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A Review on Flight Control and Actuation Systems

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Peer Review Information	Abstract
<p><i>Submission: 21 Oct 2025</i></p> <p><i>Revision: 18 Nov 2025</i></p> <p><i>Acceptance: 05 Dec 2025</i></p>	<p>The majority of modern aircraft depend heavily on flight control and actuation systems for stability, maneuverability, and overall safety. These systems control the motion of the control surfaces through various forms of actuation technologies, ranging from hydraulic, electromechanical, to electro-hydrostatic actuators. This research explores the principles of operation, structures, and uses of such actuators and how they assist in flight control. Along with this, fault-tolerant systems, management of redundancy, and future directions such as AI-driven flight control and more electric aircraft (MEA) are examined. As techniques are improved technically, the aviation industry is gradually shifting towards lighter, more dependable, and more efficient actuation systems, improving the overall aircraft performance and safety. The article delves into these changing directions and how they can have repercussions for future flight control practices.</p>
<p>Keywords</p> <p><i>Flight System, Controlling systems, Actuation Systems, Fly-by-wire system.</i></p>	

Introduction

Aircraft design made a major leap during the 1950s, and with it emerged the requirement of autopilot systems to minimize pilots' workload. These systems were referred to as AFCS (Automatic Flight Control Systems), assisting in handling lengthy flights and efficiency in fuel usage. AFCS developed into complex systems such as fly-by-wire over a period, especially with fighter jets such as the F-16, providing superior control and protection. Now, nearly all airplanes utilize AFCS as a starting point for more comfortable, more intelligent flying. [1]

The AFCS is the main in-cockpit instrument for long flight operations, and is the basis for the airspace modernization programs. In order to decrease pilot workload—especially on long flights—transport aircraft today are all equipped with AFCS. During the 1970s, improvements in AFCS made it possible for the fighter General Dynamics F-16 Fighting Falcon to be designed for fly-by-wire control and "relaxed static stability." [1]

Combat aircraft AFCSs are often devised to offer the pilot control over pitch rate at low speed, and normal acceleration (nz) at high speed. The AFCS maximizes the airplane's capability and precision along the intended route. Flight automation is the way of the future, with, of course, interference by manual flying in extreme conditions. The challenge of designing AFCS is significant, and is a matter of much analysis. [1]

Fundamentals of the Automatic Flight Control Systems

An autopilot is capable of implementing many very time intensive tasks, which helps the pilot focus on the overall status of the flight. Tasks include maintaining an assigned altitude / airspeed/heading, climbing or descending to an assigned altitude, turning, intercepting a course, guiding the aircraft between waypoints that make up a programmed route, and flying a precision or non-precision approach. [1]

Moreover, when the autopilot keeps the aircraft

- Application:
 - ✓ Applied in systems where force is required in one direction, i.e., landing gear retraction mechanisms.

3. B Double-Acting Hydraulic Actuator (Bottom Section - B)

- Commercial airliners, such as the Boeing 737 and Airbus A320, use yaw dampers to improve flight stability.
- SAS is used for high-agility flight control on fighter jets, including the F-22 Raptor and F-35 Lightning II.
- Black Hawk, Apache, and other helicopters utilize SAS to stabilize their hovering and flight.

Types Of Actuators In Flight Control System

3.1 Hydraulic Actuators

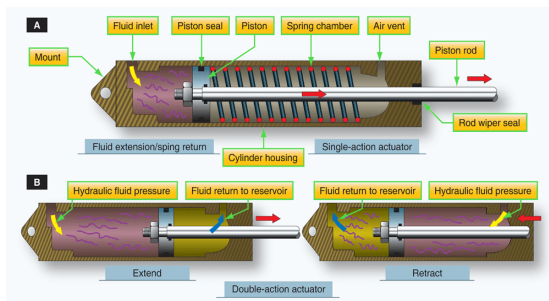


Fig 3.1: Hydraulic Actuators [3]

3. A Single-Acting Hydraulic Actuator (Top Section - A)

- Operating Principle: Utilizes hydraulic pressure in one direction with a spring mechanism returning it to its original position. [3]
- Components:
 - Fluid Inlet: Provides hydraulic fluid.
- Working Principle: Applies hydraulic fluid pressure on each side of the piston to travel in both directions (extend & retract). [3]
- Components:
 - Hydraulic Fluid Pressure: Implemented on either side of the piston.
 - Fluid Return to Reservoir: Permits fluid to be returned when pressure changes.
- Application: Implemented in aircraft control surfaces, landing gears, and flaps because they have bidirectional force capability.
- Main Key points:
 - ✓ Work based on Pascal's Law.
 - ✓ Components: Hydraulic Pump, Valves, Actuators.
 - ✓ Used in commercial aircraft like Boeing and Airbus.

3.2 Electromagnetic Actuators

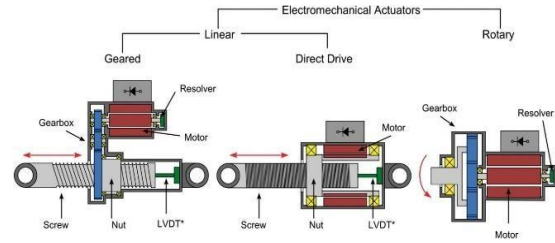


Fig 3.2: Classification of different EMA types.

3.2.1: Linear Actuators

3.2.1(A): Geared Linear Actuator (Left)

- A motor powers a gearbox, which in turn powers a screw.
- Twisting motion is translated to linear motion through a nut.
- A Linear Variable Differential Transformer (LVDT) is utilized for sensing position.
- A resolver gives feedback to the system.

3.2.1(B): Direct Drive Linear Actuator (Middle)

- The motor is mounted directly to the screw, avoiding the use of a gearbox.
- The nut travels along the screw, producing linear motion.
- There is LVDT for position sensing.
- This is a less complex design but can use more motor torque.

3.2.2: Rotary Actuator (Right)

- The motor powers a gearbox, which transfers rotational movement to an output shaft.
- A resolver is employed for positioning and feedback.
- They are utilized when rotation is required in place of linear movement.
- Key Components:
 - ✓ **Motor:** Supplies driving force.
 - ✓ **Gearbox:** Inverts torque as speed is minimized.
 - ✓ **Screw & Nut Mechanism:** Converts rotational motion into linear travel.
 - ✓ **LVDT (Linear Variable Differential Transformer):** Generates accurate position feed.
 - ✓ **Resolver:** Tracks rotational position and velocity.

Hydraulic Actuators In Aircraft



Fig 4: Hydraulics Actuator used in Airplanes

These actuators are ideal for applications requiring a lot of force since they are robust and dependable. Even as electric systems gain popularity, hydraulic systems remain crucial because of their strength and accuracy. [4]

- Working Principle
 - ✓ Hydraulic actuators operate under Pascal's Law, which dictates that "A pressure change applied to a sealed incompressible fluid is passed undiminished to all points of the fluid and walls of its container."
 - ✓ Hydraulic actuators can use this principle to multiply force and provide high power with accuracy. Pressurized hydraulic fluid displaces a piston within a cylinder to create linear or rotational motion. Control valves control fluid flow, determining actuator movement.

Closed loop control of hydraulic, electromagnetic, or smart material actuation is used for active turbomachinery control. Hydraulic actuators are commonly employed in propulsion; however, the trend is toward more electric motor-driven systems. In addition to other aviation and engine control requirements, new technologies are being developed to give alternatives to hydraulic action systems for the majority of variable cycle engine components. [5]

In order to avoid potential failures, the controls of such actuation systems will require tough operation, with the status being available at all times to the FADEC and flight control. A smart actuator will include software and electronics for monitoring, control, and health status, as well as the elimination of hydraulic lines, brackets, and associated weight from the aircraft. A smart EMA must be able to work in harsh temperatures and vibrations while responding

rapidly. [5]

- Main Elements of Hydraulic Actuators:
 - Hydraulic Fluid** – A proprietary oil-based fluid that transfers pressure in an efficient manner.
 - Hydraulic Pump** – Produces the fluid pressure needed to operate the actuator.
 - Control Valves** – Regulate hydraulic fluid flow to the actuator.
 - Cylinder & Piston** – Translates hydraulic pressure into mechanical motion.
 - Reservoir** – Holds hydraulic fluid and replaces lost volume.
 - Filters & Pipes** – Provides fluid purity and contaminant prevention within the system.
 - Accumulator** – Saves pressurized liquid to hold constant pressure and offer emergency power.
 - Servo Valves** – Employed on sophisticated aircraft to accurately move an actuator.

Hydraulic Actuator Types in Aircraft

- Single-Acting Actuators:
 - The piston is displaced by fluid pressure in one direction.
 - Returned to the initial position by a spring or external load.
 - Utilized in emergency landing gear deployment and brake systems.
- Double-Acting Actuators
 - Displaces the piston in both directions using hydraulic pressure.
 - Delivers accurate bidirectional control.
 - Used in flaps, primary flight controls, and slats.
- Rotary Hydraulic Actuators
 - Transfers hydraulic energy to rotational motion.
 - Utilized in flap actuation, landing gear doors, and thrust reversers.
- Telescopic Actuators
 - Designed for long reach and multi-stage motion.
 - Utilized in cargo doors and landing gear extension mechanisms.

The Design Of Fly-By-Wire Flight Control Systems

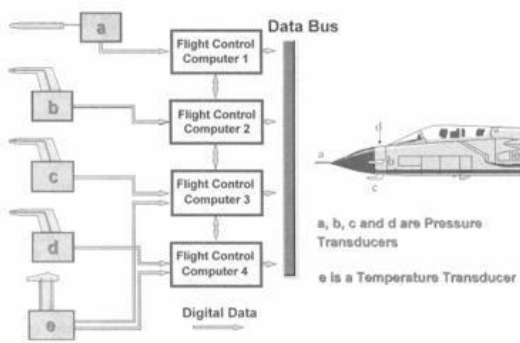
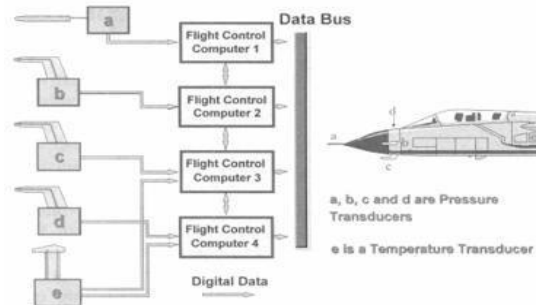


Fig 5: Distributed Air Data System

- Elements of the Diagram:
 1. Sensors (a, b, c, d, e):
 - ✓ (a, b, c, d) Pressure Transducers – Sense air pressure at various locations around the plane, feeding data used in flight control adjustments.
 - ✓ (e) Temperature Transducer – Sensors external temperature to aid in performance optimization and environmental adjustments.
 2. Flight Control Computers (1, 2, 3, 4):
 - Each pressure and temperature sensor sends data to one of the four Flight Control Computers (FCCs).
 - These computers process sensor inputs and make decisions to control surfaces (e.g., ailerons, elevators, rudders) for flight stability.
 - There are redundant computers to provide redundancy and fault tolerance – if one fails, others still operate.
 3. Data Bus:
 - A high-speed data communication channel that carries digital data from the flight control computers to other aircraft systems.
 - The data bus provides real-time information exchange between various flight control components.
 - How It Works:
 - i. The pressure transducers (a, b, c, d) sense air pressure at various points on the nose of the aircraft.
 - ii. The temperature transducer (e) senses ambient temperature readings.
 - iii. These are converted into digital signals and transmitted to the corresponding Flight Control Computers (FCCs).
 - iv. The FCCs process the data and calculate control surface adjustments

as needed.

- v. The processed data is sent via the data bus to the control systems, which take the necessary actions.



- Applications & Importance:
 - i. Utilized in contemporary Fly-by-Wire (FBW) systems to make aircraft safer and more efficient.
 - ii. Guarantees safe flight operations when flying in variable atmospheric conditions.
 - iii. Facilitates real-time monitoring of the most important parameters for automatic or pilot- controlled modifications.
 - iv. Improves redundancy and dependability in case of system faults.

Flight Control System Failures & Redundancy Management

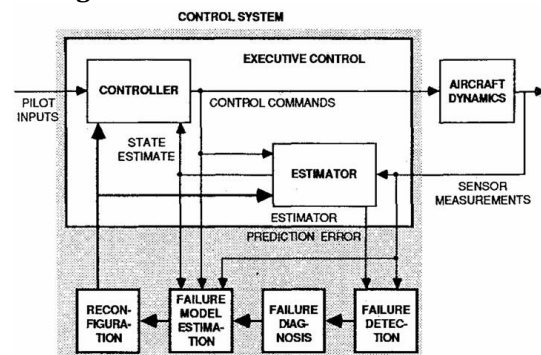


Fig 6: Organization of the Rule-Based Flight Control System.

The search is utilized by the Rule-Based Flight Control System to enhance fault tolerance. Procedural failure accommodation varies from search in the way control system actions to be taken are planned and chosen. Contrasting with adhering to a step-by-step method, the search methodology outlined below strives to duplicate the human decision-making process and only continues to act on moves that are needed and adequate in order to continue to fly the aircraft safely. [4] RBFCs uses a search strategy identical to the MYCIN expert system.22 The search algorithm uses a knowledge base and an inference engine. [5]

The knowledge base holds information regarding the world. The inference engine processes the knowledge base trying to infer more information from that which is already stored. Precisely, the knowledge base holds factual information in the form of parameters and procedural information in the form of rules. Examples of fact statements regarding failure are, "The sensor readings are normal" and "The prediction error in the estimator is small." In this, J is the parameters.

GUIDANCE CONTROL SYSTEM Fig. 1 Organization of the Rule-Based Flight Control System. SENSOR MEASUREMENTS with values REASONABLE and UNREASONABLE, and ESTIMATOR PREDICTION ERROR with values SMALL and LARGE. Examples of procedural knowledge are, "If sensor values are reasonable and the estimator error of prediction is small, then abnormal behavior is not reported," and, "If sensor values are unreasonable or the estimator error of prediction is largest, then abnormal behavior is reported." The action of every rule contains only a premise to be evaluated for truth. Only when a premise of a rule is discovered to be true by evaluation, a rule's action is carried out. [6]

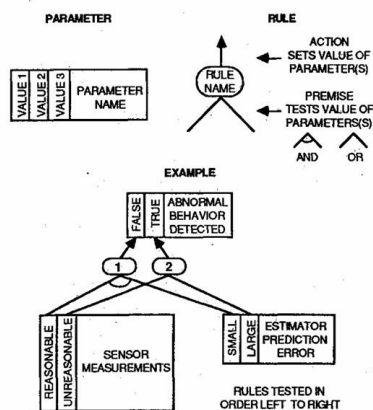


Fig 6.1: Knowledge-based graphical representation.

Figure 6.1 is a diagram of this sample knowledge base. In this diagram, rectangles denote parameters. Slots in a given rectangle hold all values that the corresponding parameter can take. With arcs between parameters denoting rules, the resulting "and/or" graph can be used to follow the logic path taken by the search process. The issue of search arises when more information is to be deduced from the current situation of the knowledge base. All parameters that have no initially known value are taken as unknown before any search is initiated. [6]. This

step is referred to as knowledge-based initialization. In a search, parameters acquire values by testing rules, but the rules tested and parameters set vary with the type of search employed. Two kinds of searches are employed in the RBFC: goal-directed (backward-chaining) and data-driven (forward-chaining). The goal of a goal-directed search is to determine a value for a given parameter. Applying the example previously stated, a goal-directed search would be the query, "Is abnormal behavior detected?" or more precisely, the instruction (goal),

Case Studies Of Flight Control System Failures

Flight control system malfunctions have serious implications on aircraft safety, maneuverability, and overall flight performance. Here are three crucial case studies of flight control system malfunctions in various aircraft models.

a) Airbus A380 (Airbus 380 Hydraulic Failure)



Fig 7: Airbus A380

- Background

The world's largest passenger airliner, the Airbus A380, has three independent high-pressure hydraulic systems, each operating at 5,000 psi. An engine explosion ruptured vital hydraulic systems on Qantas Flight 32 in 2010. This malfunction rendered several control surfaces useless, but the plane landed safely thanks to system redundancy and pilot competence. The incident highlighted the significance of backup facilities and layered security in large aircraft design.

- Incident

- i. In 2010, Qantas Flight 32, an Airbus A380, had a catastrophic engine explosion after departure from Singapore.
- ii. The explosion badly damaged hydraulic lines, resulting in loss of several flight control surfaces (elevators, ailerons, and spoilers).
- iii. Pilots used remaining redundant

- systems to manually control the plane.
- iv. The plane was landed safely, in spite of several failures, because of the fail-safe design and redundancy in the flight control system.

- Lessons Learned
 - i. Redundancy in Flight Control
 - ii. Systems: Safety is ensured with several independent hydraulic systems.
 - iii. Manual Flight Control Capability: Pilots should be trained for manual flight in case of failures despite automation.

b) Boeing 737 MAX (MCAS Problem)



Fig 7.1: Boeing 737 Max

- Overview:
- The Boeing 737 Max has an MCAS system that aids with pitch control. However, because to inaccurate sensor readings, it malfunctioned, pulling the plane's nose down against the pilot's will. Sadly, this resulted in two catastrophic accidents. These events demonstrated that using software as a primary control measure might be damaging if not properly understood and tested.

- Failure & Crashes
 - i. Lion Air Flight 610 (October 2018) and Ethiopian Airlines Flight 302 (March 2019) both crashed as a result of MCAS failure.

- Overview



Fig 7.2: F-22 Raptor

- ii. A defective Angle of Attack (AoA) sensor improperly activated MCAS, pushing the nose of the aircraft down repeatedly.
- iii. Pilots were finding it difficult to take control back from the system, resulting in unstoppable dives and crashes.

- Lessons Learned
 - i. Risks in Software-Based Flight Control: Blindly relying on automatic systems with too little awareness from the pilot is risky.
 - ii. No Redundancy in Sensors: One defective sensor caused critical failures; the system needs redundant sensors.
 - iii. Pilot Training & Manual Override: MCAS was not covered during early pilot training, which identifies a need for greater communication and training.

- Fixes & Solutions
 - i. Boeing updated the MCAS software to use two AoA sensors' input instead of one.
 - ii. Pilots received improved training on MCAS and its override procedures.
 - iii. Extra stall prevention steps were incorporated into the flight control system.

c) F-22 Raptor (Electrical Actuation System Failure)

The F-22 Raptor, an advanced fifth-generation stealth fighter aircraft, employs an Electrical Actuation System (EAS) as a replacement for conventional hydraulic actuators to actuate flight surfaces. This renders the aircraft lighter, stealthier, and more fuel-efficient.

- Failure Case
 - i. In 2006, a flight control system failure was suffered by an F-22 Raptor during a test flight above Alaska.
 - ii. All control inputs of the aircraft were lost due to a computer software malfunction in the electrical actuation system.
 - iii. The malfunction made the pilot eject as the aircraft became totally unresponsive.

- Lessons Learned
 - i. Risk of Full Electrical Actuation: Electrical systems may fail from software bugs, and therefore, backup hydraulic or mechanical options should be available.
 - ii. Software Validation & Testing: Intensive software testing is essential for fly-by-wire systems.
 - iii. Emergency Recovery Procedures: Contemporary aircraft must have fail-safe

features in critical flight control functions.

- Improvements in the F-22 Flight Control System
 - i. Increased redundancy in electrical systems.
 - ii. Enhanced software fault detection and recovery capabilities.
 - iii. Pilot training using a simulator for electrical failure management.

Future Trends In Flight Control & Actuation System

Looking ahead, flight control systems will increasingly rely on electric actuators, artificial intelligence, and lightweight parts. Fly-by-wire is replacing older hydraulic systems because it is easier to maintain and more efficient. We're also seeing smart actuators that can monitor their own health and make changes in mid-air. These developments could make future planes safer, more dependable, and technologically advanced than ever before. The main trends are:

1. Shift towards More Electric Aircraft

(MEA): Conventional hydraulic actuators are being substituted by Electromechanical Actuators (EMAs) and Electro-Hydrostatic Actuators (EHAs).

- **Advantages:**
 - i. Weight savings (removal of hydraulic fluid & pumps).
 - ii. Less maintenance (no leakage, reduced moving parts).
 - iii. Enhanced efficiency & reliability (electric actuators are faster & more efficient).
- **Examples:**
 - i. EHAs are applied in primary flight control surfaces by Boeing 787 Dreamliner and Airbus A350.
 - ii. EMAs are applied in advanced maneuverability by F-35 Lightning II.

2. AI-Based Control Systems & Autonomous Flight:

- a. Future aircraft will be equipped with Artificial Intelligence (AI) to support or displace human pilots.
 - b. AI-based Fly-by-Wire 2.0 systems will adjust themselves to optimize control surface movement.
- **Applications:**
 - a. UAVs (Unmanned Aerial Vehicles): AI-based flight control is already being applied in military drones.
 - b. Urban Air Mobility (UAM): Autonomous flying taxis such as Joby Aviation's

EVTOL.

3. Smart **Materials** Integration in Actuation: Shape Memory Alloys (SMA):

- a. They undergo shape change with respect to temperature, supporting the use of lightweight actuators.
- b. Reduces complexity over conventional motors or hydraulics.

4. **Piezoelectric Actuators:**

- a. Electrical energy is converted to accurate mechanical motion.
- b. Applied in micro-control surfaces for hypersonic flight.

5. **Power-by-Wire (PBW) Technology**

- a. Rids of centralized hydraulic systems.
- b. Every actuator power itself, enhancing redundancy and fault tolerance.
- c. Reduces cabling and fluid leakage hazards.

6. **Next-Generation Redundancy & Safety Measures**

- a. Future flight control systems will feature real-time prediction of failure by machine learning.
- b. Redundant distributed actuator networks will provide fail-operational capability.

Conclusion

The history of flight control and actuation systems has played a significant role in defining the current state of aviation. Flight control progressed from mechanical linkages in the early years to today's highly modern fly-by-wire and artificial intelligence-based systems, significantly improving aircraft safety, efficiency, and flying characteristics. The transition from hydraulic to electromechanical (EMA) and electro-hydrostatic actuators (EHA) is a critical step toward More Electric Aircraft (MEA), reducing reliance on traditional hydraulic systems while increasing overall performance.

One of the most important components of flight control systems is redundancy and fault tolerance, which are vital for aircraft safety. Previous system failures, such as the Boeing 737 Max MCAS debacle and the Airbus A380 hydraulic system accident, have underlined the significance of having reliable, fail-safe mechanisms in modern aircraft. This has expedited the development of triple-redundant systems, intelligent actuators, and self-healing AI algorithms to improve reliability in critical flight conditions.

The implementation of artificial intelligence-

controlled flight systems is the next step in aviation. Artificial intelligence-based automation provides real-time monitoring, self-adjustment, and predictive maintenance, lowering the likelihood of flight control system failure. Furthermore, the use of shape memory alloys (SMA), piezoelectric actuators, and fly-by-light technology has accelerated the development of lighter, more responsive control systems that improve aircraft agility and fuel efficiency.

In the future, the air transportation industry is intensively investigating the viability of fully autonomous flight control systems. AI-powered autopilot functionality, along with data analytics and machine learning-based flight prediction patterns, has the potential to pave the way for future pilotless commercial flights. Even while human pilots are expected to play an important role in air transport for the foreseeable future, the rising reliability of autonomous systems points to a future in which planes operate with minimal human intervention.

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