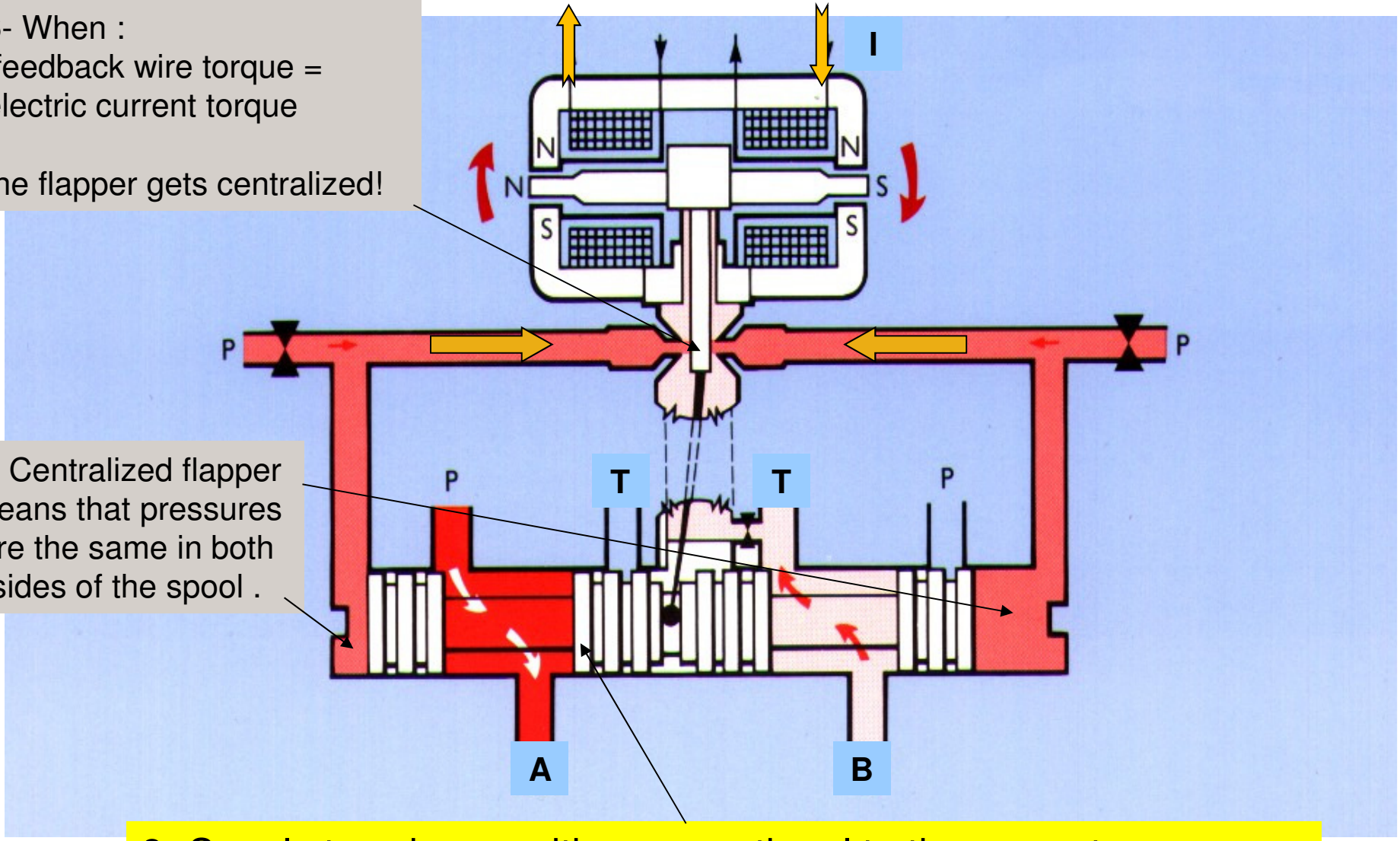


REACHING THE FINAL POSITION

(defined by the current command)

6- When :
feedback wire torque =
electric current torque

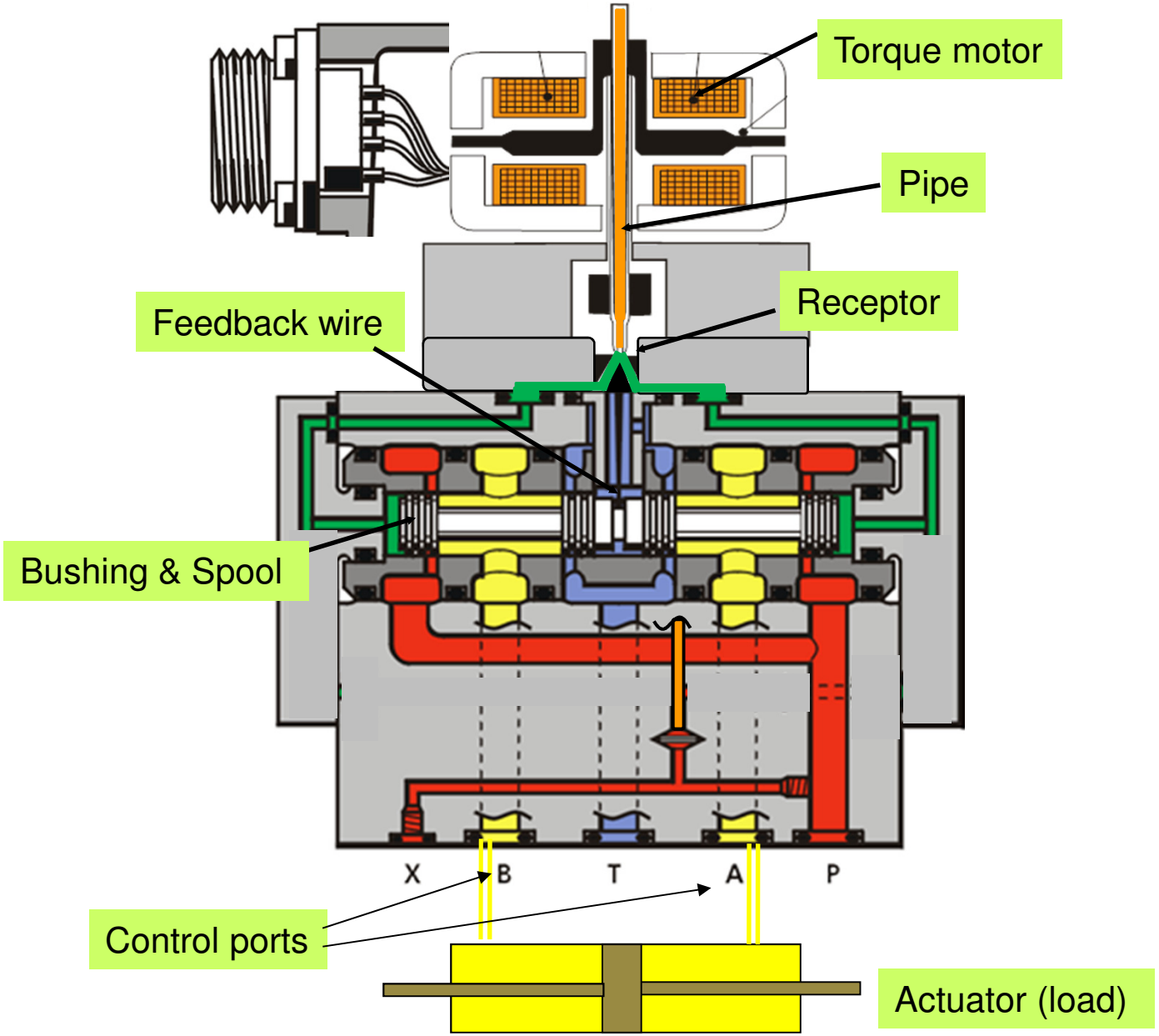
the flapper gets centralized!



7- Centralized flapper means that pressures are the same in both sides of the spool .

8- Spool stays in a position proportional to the current command.

JET PIPE SERVOVALVE

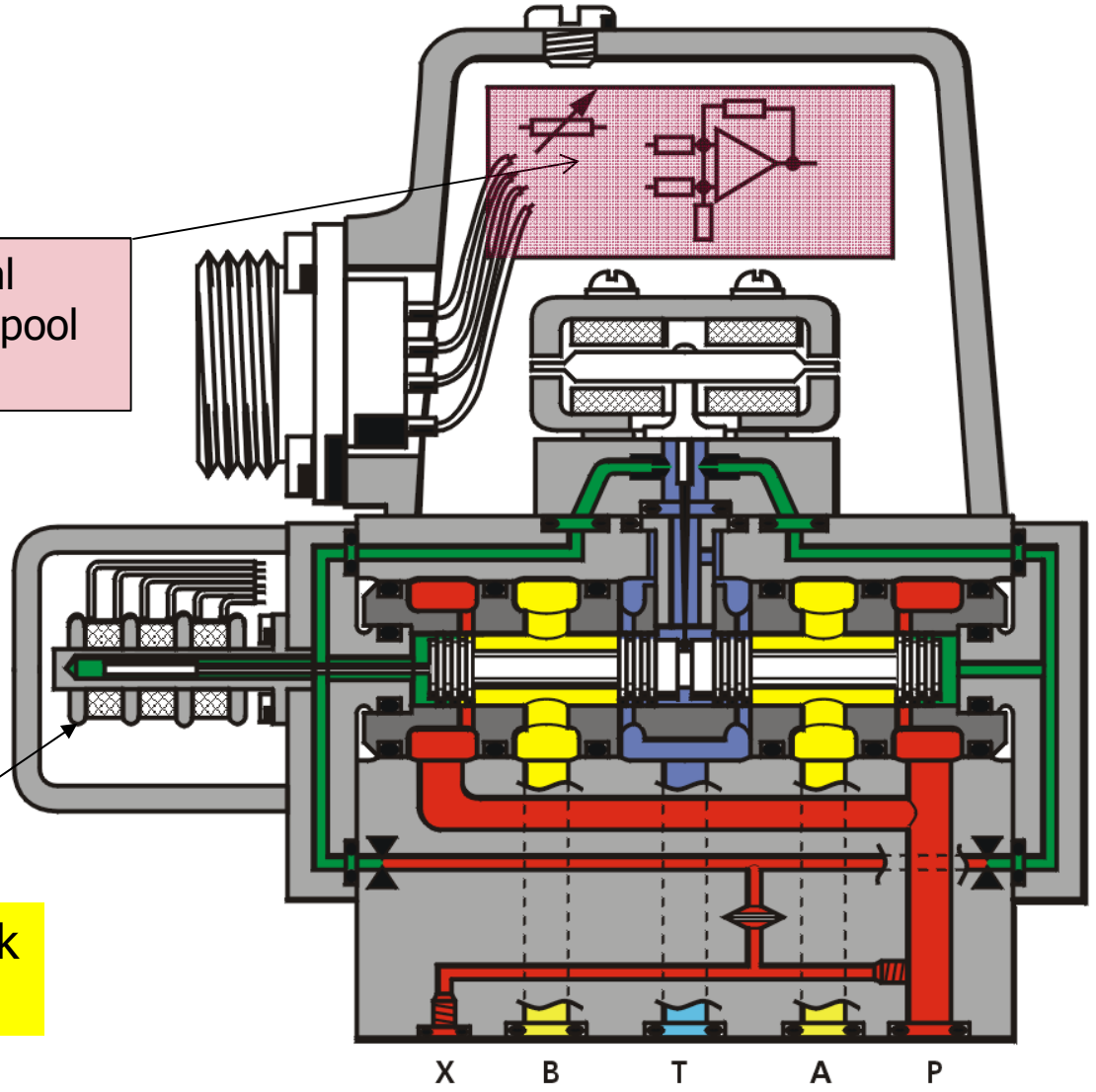


INTEGRATING A POSITION TRANSDUCER

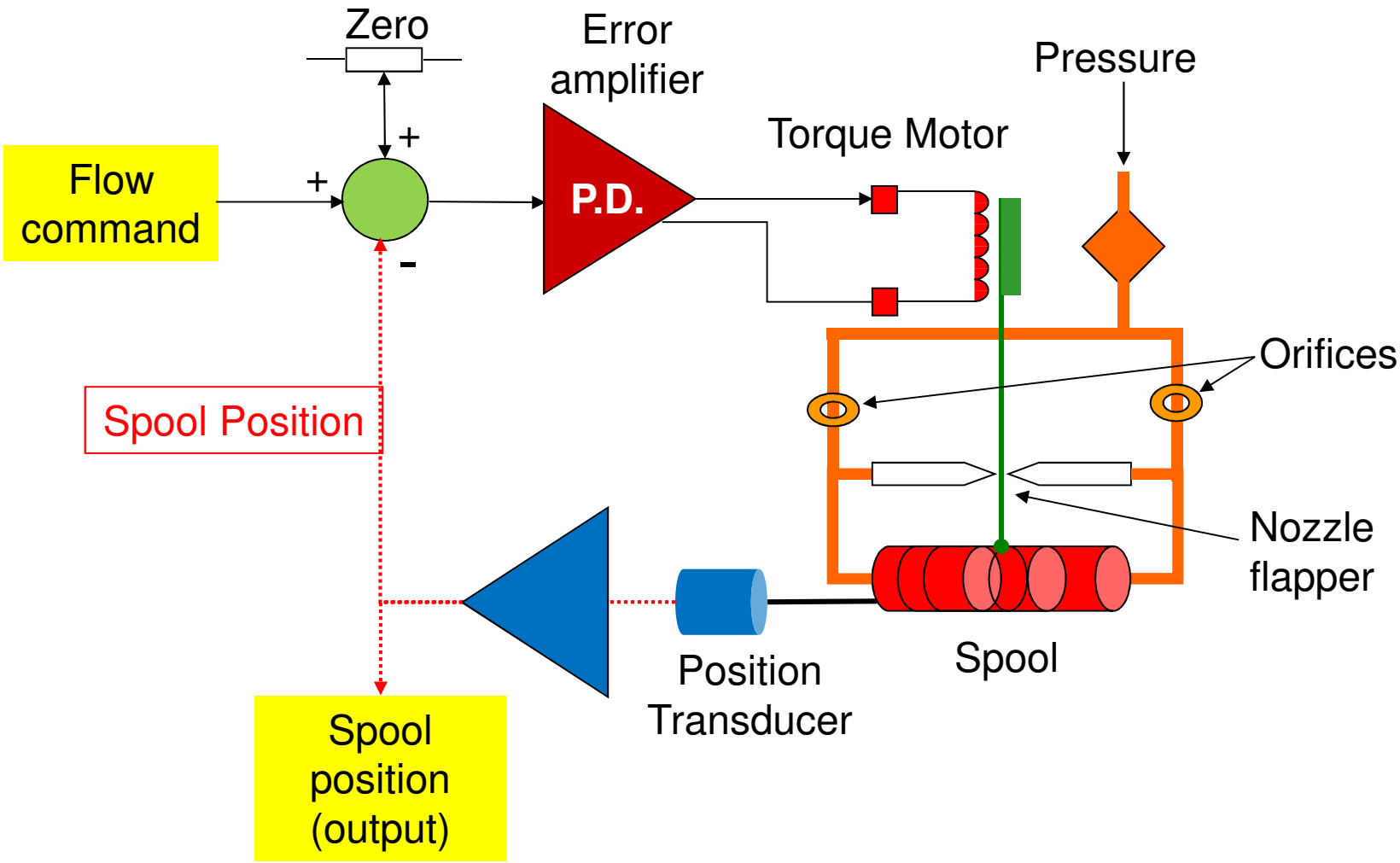
(to implement electronic spool position loop control and diagnostics)

Integrated or external electronics to close the spool position loop

EFB= electrical feedback (position transducer)



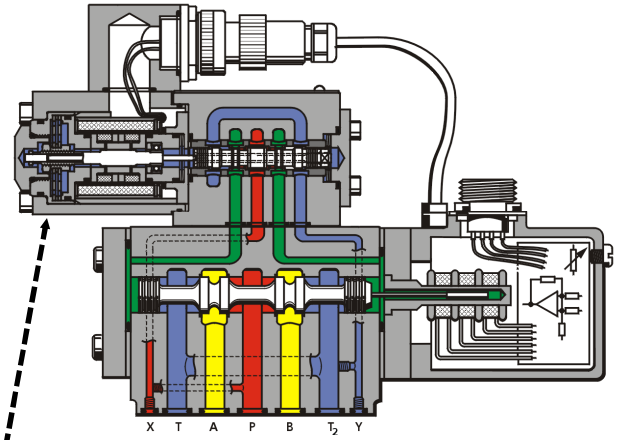
EFB SERVOVALVE
SPOOL POSITION CLOSED LOOP



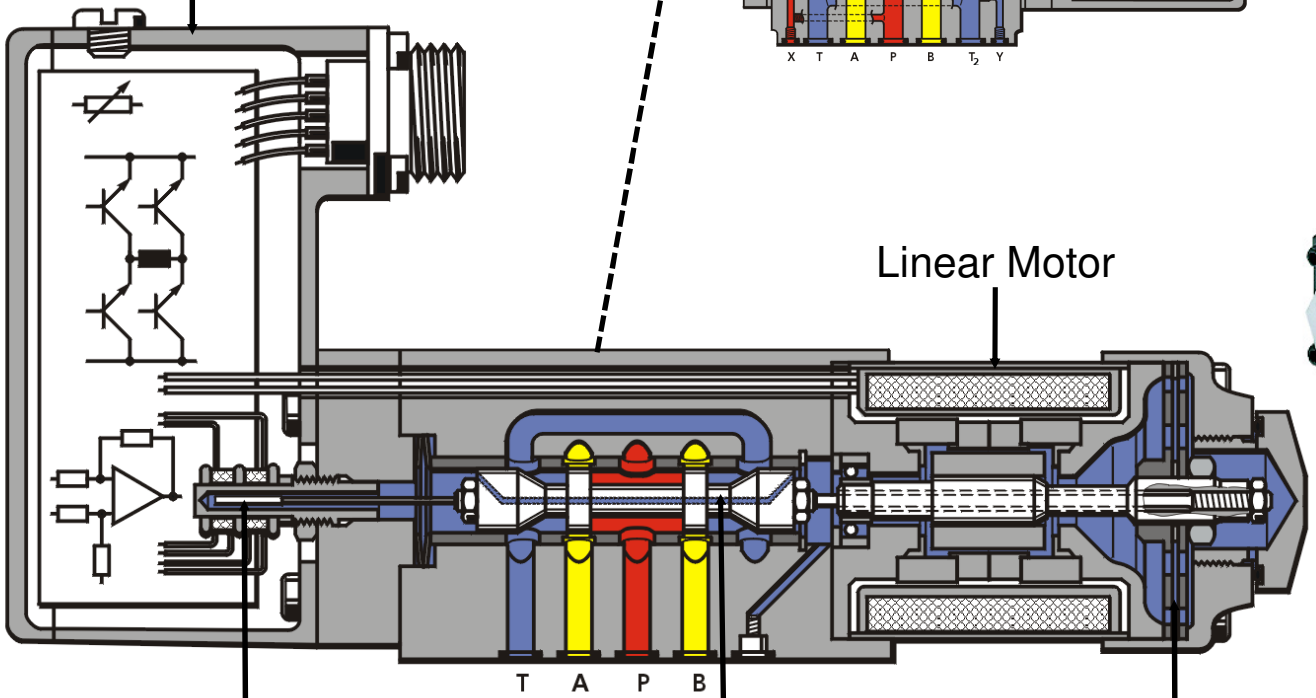
DDV Direct Drive Valve

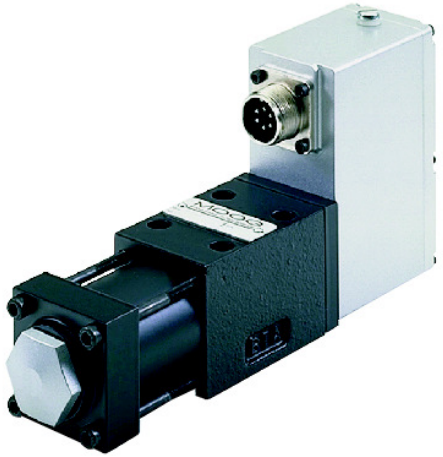
MOOG

High-flow configuration



Integrated Control Electronics





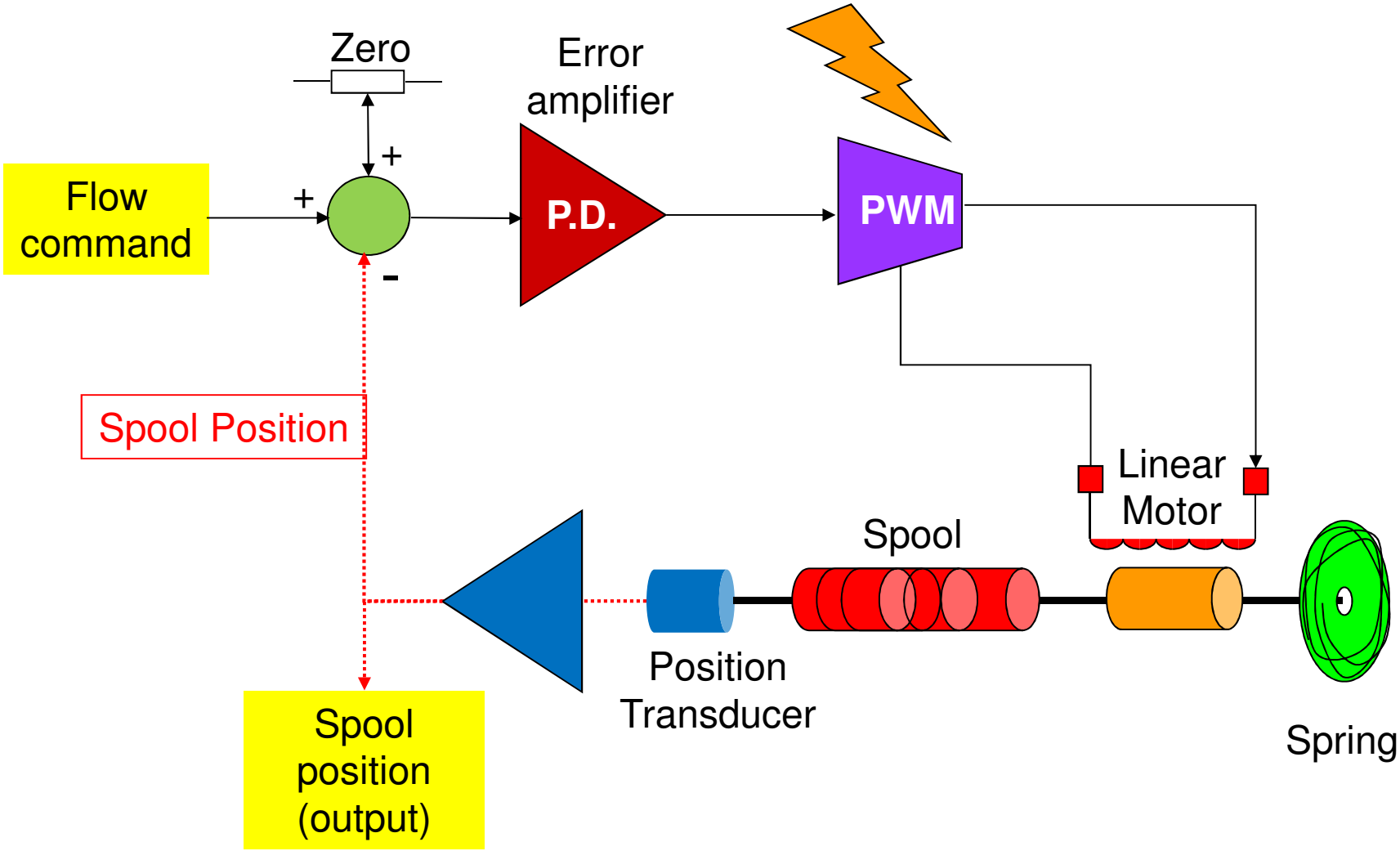
Linear Motor

Position Transducer

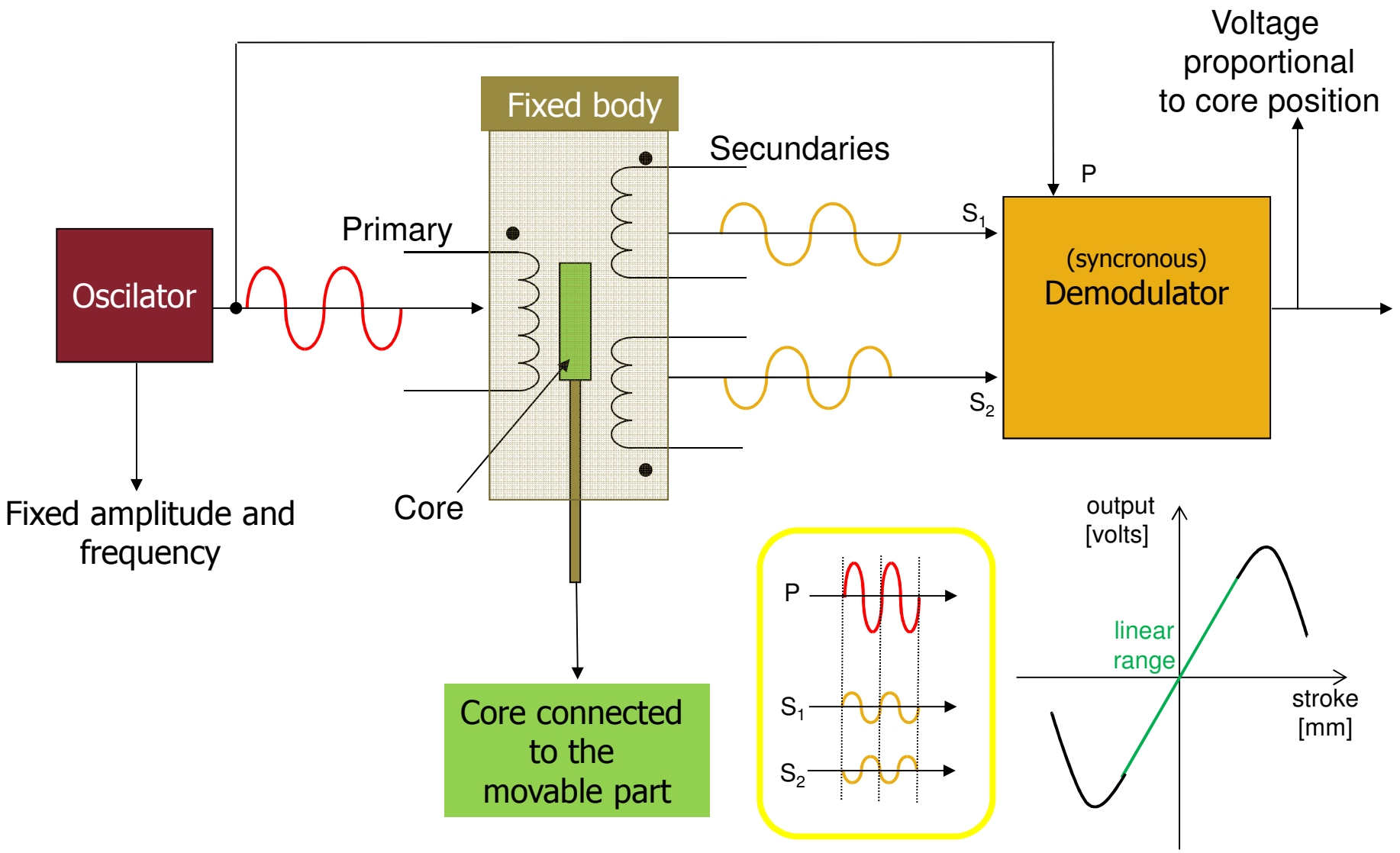
Spool

Spring

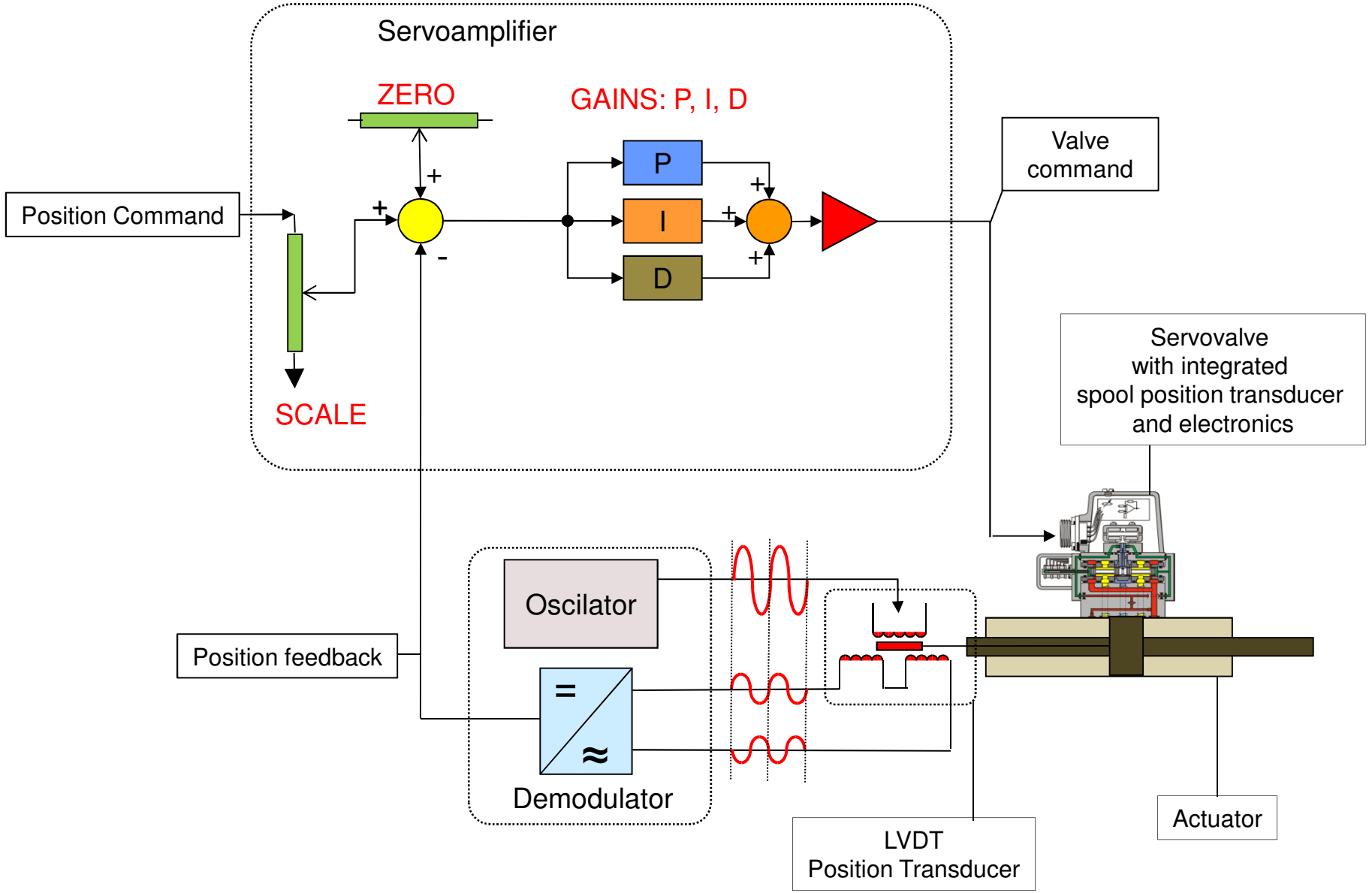
SPOOL POSITION CLOSED LOOP



LVDT
LINEAR VOLTAGE DISPLACEMENT TRANSDUCER

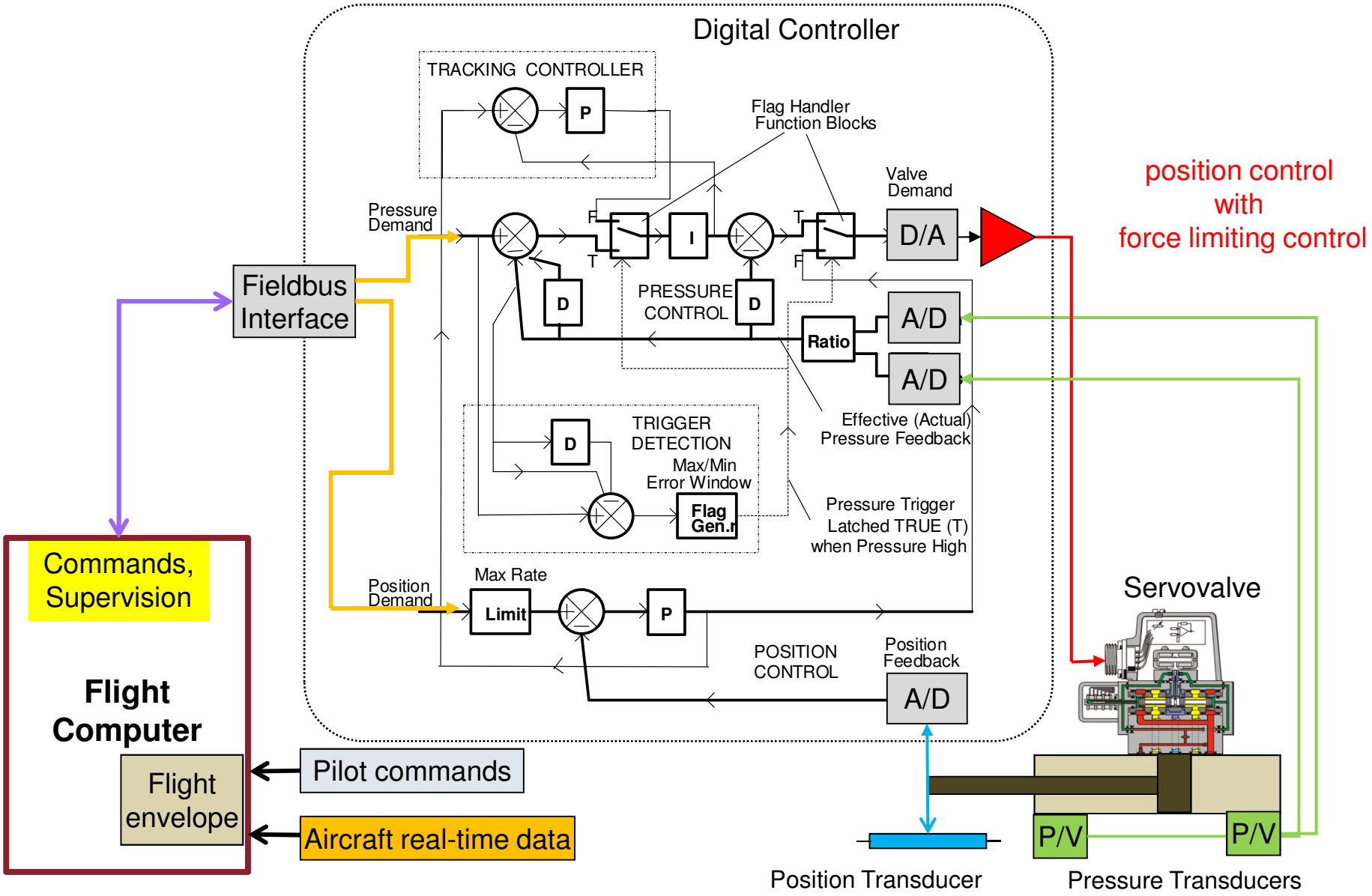


ACTUATOR POSITION CONTROL CLOSED LOOP



ACTUATOR POSITION CONTROL

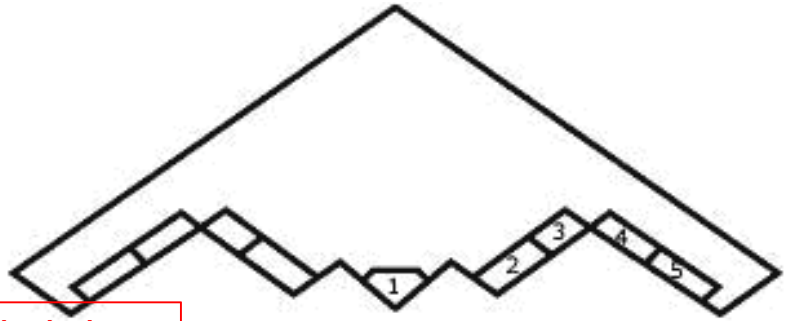
DIGITAL CLOSED LOOP : Complex Algorithms + Diagnostics + Fieldbus

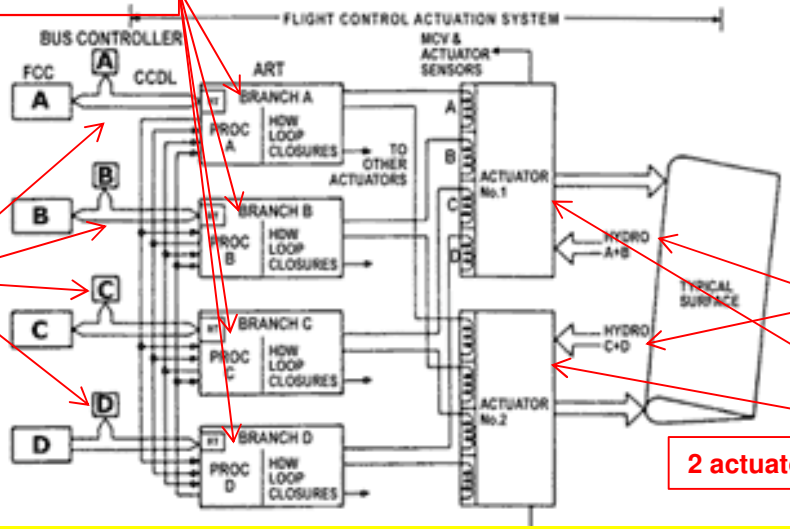


REDUNDANCY: the "soul" of modern flight control

In large and military airplanes each flight control surface is either:

- operated by 2 or more actuators in "parallel" (active-bypass-damper modes)
- operated by one actuator with redundant servovalves, transducers, electrical conections and oil supply connections
- a mix of the above :





4 electronics driving 2 redundant actuators

4 redundant fieldbuses connections to the flight computer

2 oil supply lines per actuator

2 actuators controlling the same surface

Flight Control Actuation System Integrator for the B-2 Spirit

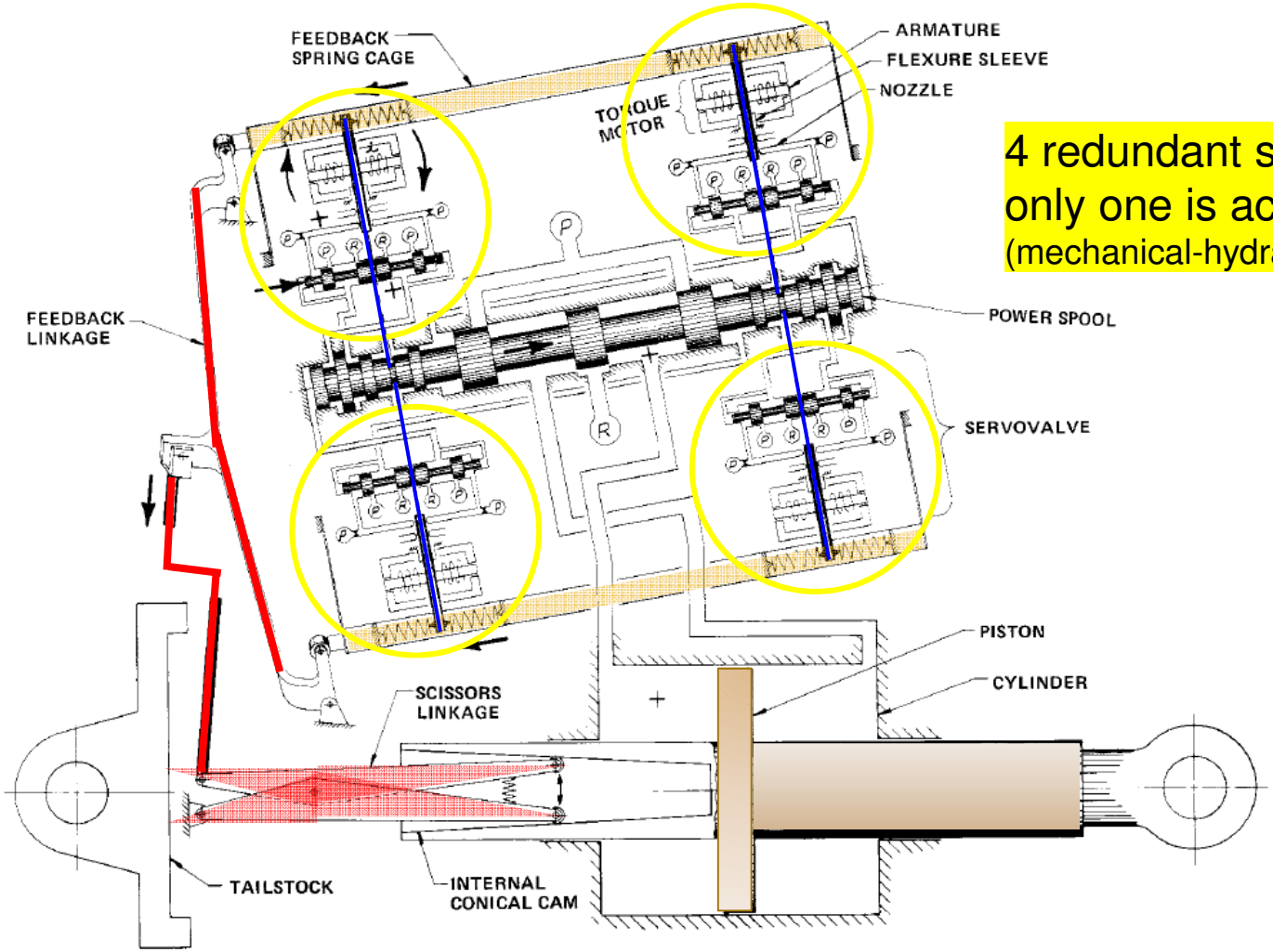
A quadraplex system controls the B-2's flight control surfaces and is comprised of Flight Control Computers, Actuator Control Electronics, Servoactuators, Sensors, System Software and Redundancy Management

The B-2 Spirit Actuation System features:

- Quadraplex redundant electrical and hydraulic systems
- Advanced electronic controls with fault diagnostics
- 4000 psi Hydraulic system
- Redundancy management

REDUNDANCY requires complex "decision" algorithms implemented by the aircraft flight control software

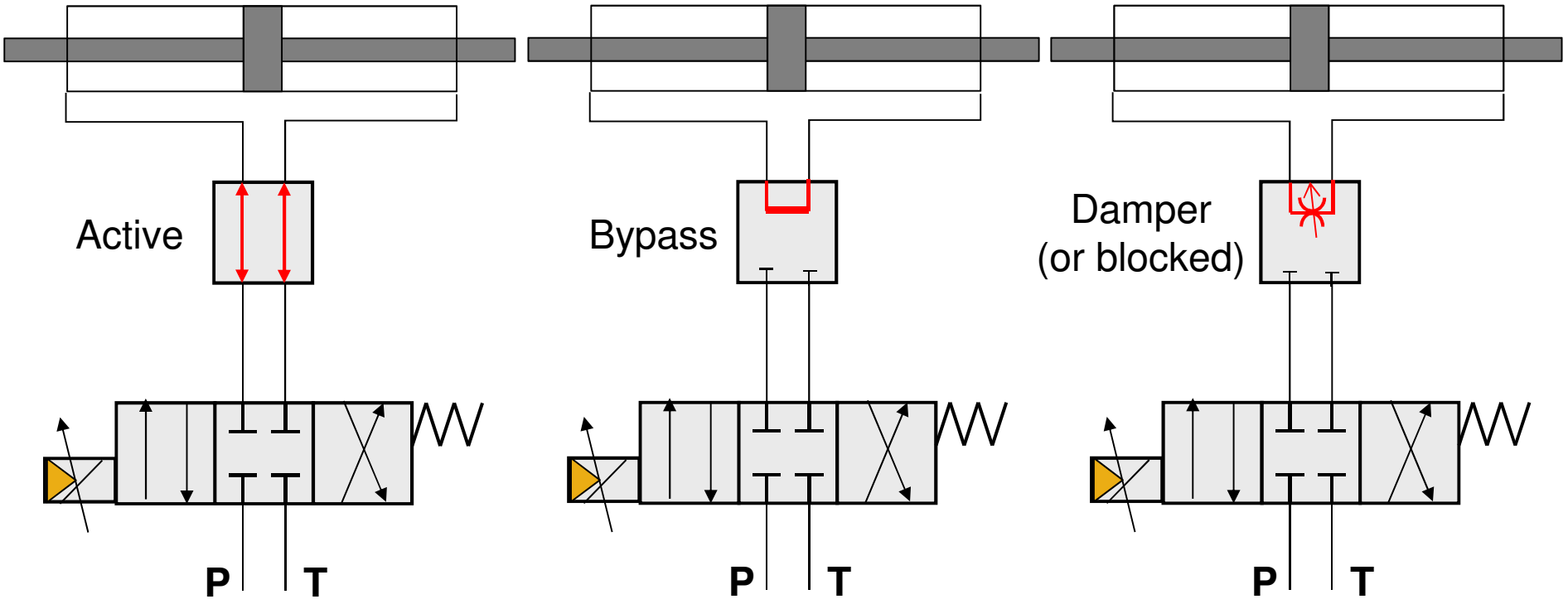
NASA – SPACE SHUTTLE
TRUST VECTOR ACTUATORS (Designed in 1973)



4 redundant servovalves, only one is active
(mechanical-hydraulic selection)

SIMPLIFIED SCHEMATIC OF TVC SERVOACTUATOR POSITION LOOP

REDUNDANCY MODES IN ELECTROHYDRAULIC ACTUATORS



TYPICAL REDUNDANCY- AILERONS

MOOG

Active – Active on each surface

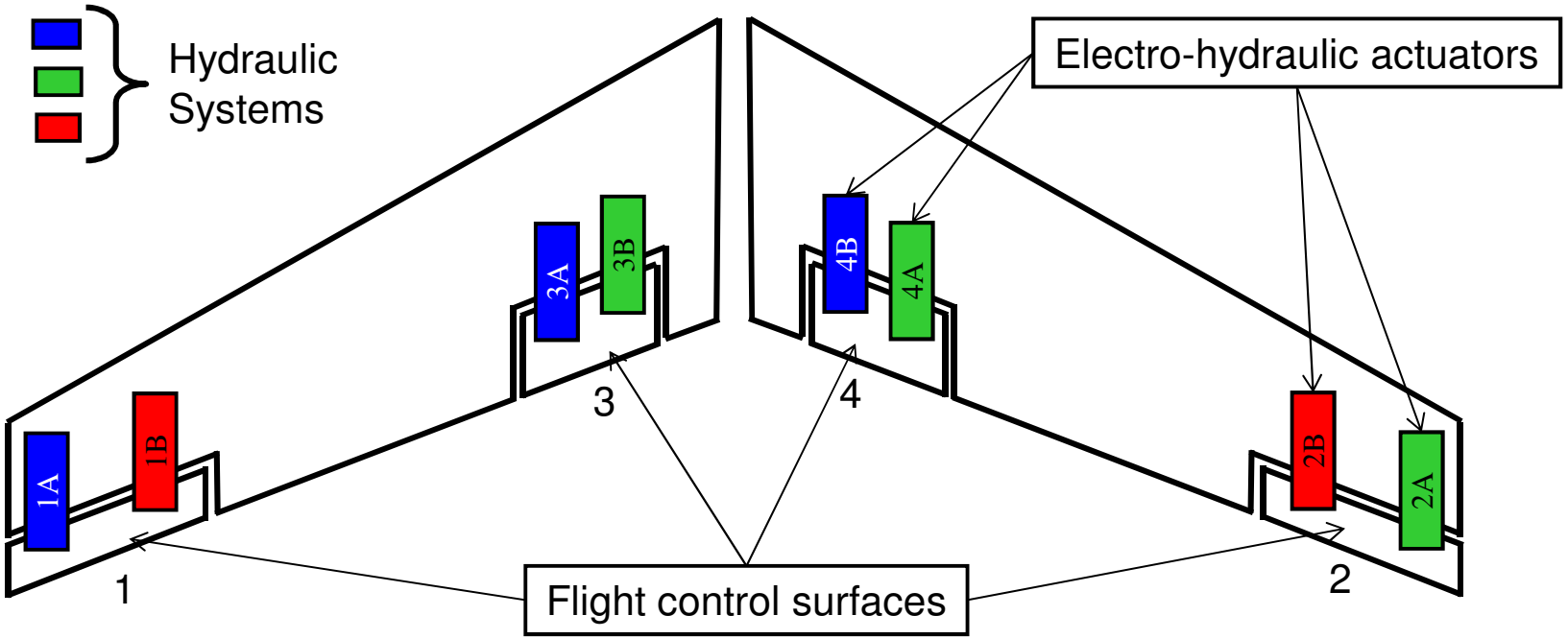
Sized for hinge moment with both active

- Normal mode 1: active , active
- First Failure 1: damped , active
- Second failure1: damped, damped

Active – Standby on each surface

Sized for hinge moment with one active

- Normal mode 2: active, bypass
- First Failure 2: bypass, active
- Second failure 2: damped , damped



damped = damped or blocked, depending on the flight control design

TIPYCAL REDUNDANCY- ELEVATOR

MOOG

Active – Active on each surface

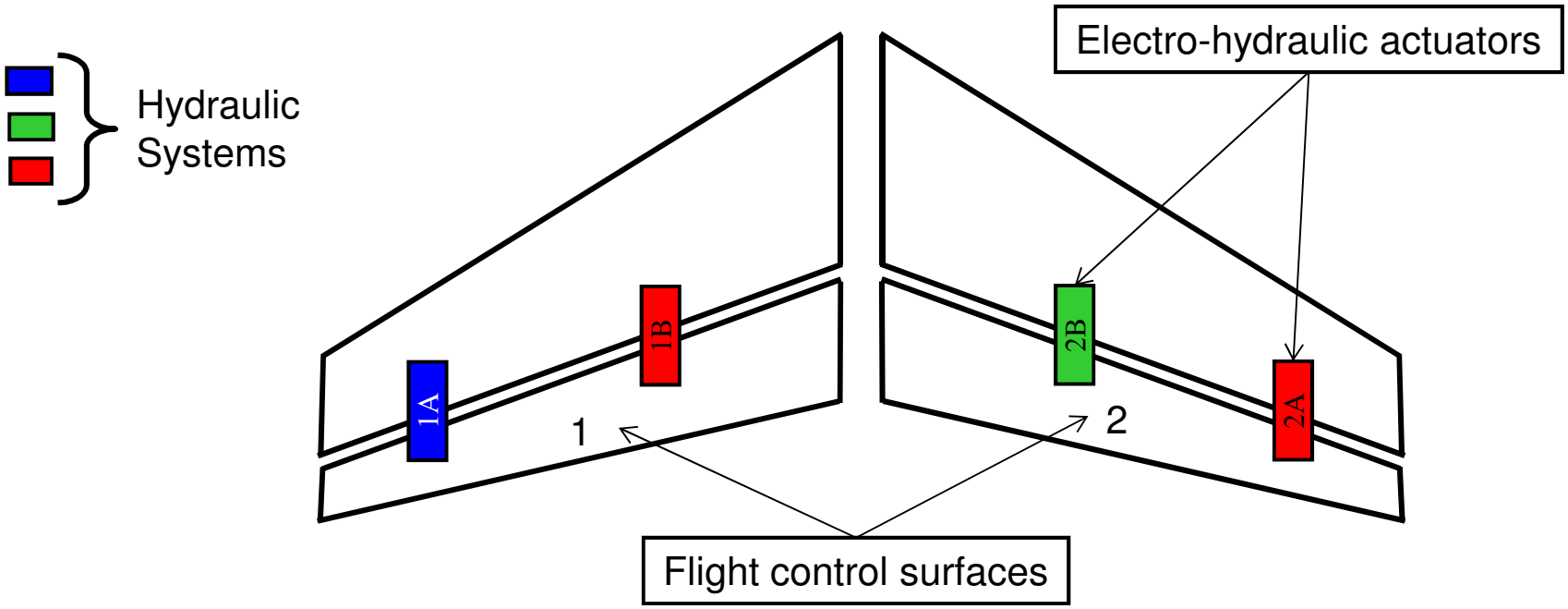
Sized for hinge moment with both active

- Normal mode: active , active
- First Failure: bypass , active
- Second failure: damped, damped

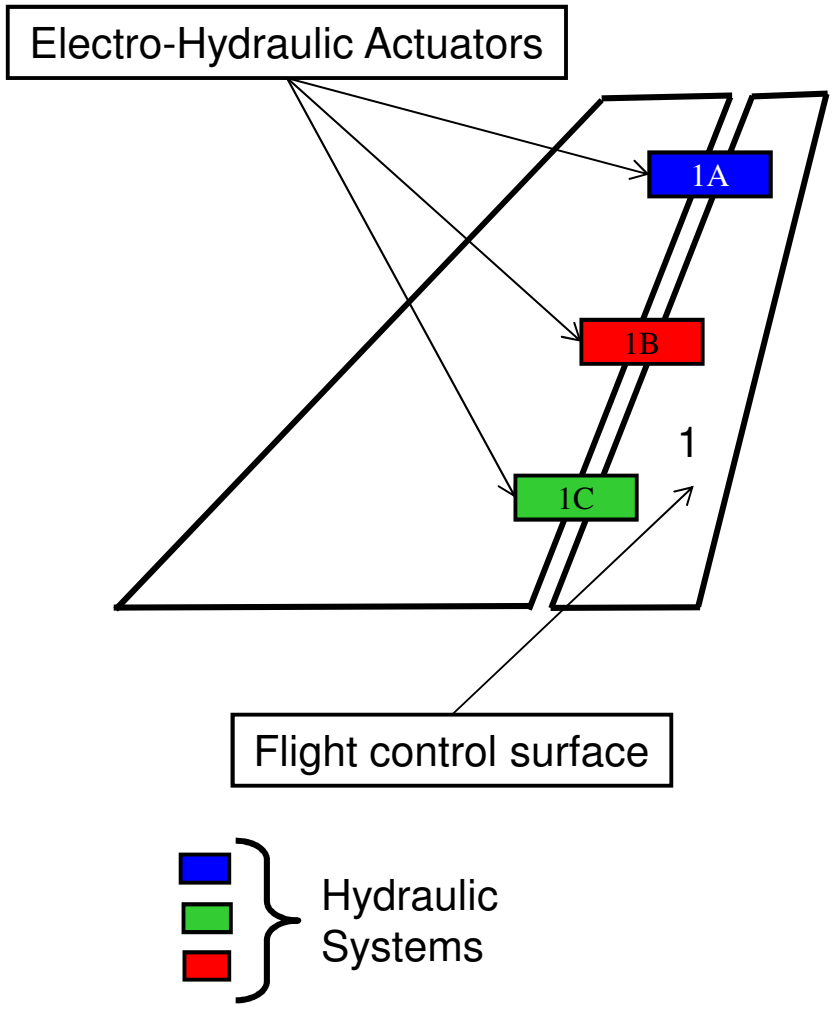
Active – Standby on each surface

Sized for hinge moment with one active

- Normal mode: active, bypass
- First Failure: bypass, active
- Second failure: damped , damped



TYPICAL REDUNDANCY - RUDDER



Active – Active - Active

Sized for hinge moment with all active

- Normal mode: active, active, active
- First Failure: bypass, active, active
- Second failure: damped, bypass, active
- Third failure: damped, damped, damped

ELECTRO-HYDRAULIC ACTUATORS - EHA

MOOG

Features

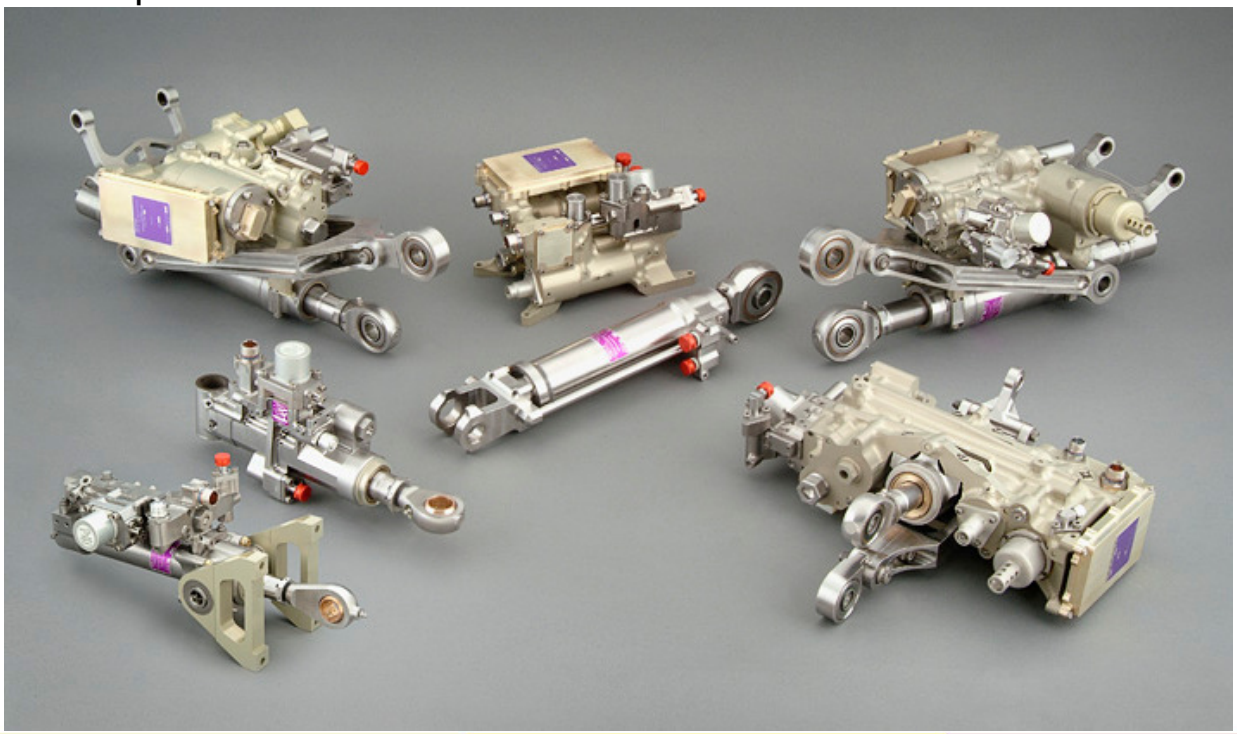
- Low weight
- Manageable failure modes
- Flexible packaging
- Multiple hydraulic supplies possible
- Multiple electrical channels possible
- Low power consumption to hold load

Issues

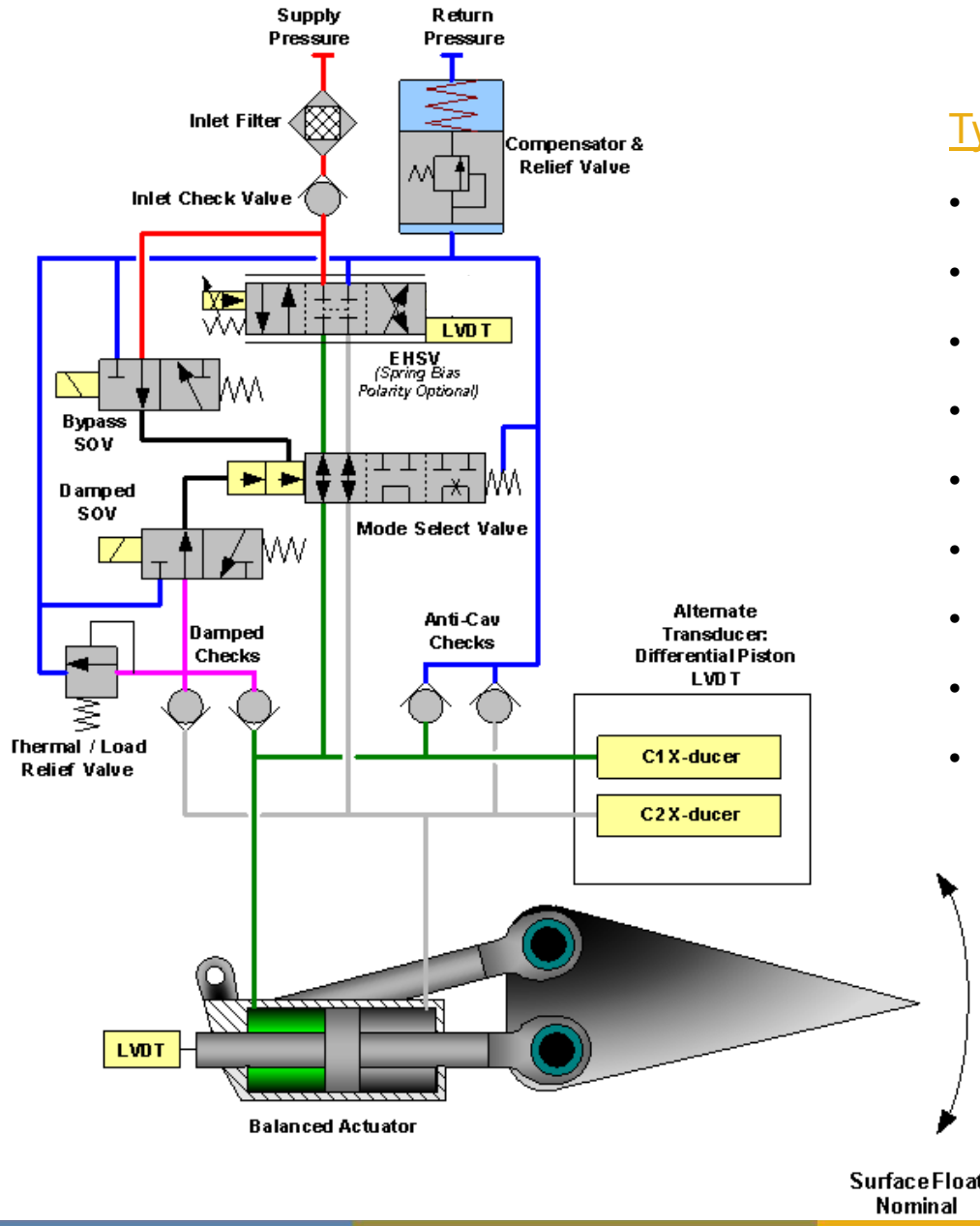
- High tare power consumption
- Lower stiffness

Options

- Overload relief
- Multiple modes
  - ✓ Normal servocontrolled operation
  - ✓ Bypass (to allow other actuators to operate the control surface)
  - ✓ Damped
  - ✓ Blocked
  - ✓ Damped - Blocked



ELECTRO-HYDRAULIC ACTUATORS - EHA



Typical Rudder Actuator Components

- Inlet Filter
- Inlet Check Valve
- Servovalve with monitoring LVDT
- Mode Select Valve (3 way)
- Solenoid Valves to pilot Mode Select Valve
- Damped Check Valves
- Differential Pressure Transducers
- Anti Cavitation Check Valves
- Compensator & Return Relief Valve

ELECTRO-MECHANICAL ACTUATORS – EMA

MOOG

Features

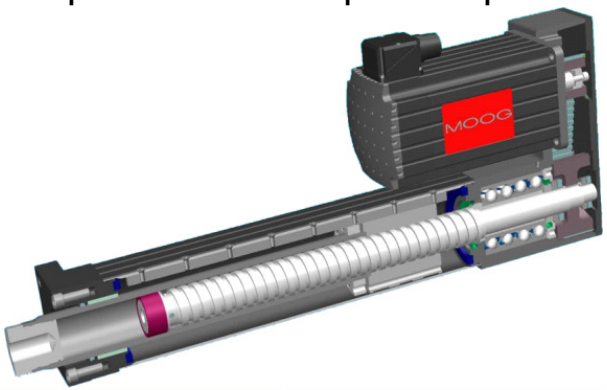
- Undesirable failure modes
- Limited packaging flexibility
- Multiple electrical channels possible
- No hydraulics
- Low power consumption when idle

Issues

- High weight
- High stiffness
- No overload relief
- Draws power to hold load stationary ($P = R \cdot I^2$)

Options

- Multiple motors torque or speed summed



ELECTROHYDROSTATIC ACTUATOR – EHSA

MOOG

Features

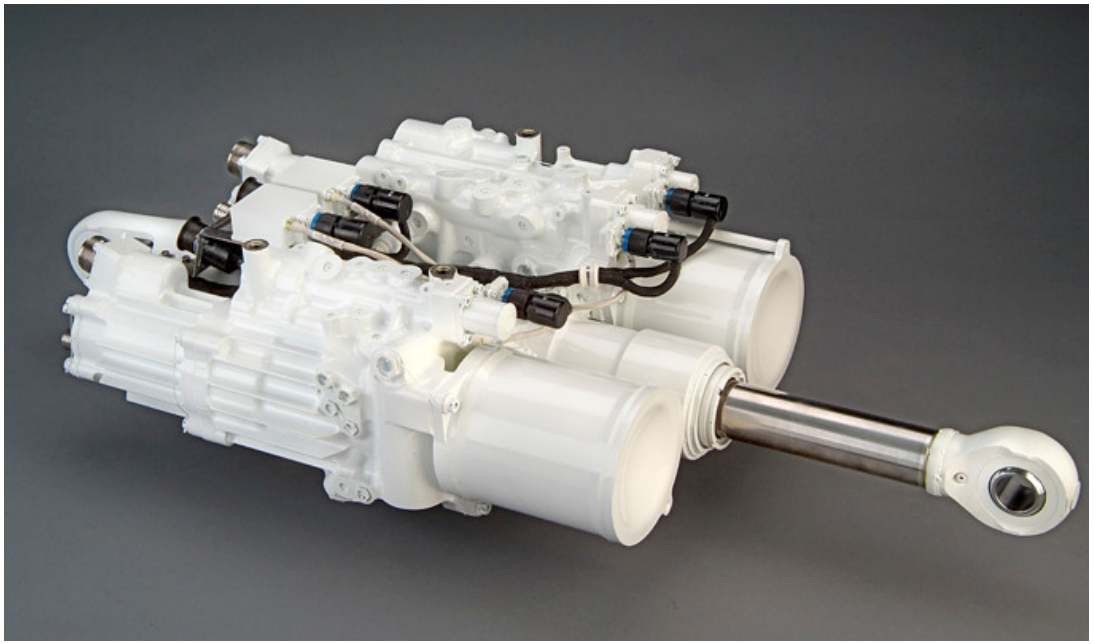
- High weight
- Manageable failure modes
- Flexible packaging
- Multiple hydraulic channels possible
- Multiple electrical channels possible
- High power consumption to hold load

Issues

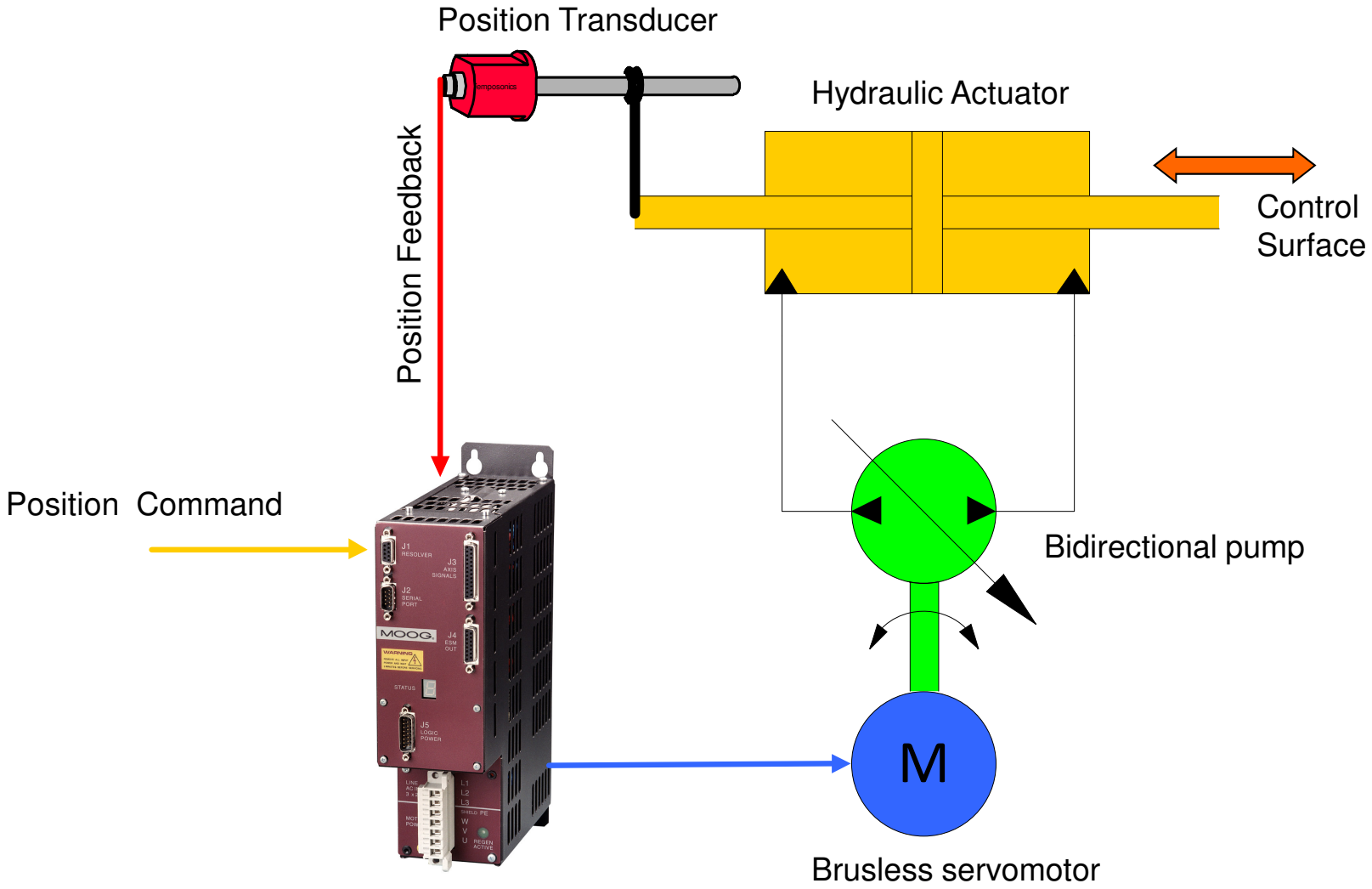
- Low power consumption when stationary
- Lower stiffness

Options

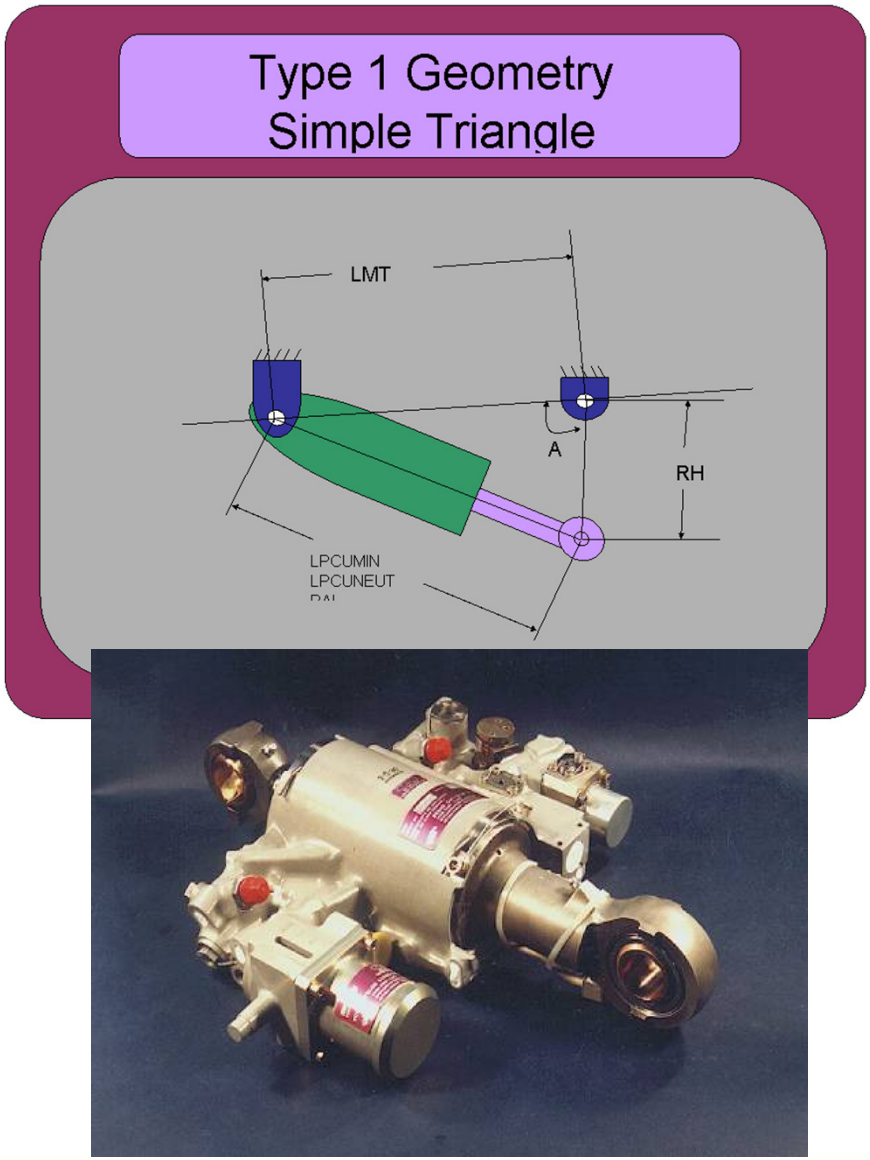
- Overload relief
- Multiple modes
  - ✓ Normal servocontrolled operation
  - ✓ Bypass (to allow other actuators to operate control surface)
  - ✓ Damped
  - ✓ Blocked
  - ✓ Damped - Blocked



ELECTROHYDROSTATIC ACTUATOR – EHSA

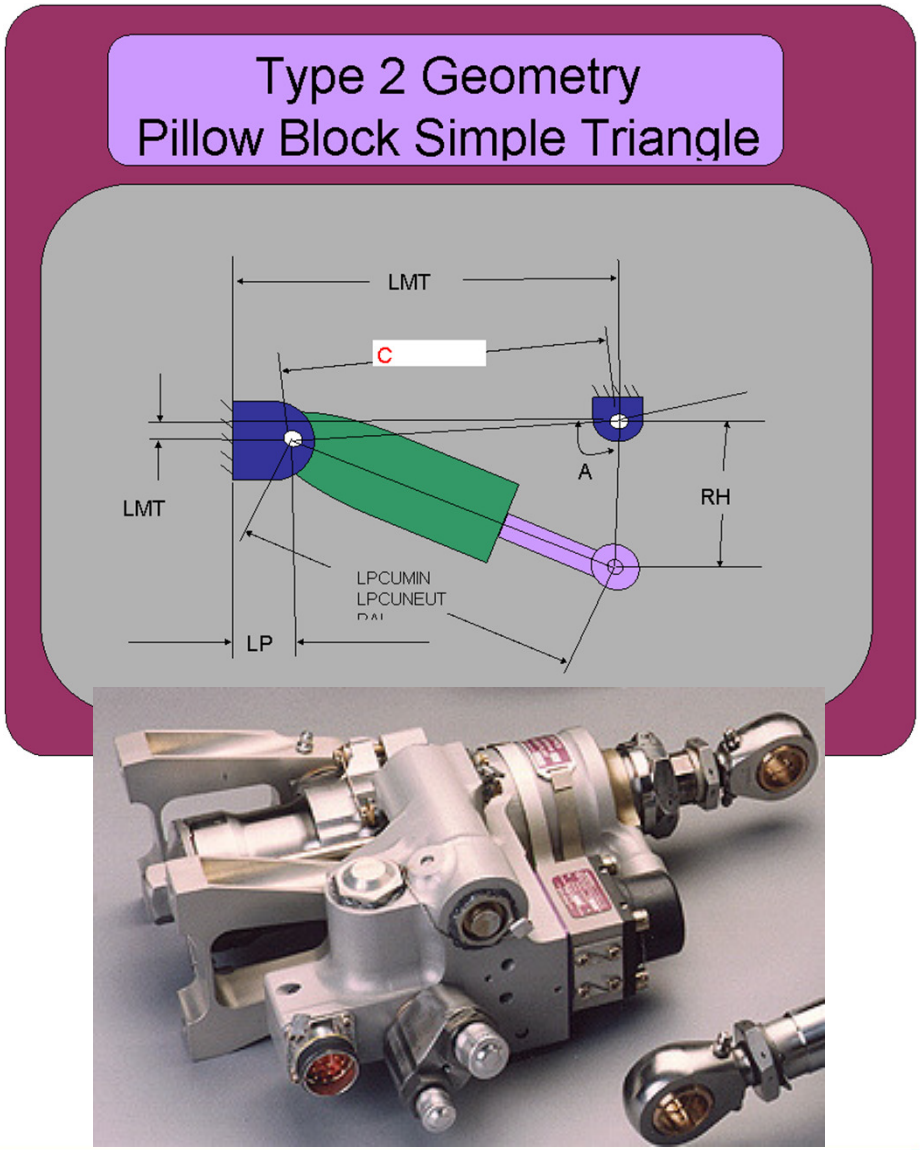


FLY CONTROL ACTUATORS
Kinematic Installation : Simple Triangle



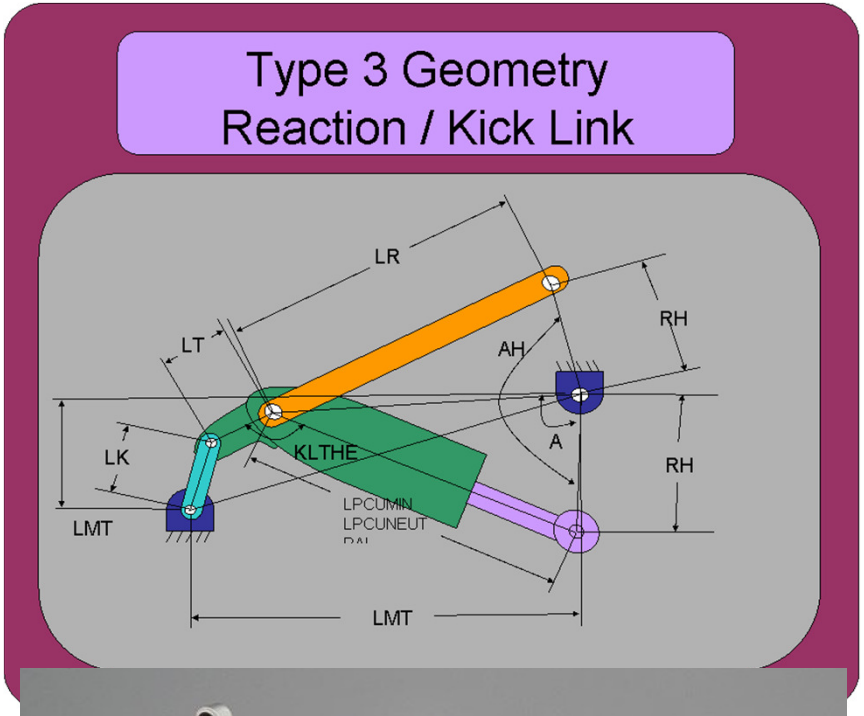
- Actuator body moves
- Hinge generally off surface center
- Envelope must include body motion
- Hydraulic & electrical connections move with body
- Aircraft structure reacts all actuation & surface loads
- Application: Ailerons, Rudder, Elevator, Flaperon, Spoilers

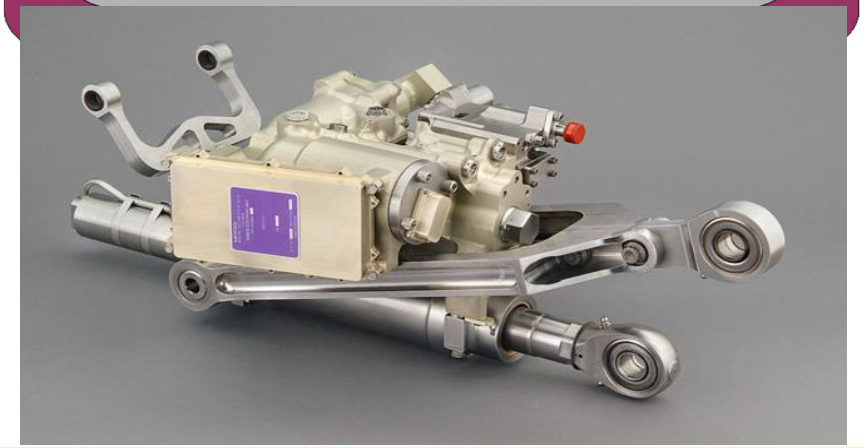
FLY CONTROL ACTUATORS
Kinematic Installation : Pillow Block Simple Triangle



- Actuator body moves
- Hinge off surface center
- Envelope must include body motion
- Hydraulic & electrical connections move with body – but some units built with swivels on mounting centerline
- Aircraft structure reacts all actuation & surface loads - with lateral load and torsion at pillow block mount
- Application: Spoilers

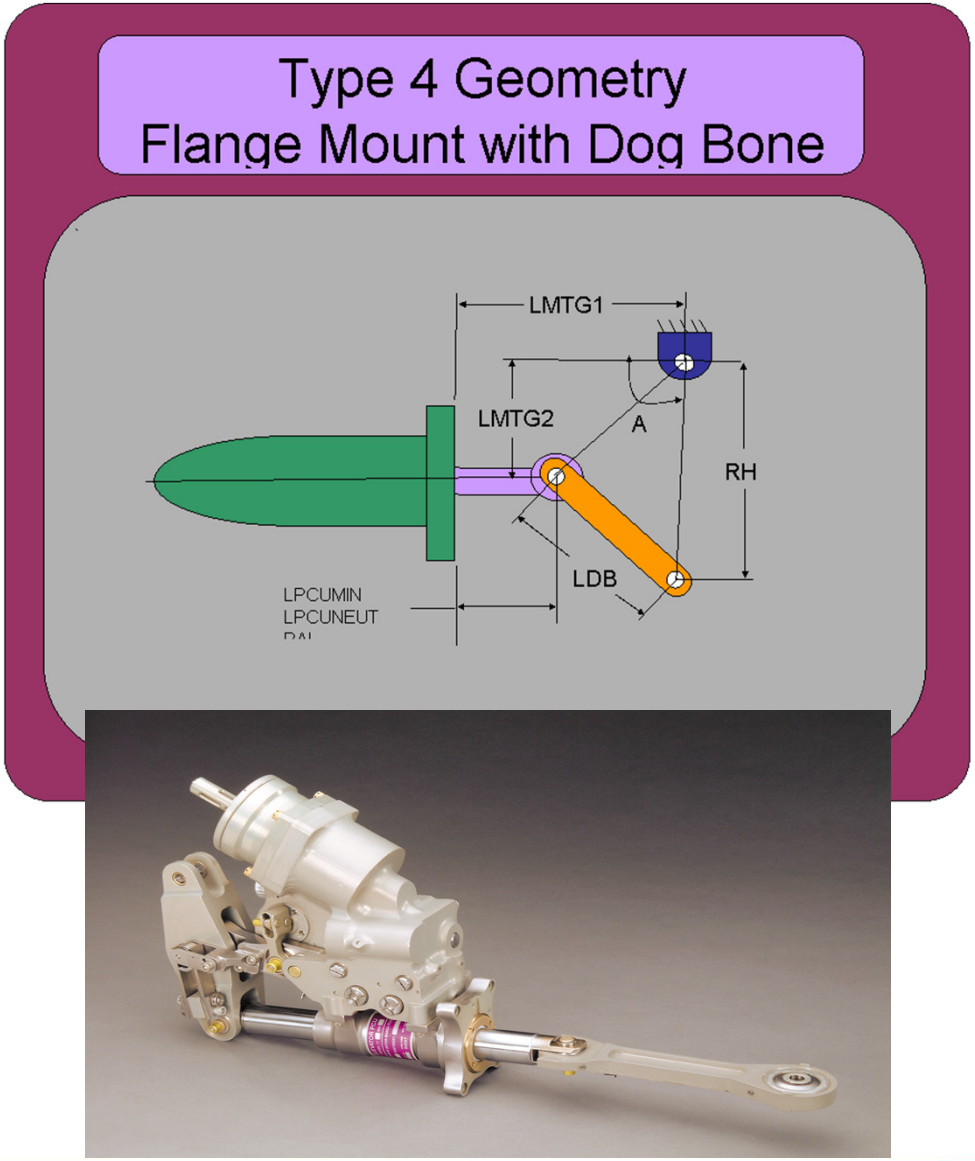
FLY CONTROL ACTUATORS
Kinematic Installation : Reaction/Kick Link





- Surface hinge can be centered
- Actuator body motion has additional axial displacement
- Envelope must include body motion
- Hydraulic (usually hoses) & electrical connections move with body
- Reaction link reacts major actuation loads – lighter aircraft structure
- Higher stiffness with lower weight
- Application: Rudder, Elevator, Aileron

FLY CONTROL ACTUATORS
Kinematic Installation : Flange Mount with Dog Bone



- Actuator body stationary
- Hinge off surface center
- Effective horn radii reduced
- Lower stiffness design
- Hydraulic & electrical connections fixed – simplest of all geometries
- Aircraft structure reacts all actuation & surface loads – lateral loads applied to actuator and structure

Flight Controls For Commercial Aircraft

BOEING 787 PRIMARY FLIGHT CONTROLS

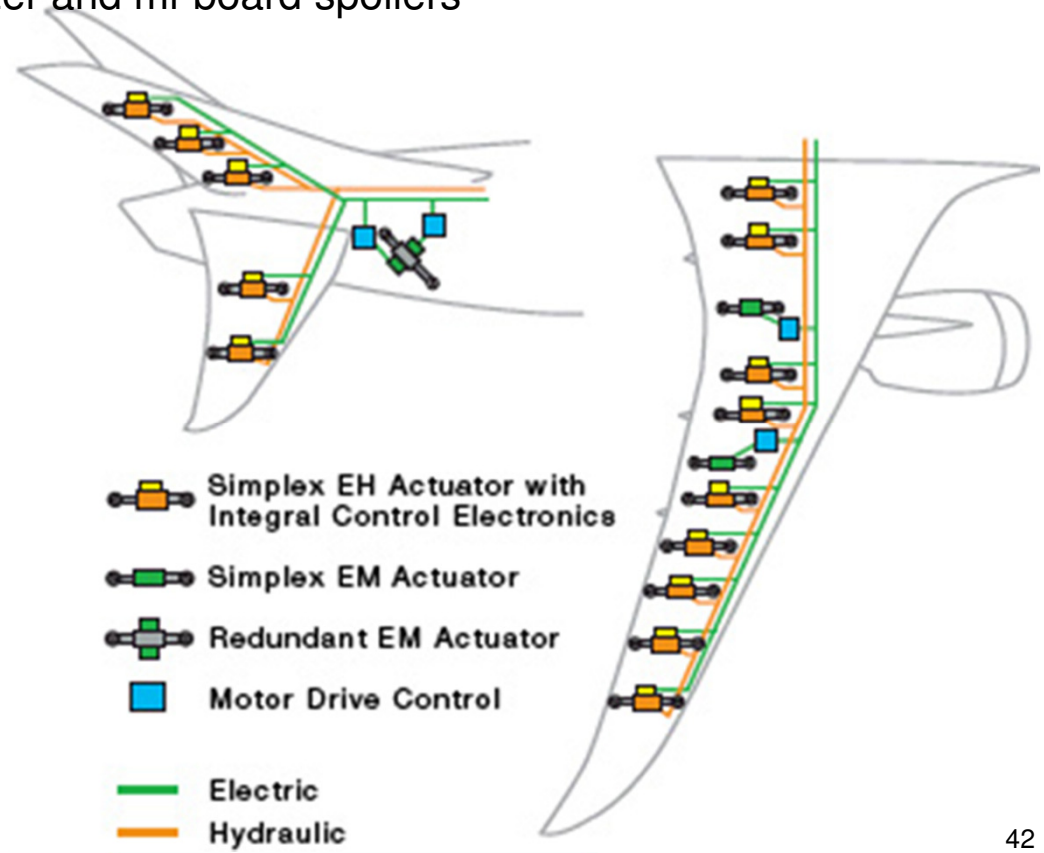
The Moog system controls all the primary flight control surfaces on the airplane. The system controls 21 flight surfaces and includes a mix of electrohydraulic (EHA) and electromechanical (EMA) servoactuators and all associated control electronics.

EH servoactuators : Ailerons, Flaperons, Inboard + Outboard Spoilers, Elevator and Rudder.

EM servoactuators : horizontal stabilizer and mi-board spoilers

Key features :

- **Smart actuators with on-board loop closure electronics**
- 5000 psi system operating pressure
- High power motor controllers
- EM actuators with dual load path and integrated motor drive
- Advanced materials for weight-performance optimization



BOEING 787 PRIMARY FLIGHT CONTROLS

MOOG

Complete Primary Flight Control Actuation System

BOEING 787 HIGH LIFT ACTUATION SYSTEM

The Moog systems control the primary and secondary surfaces, horizontal stabilizer, leading edge slats and trailing edge flaps in response to pilot commands.

The High Lift System includes the complete Flap and Slat Actuation Systems compromising nearly 450 discrete assemblies including: power drives, electronic controls, trim controls, geared rotary actuators, rack and pinion roller assemblies, transmissions shafts, offset gearboxes, sensors and accessory components. The High Lift System features a number of technical advancements to improve wing aerodynamics. To decrease system weight a number of advancements were also incorporated, including the use of advanced composites and increased use of electronic controls.

Key Features of the High Lift System Include:
- Advanced flap trim control
- Composite transmission components
- 5000 psi system operating pressure
- Hybrid hydraulic and electric power drive

BOEING 787 HIGH LIFT ACTUATION SYSTEM

MOOG

Complete Secondary Flight Control System

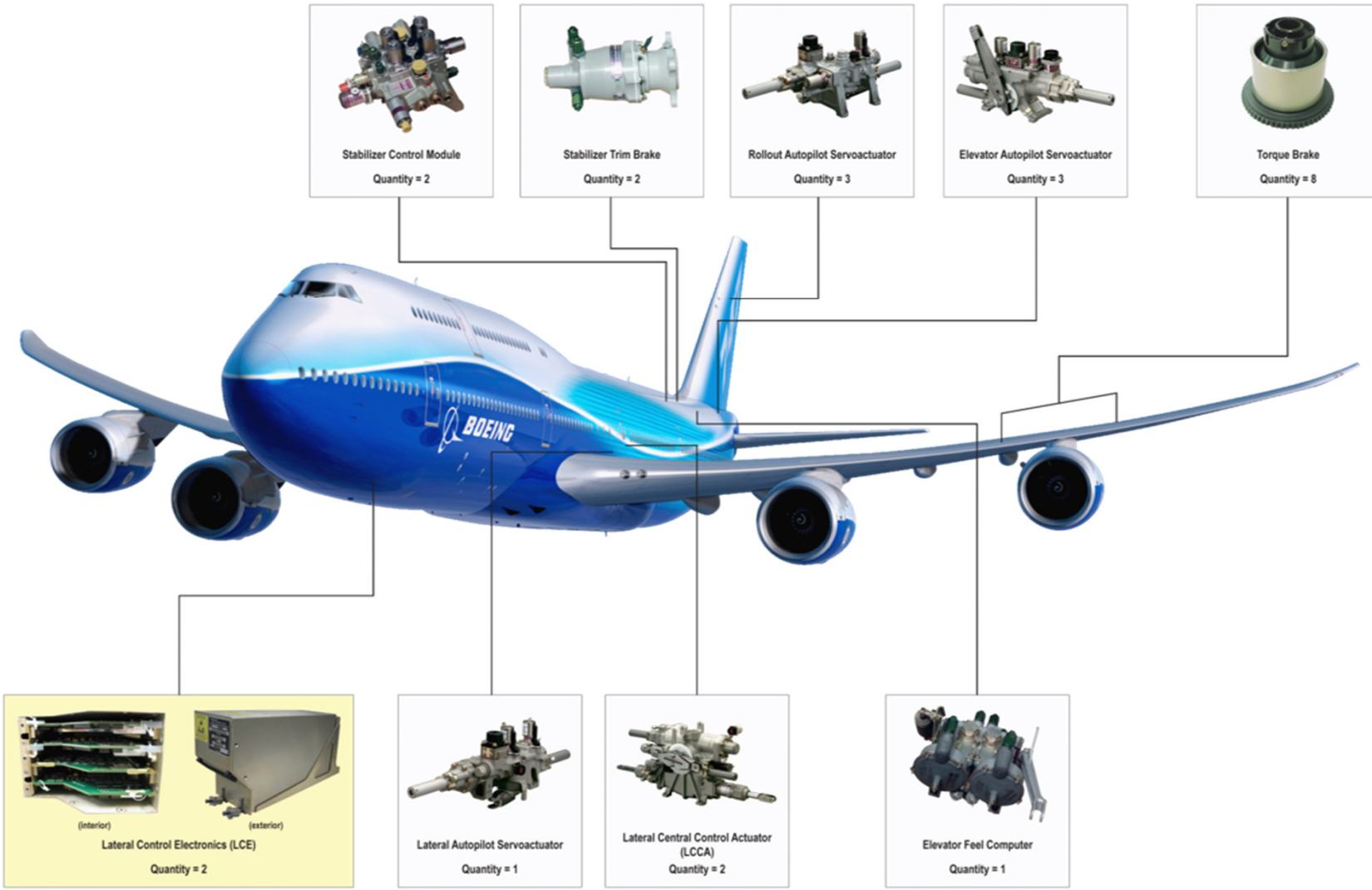
Boeing 777 High Lift Actuation

MOOG

Primary and High Lift Actuation Products

Boeing 747-8 Lateral Flight Controls

Lateral Fly-By-Wire Flight Control Computers



Primary Flight Control for Airbus A350 XWB

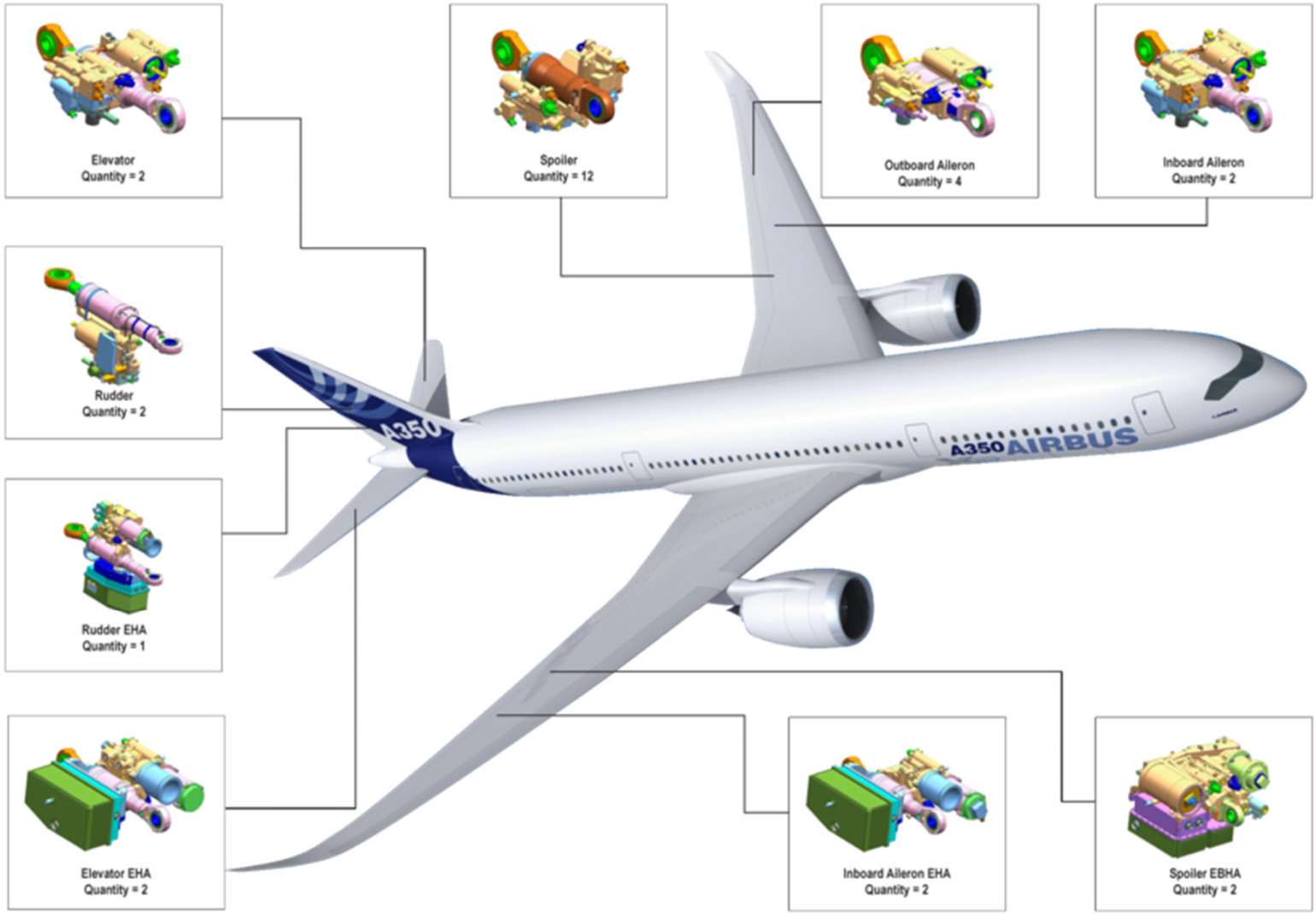
Moog is providing 27 discrete actuators and associated control electronics on this program. This system includes a mix of electrohydraulic (EH) and advanced electrohydrostatic (EHA) actuators to control the Aileron, Elevator, Rudder and Spoiler flight surfaces.

Moog products features:

- More electric actuation technology
- On board electronics for actuator power and control
- Highly integrated assemblies to meet challenging envelope constraints

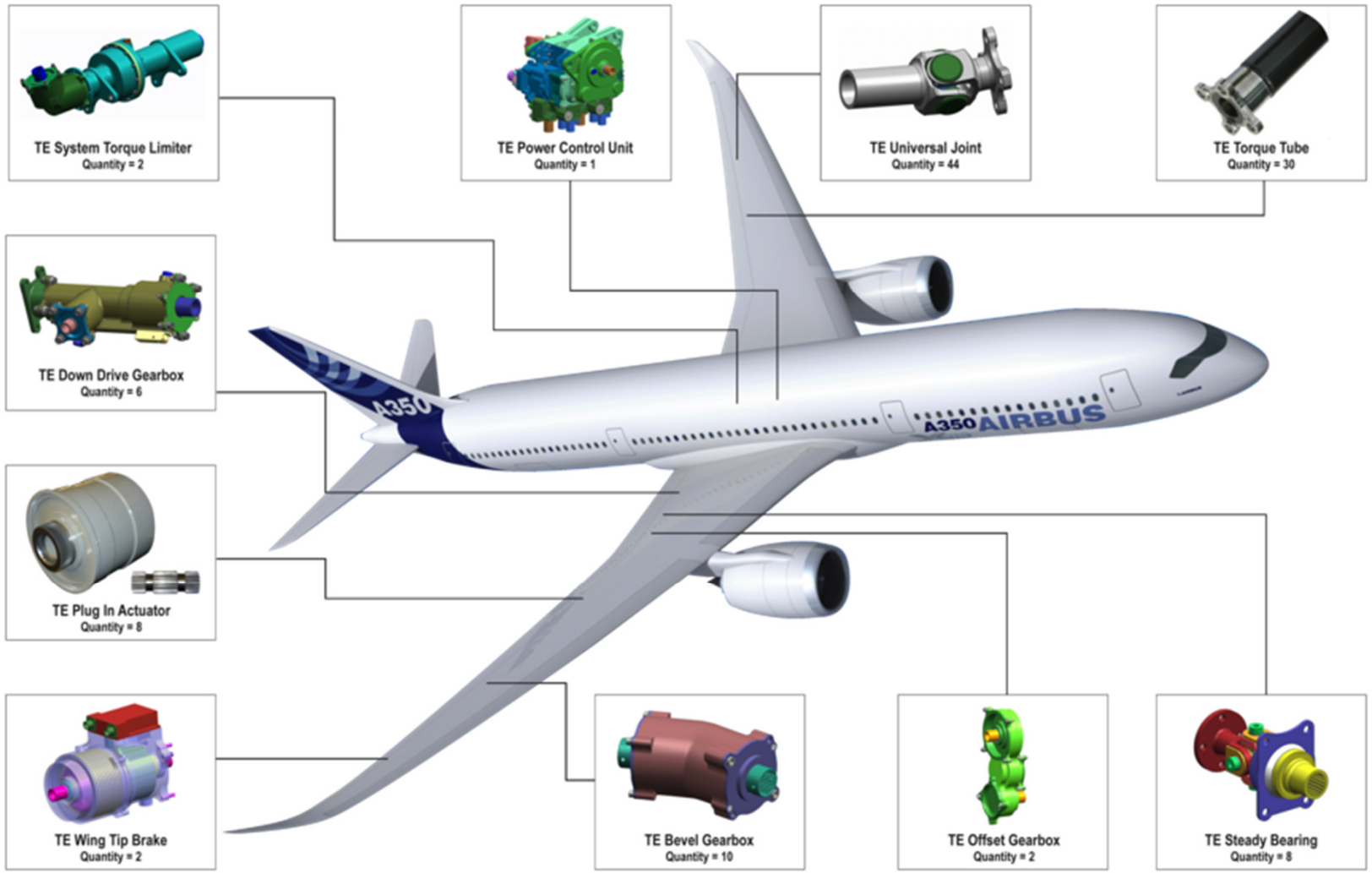
Airbus A350XWB Primary Flight Controls

Complete Primary Flight Control Actuation System



Airbus A350XWB High Lift Actuation

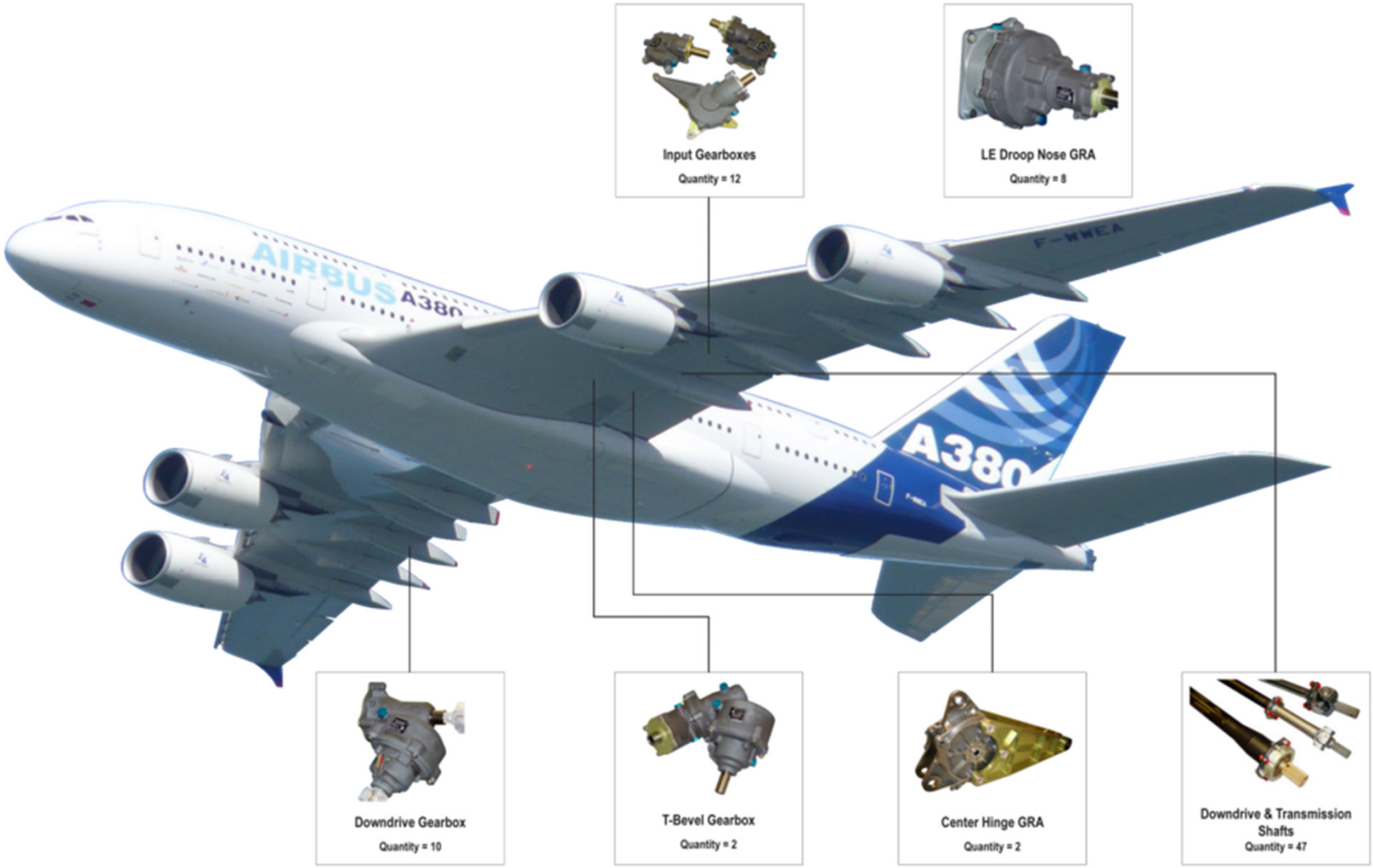
Trailing Edge Flap Actuation



Airbus A380 High Lift Actuation

MOOG

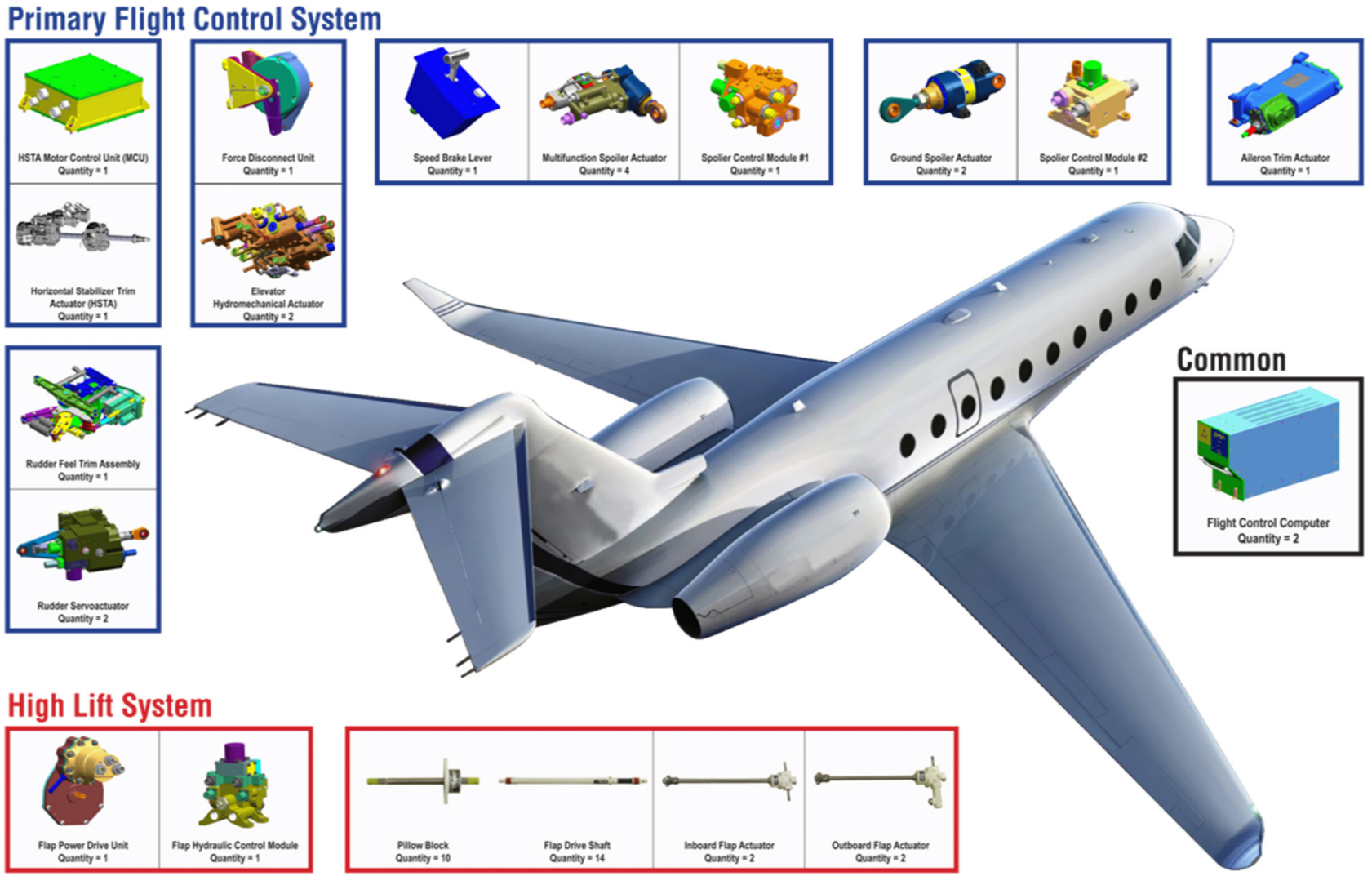
Leading and Trailing Edge Flight Controls



Gulfstream G250 Integrated Flight Control

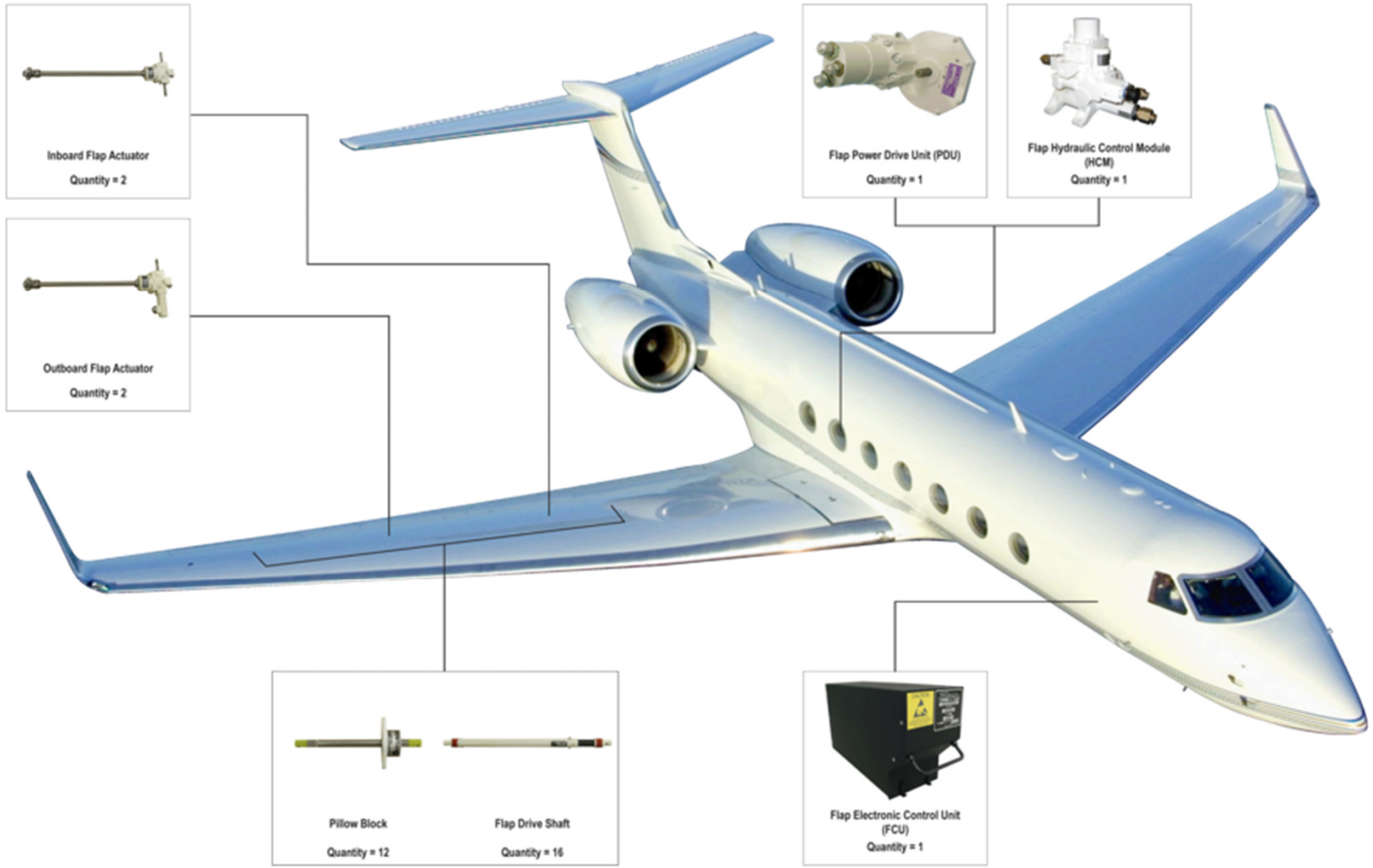
MOOG

Complete Primary and High Lift Flight Control Systems



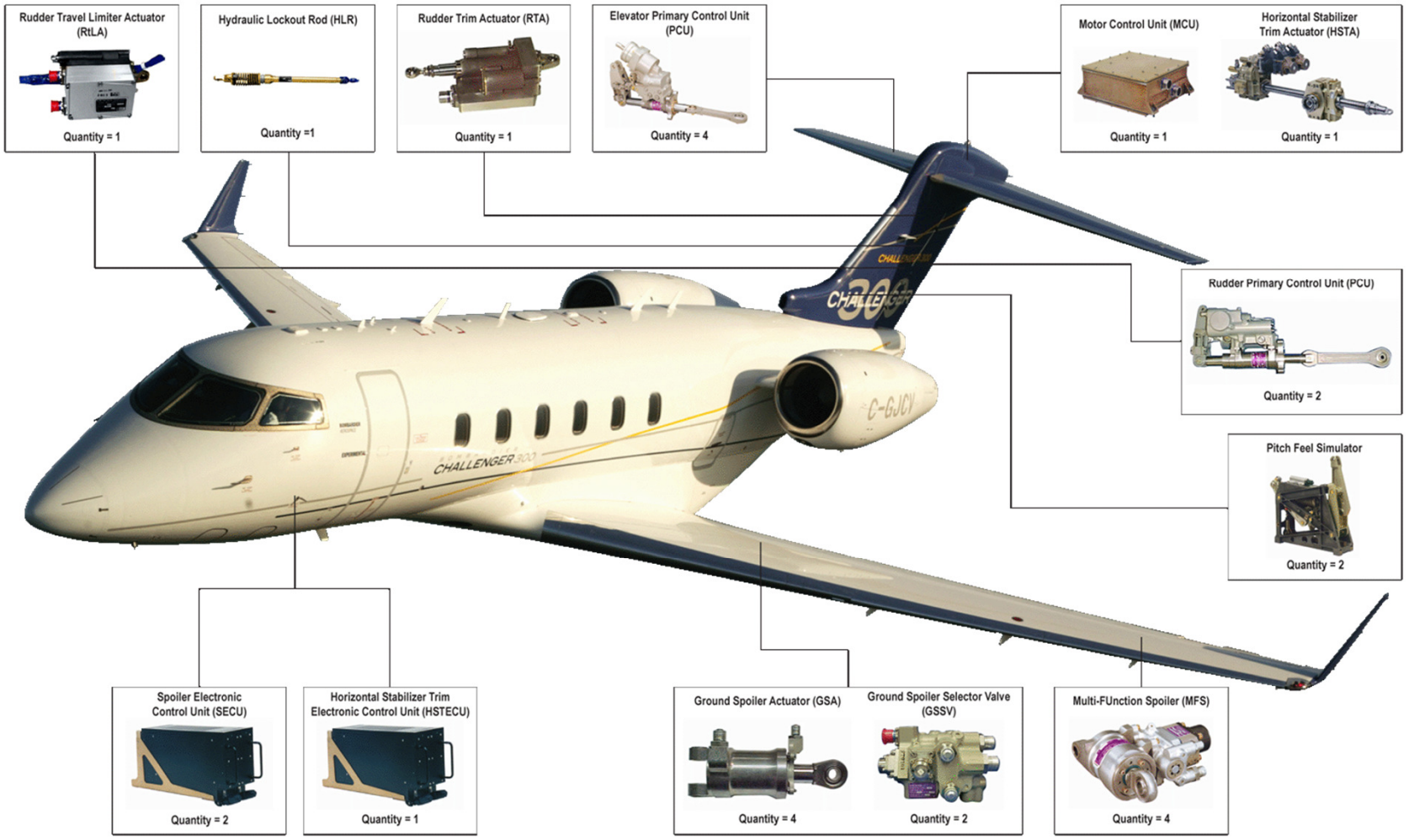
Gulfstream G650 High Lift Actuation System

Complete Flap Actuation System

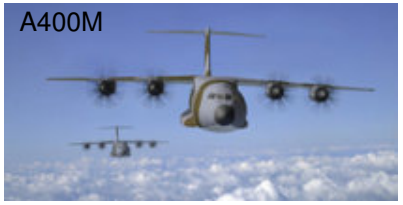


Bombardier Challenger 300 Flight Controls

Complete Flight Control System



Flight Controls For Military Aircraft

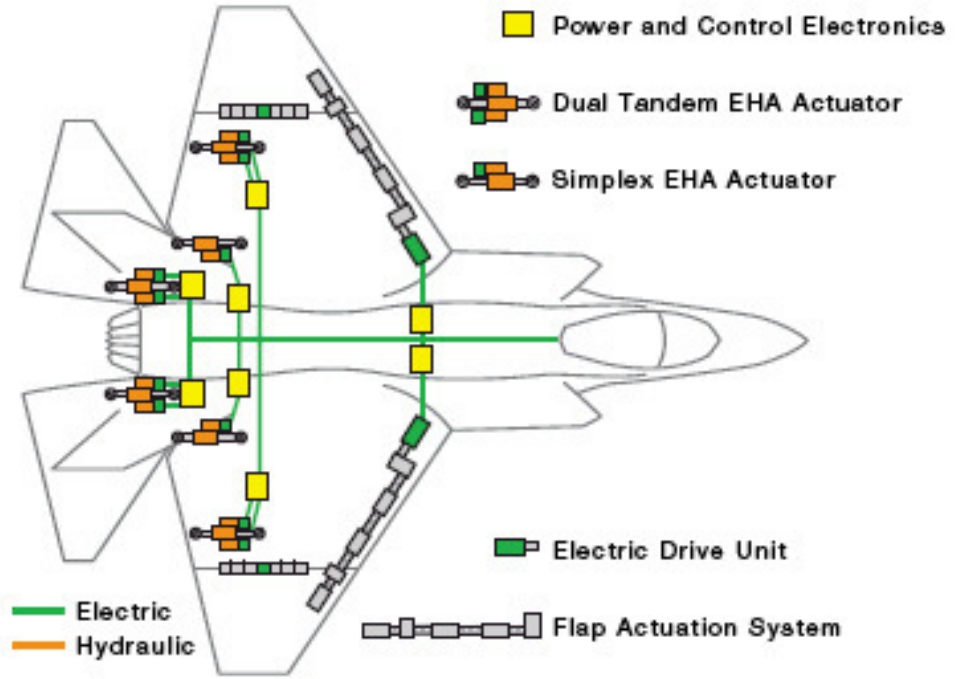


LOCKHEED MARTIN F-35 FLIGHT CONTROLS

The F-35 “power-by-wire” system represents an advancement on the more electric aircraft topology integrating:

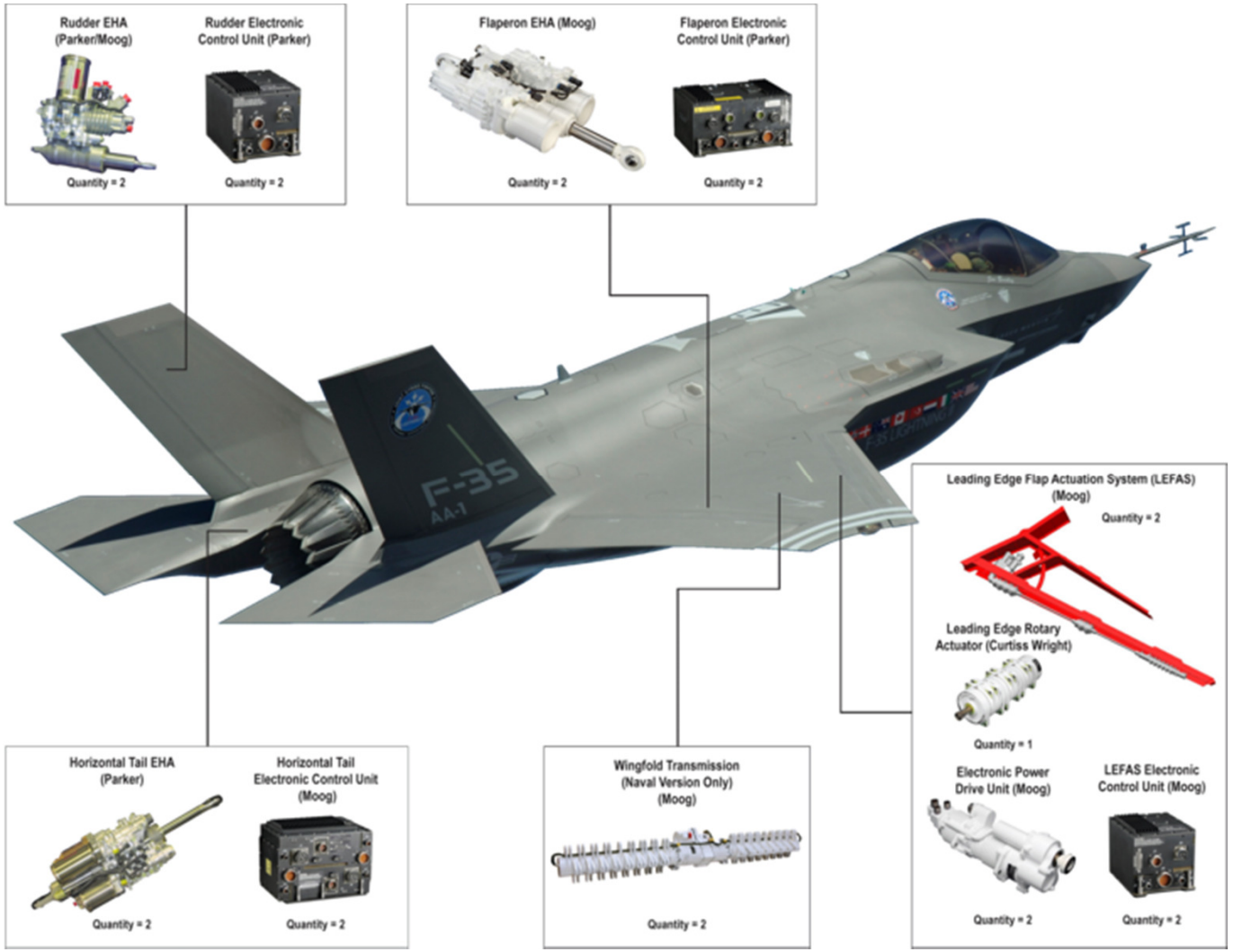
- Self-contained electrohydrostatic (EHSA) actuators to position primary flight surfaces
- Electronic Control Units to remotely drive and control the EHSAs
- Electrically driven PDUs to position the maneuvering leading edge flaps

As the Prime Contract holder, Moog’s role includes managing the industry team, integration of the complete actuation system, and supplier of critical technologies and major sub-systems.



LOCKHEED MARTIN F-35 FLIGHT CONTROLS

Primary and Secondary Flight Control System

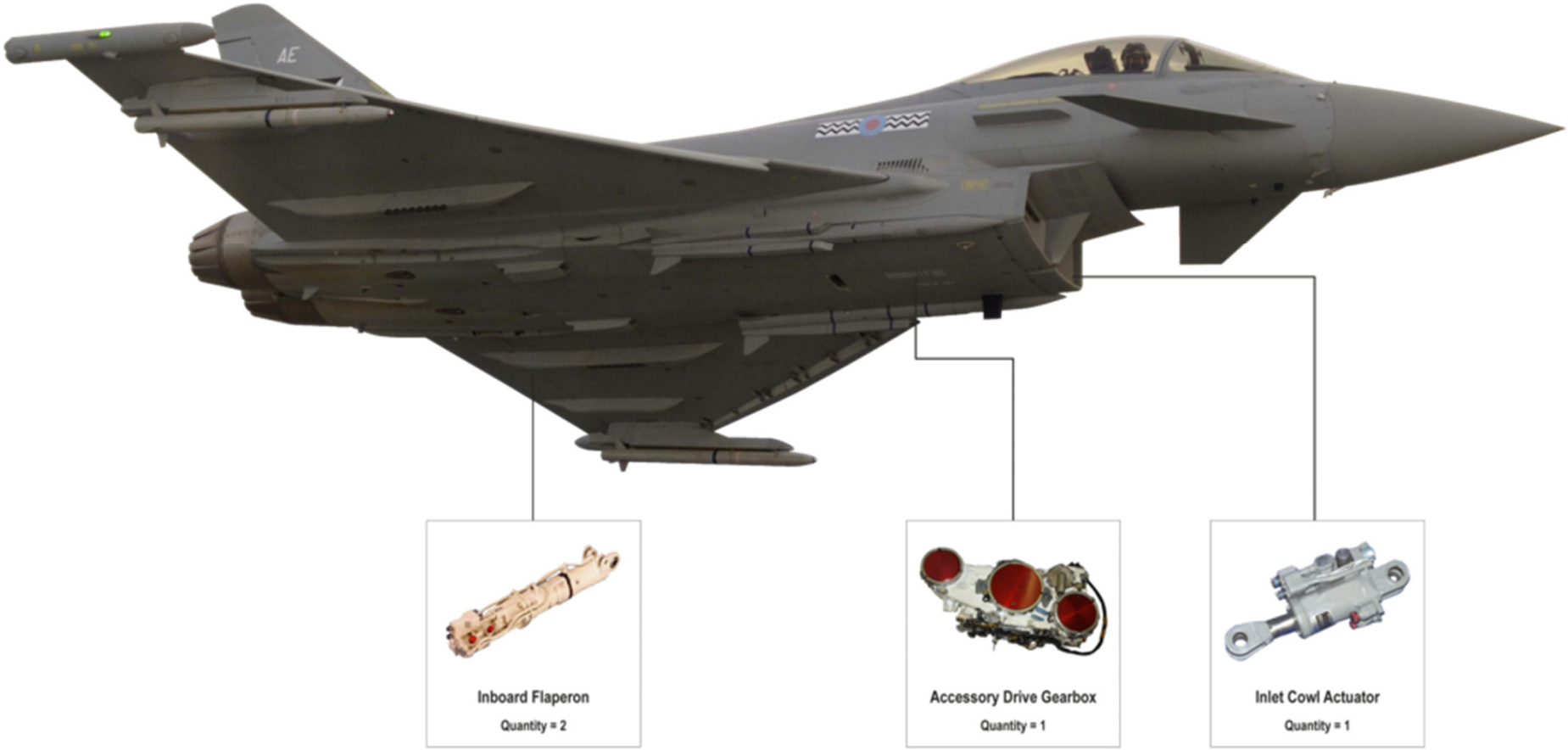


Lockheed Martin F-35B STOVL Lift Fan Actuation

Engine Lift Fan & Swivel Module Actuation Systems

Eurofighter Typhoon

Flight Control Actuation and Critical Control Subsystems



Airbus A400M Flight Controls

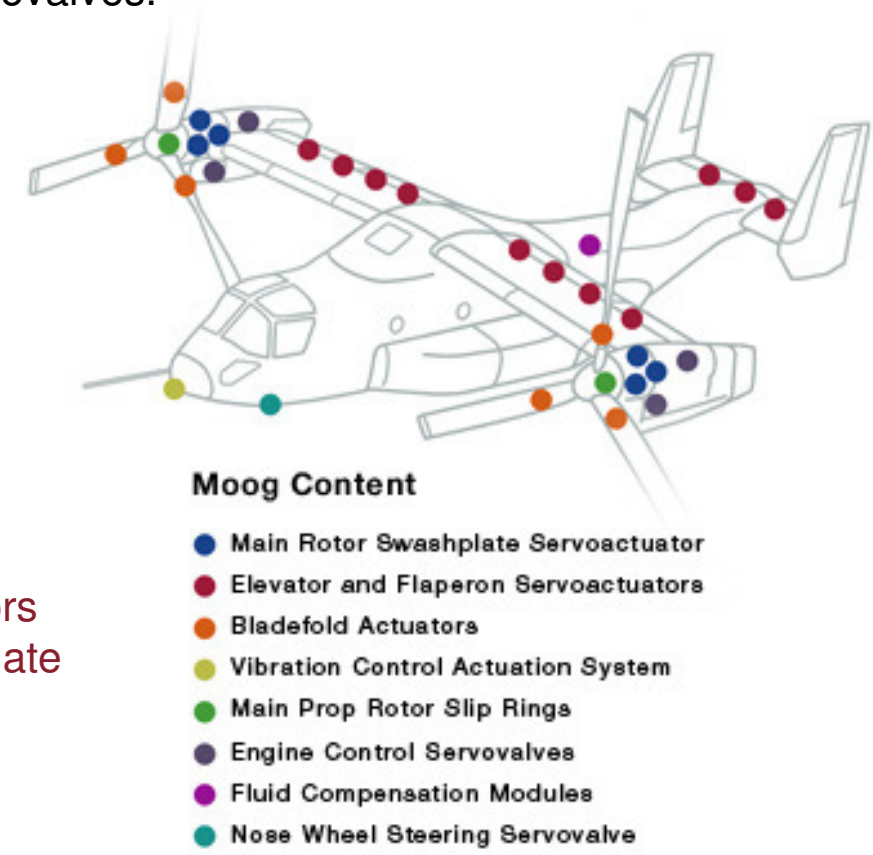
Primary Flight Control Actuation

Rotorcraft

V-22 Primary Flight Control Actuation

Design, manufacture and integration of Primary Flight Control Actuators: main rotor swashplate, flaperon and elevator.

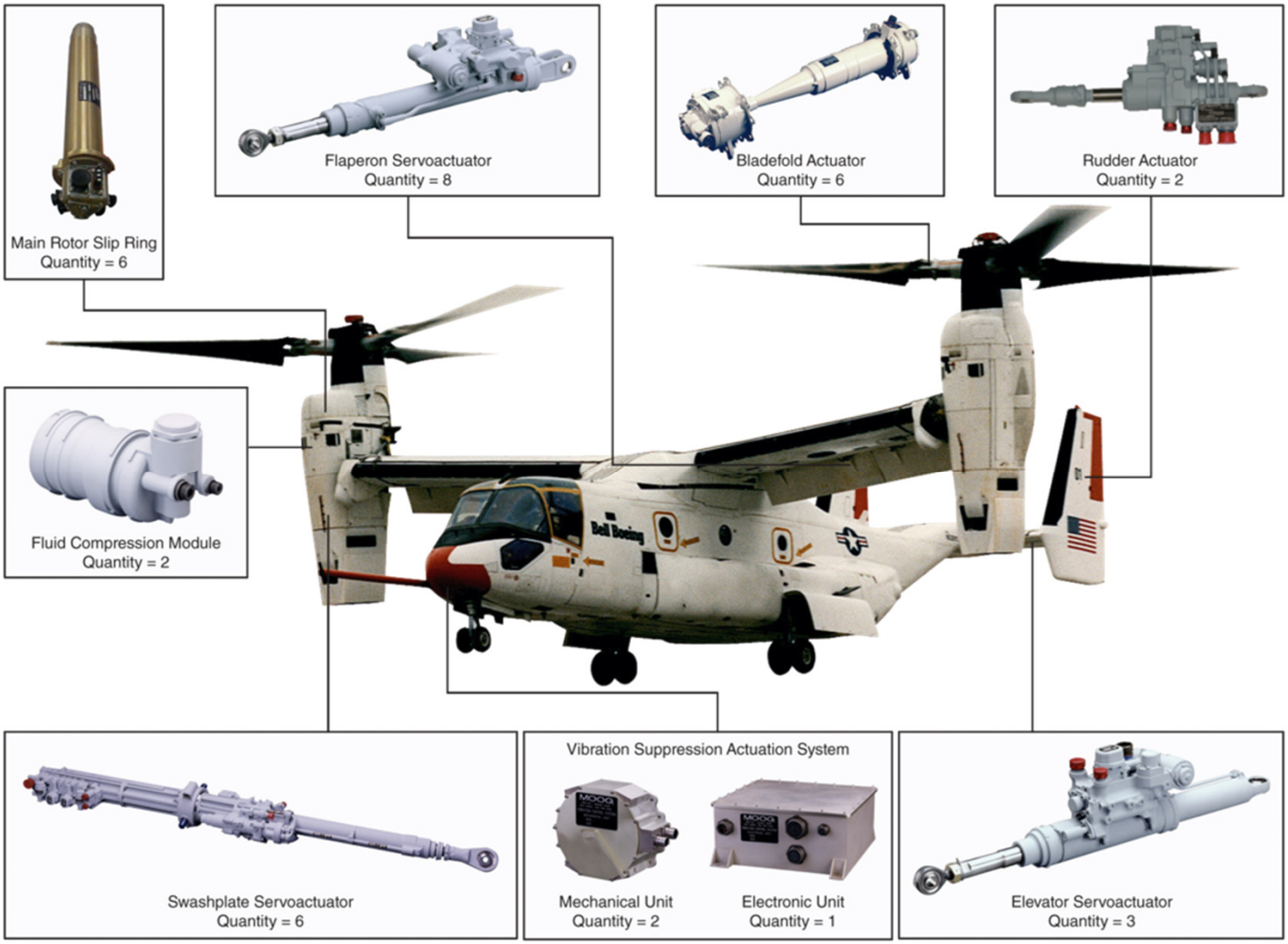
Moog is also providing the vibration control actuation system, bladefold actuation, nose-wheel steering servovalves, main prop rotor slip ring, hydraulic fluid compensation module and engine fuel control servovalves.



Key Features:
- 5000 psi operating pressure
- Duplex hydraulic/triplex electrical redundancy on the Swashplate actuators
- Ballistic tolerant Elevator and Swashplate actuators

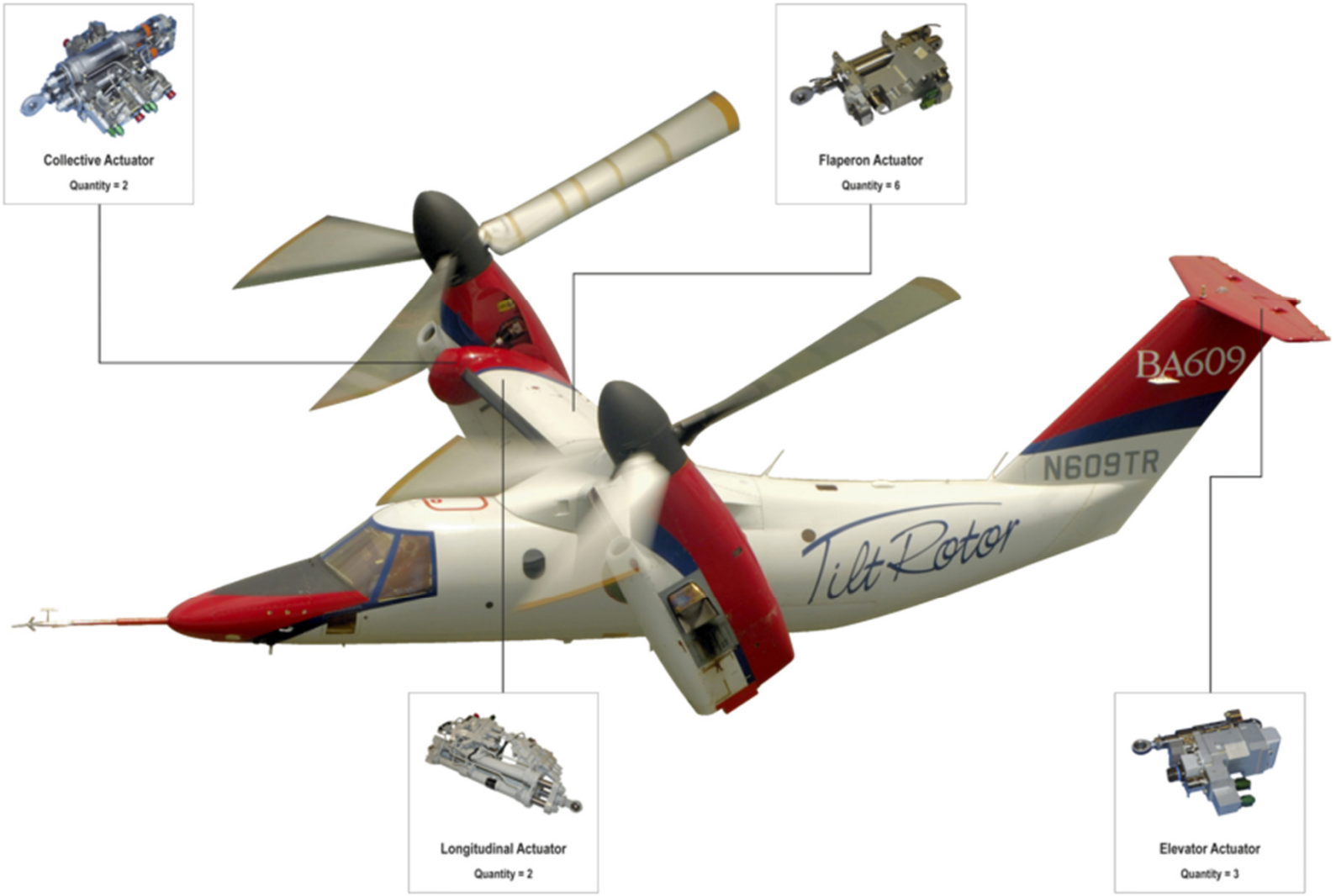
Bell/Boeing V-22 Flight Control Hardware

Primary Flight Control Actuation and Vibration Suppression Actuation



Bell/Agusta BA609 Flight Control Actuation

Primary Flight Control Actuation



Agusta Westland AW159 Future Lynx

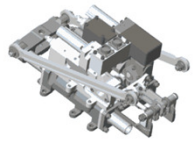
Primary Flight Control Actuation

AgustaWestland AW129 ATAK

Complete Primary Flight Control Actuation

Tail Rotor Actuator

Quantity = 1



Main Rotor Actuator

Quantity = 3

Sikorsky H-60

Pitch Trim and Active Vibration Control

Self Displacing Accumulator
Quantity = 1

Pitch Trim Servoactuator
Quantity = 1

Roll Trim Servoactuator
Quantity = 1

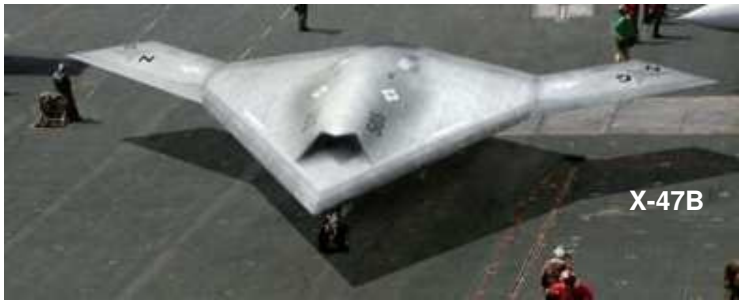
Yaw Trim Servoactuator w/SAS
Quantity = 1

Vibration Suppression Actuation System

Mechanical Unit
Quantity = 6

Electronic Unit
Quantity = 1

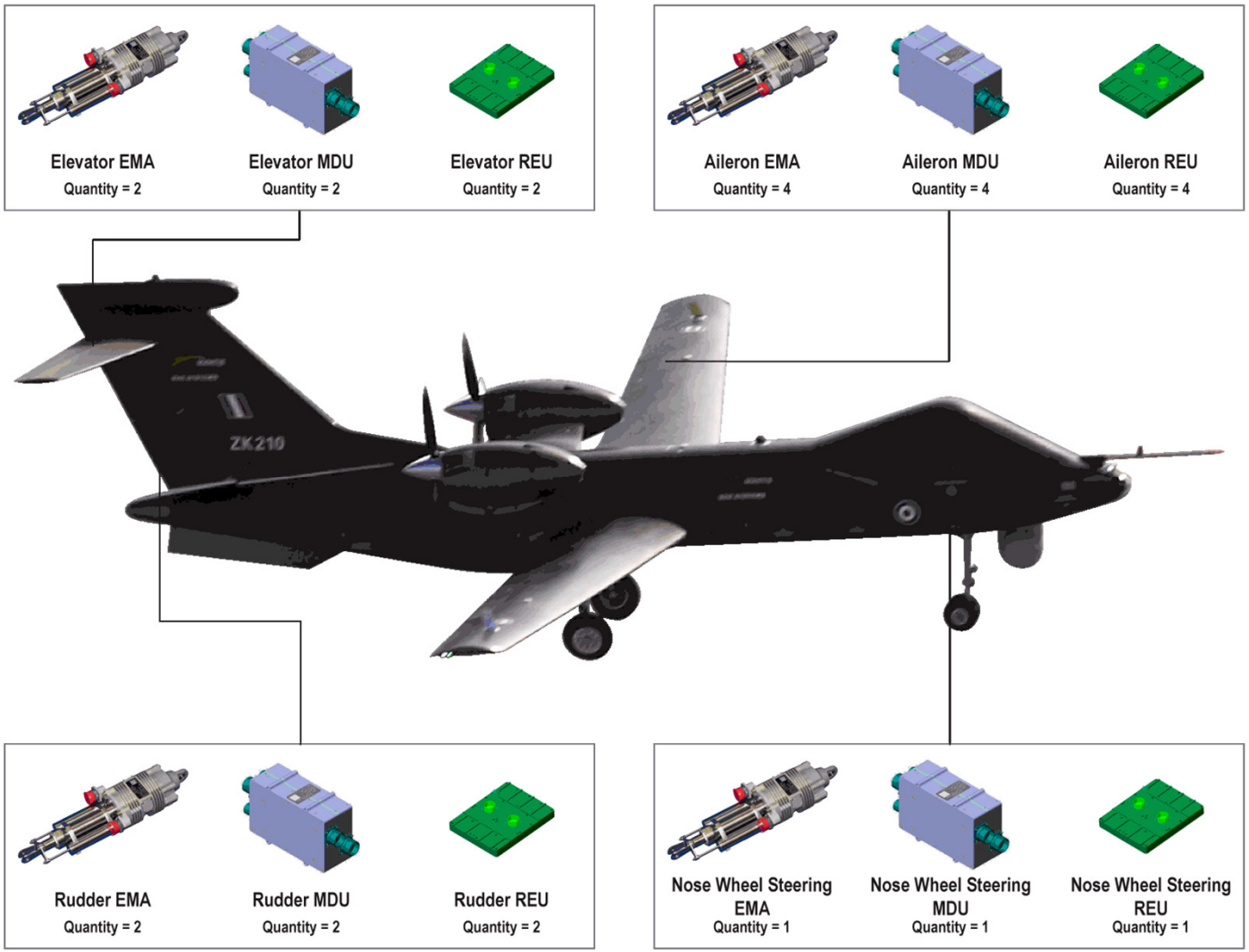
Unmanned Air Systems (UAS)
Unmanned Air Vehicles (UAV)



BAE Mantis Flight Controls

MOOG

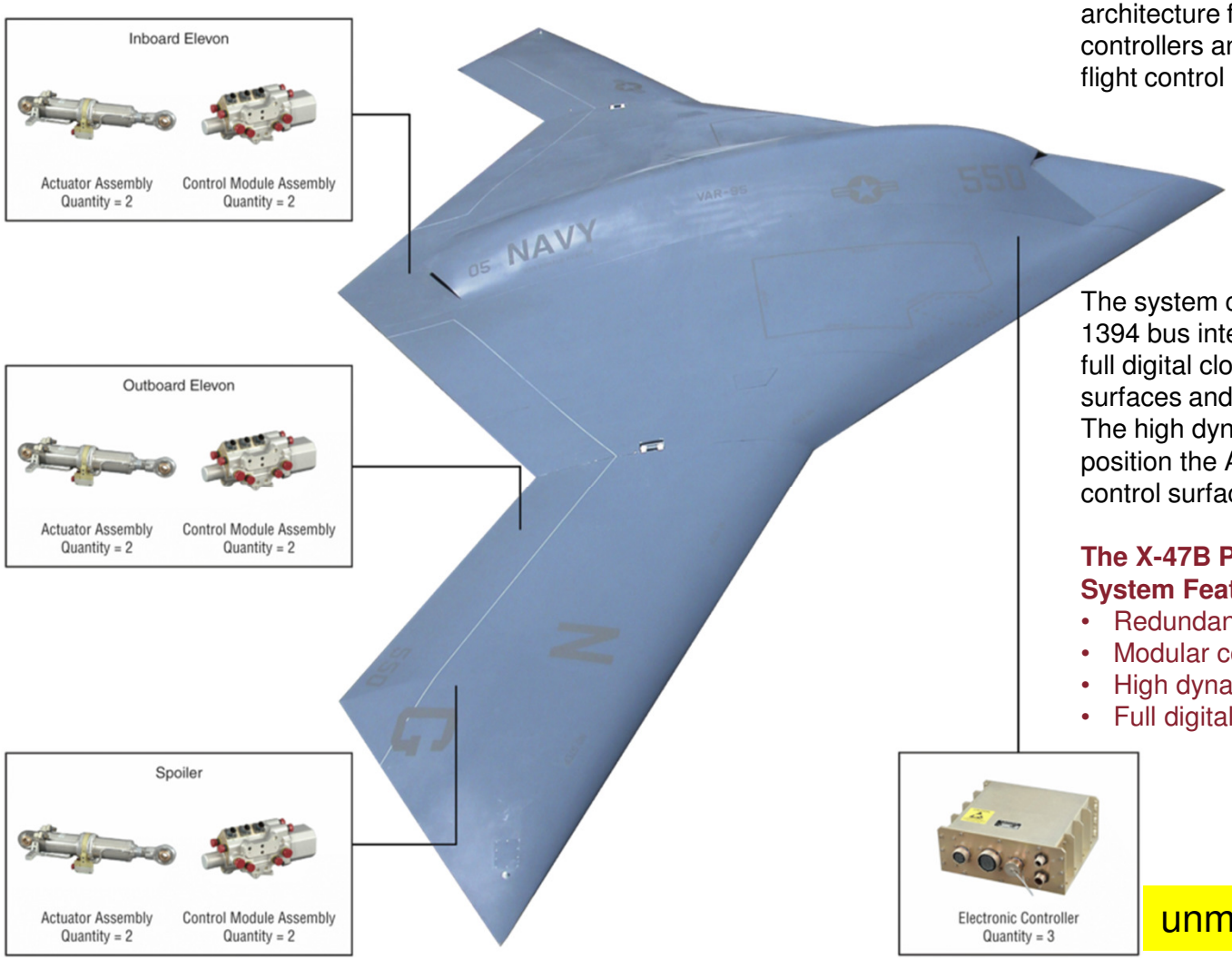
Primary Flight Control Actuation System



Northrop Grumman X-47B Flight Controls

MOOG

Complete Primary Flight Control System



System Integrator for X-47B Primary Flight Control System

The system includes a fully redundant architecture featuring multifunction system controllers and modular Electrohydraulic (EHA) flight control actuators.

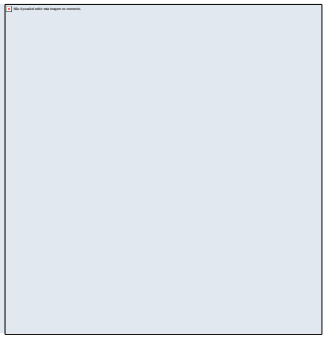
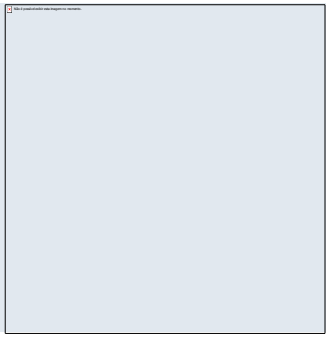
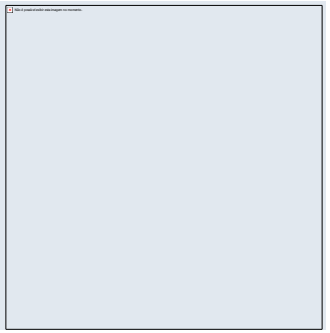
The system controller features a high speed 1394 bus interface, redundancy management, full digital closed loop control for all flight surfaces and advanced vehicle functionality. The high dynamic dual tandem EH actuators position the Aileron, Elevon and Spoiler flight control surfaces.

The X-47B Primary Flight Control Actuation System Features:

- Redundant hydraulic and electrical designs
- Modular construction to optimize installation
- High dynamic response
- Full digital loop control

unmanned combat air system

OUR VALUE TO CUSTOMERS

We support our customers' success	• With motion control application and product know-how • By jointly developing unique solutions that allow our customers to differentiate	
We specialize in high performance	• By offering high performance products, services and solutions that solve real world machine challenges • Through matching the unique requirements of our customers	
We offer expertise	• Through know-how, capabilities, experience, and open minds capable of developing a new approach for demanding motion control applications • Ready to support you in addressing your challenges for your next generation machines or latest project	

THANKS FOR YOUR ATTENTION.....

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