NOTES ON "THE ELECTRIC CONTROL OF LARGE AEROPLANES"

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IN THE BEGINNING

About 70 years ago, Mr. D. T. Glass-Hooper wrote an article for *Flight Magazine* which proposed "The Electric Control of Large Aeroplanes" [1,2].

Mr. Glass-Hooper suggested operating the control surfaces from solenoid devices, the current being provided by a battery-generator combination. The generator was driven by the aeroplane engine or, in the event of its failure, from an auxiliary propeller. The control levers would move over arcs of contact to regulate the current to the solenoids.

Mr. Glass-Hooper's proposal had some soft spots in it. For example, the pilot would have no real or artificial "feel" but Mr. Glass-Hooper thought that he could

> "...observe the current readings on easy-to-see ammeters..."

This would not be totally accepted by most of today's pilots. In addition his analysis of potential electrical failures, also comes up a little lacking:

> "...as to the breaking of the circuits accidently, by a wire snapping, or some such reason, it is a contingency so unlikely as to be hardly worth consideration...!"

However Mr. Glass-Hooper's idea of a battery-generator with an auxiliary propeller sounds modern in that he covered potential dissimilar failures. In addition his opinion on saving cockpit space is shared by many people today.

> "...increased space in the pilot's cockpit owing to the absence of large and cumbersome mechanical controls..."

Mr. Glass-Hooper's proposal for all electric flight control was largely ignored.

What kind of an airplane flight control system was Mr. Glass-Hooper trying to improve on?

Let's take a look at Mr. Charles Pfitzner's airplane as it appeared in a 1910 issue of *Flight Magazine,* Figure 1 [3]. Note also that his aircraft is a pusher monoplane with canard pitch controls. A couple of novel sounding ideas.

The controls are very straight forward — a system of cables and pulleys linking the control column directly to the control surfaces and with the pilot providing all of the "muscle."

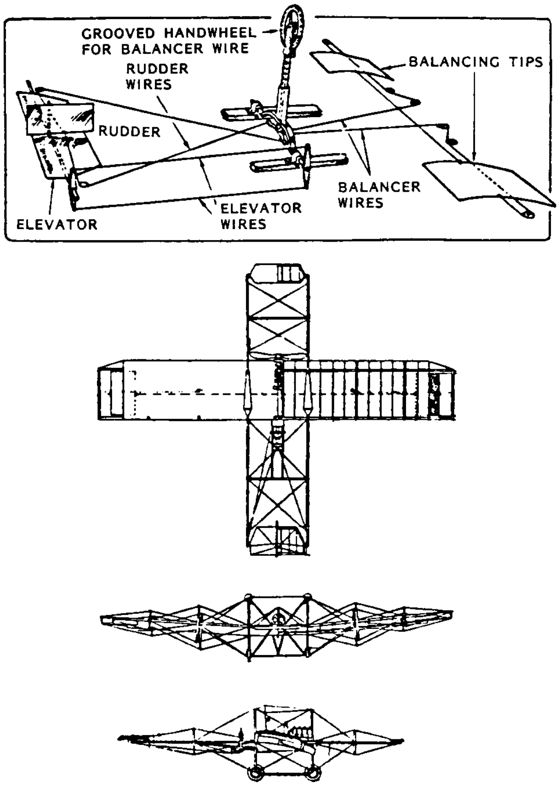

Figure 1. The Pfitzner Monoplane

Based on a presentation at NAECON 1987.

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MORE BACKGROUND

The type of control system implemented by Mr. Pfitzner was used almost universally in aircraft through the end of WWII. The need for extra "muscle" led to hydraulic actuation systems in the late 1940s as pioneered by the Northrop B-49 flying wing bomber. As time went by the increased performance demands placed on aircraft led to Stability Augmentation (also found on the B-49), Command Augmentation and a host of other automatic functions. The hydraulic actuation systems grew to accept electrical as well as mechanical input, and redundancy in the interest of survivability, led to dual and triple hydraulic systems with flight control electronics quickly moving from two to three to four channels deep. The increase in redundancy, new problems in redundancy management, increasingly complex flight control laws and algorithms, and intricate switching requirements, has brought about the use of multiple, digital flight control computers. The mechanical, manual input system of linkages, cables, and pulleys, which had proved adequate for so many years has become increasingly complex and is in danger of extinction. The Fly-by-Wire concept, whereby all pilot input is sensed electrically and the mechanical input system is eliminated, is becoming more and more common.

The modern day flight control system has thus become heavily electrical involving electric fly-by-wire input systems with multiple digital computers and redundant electrical systems. The hydraulic actuator is the last major non-electrical element.

THE ALL-ELECTRIC AIRPLANE

In depth analyses have been performed on the All-Electric Airplane concept whereby all the aircraft secondary power is generated electrically and the pneumatic and hydraulic systems are eliminated. The All-Electric Airplane offers a heavy dose of potential benefits not the least of which is billions of dollars in life cycle cost savings. Mr. J. Cronin of Lockheed-California Company, in a study performed for NASA, predicts a savings of 9.4 billion dollars for a fleet of 300 transport aircraft operated over a 16 year period [4].

In order to build an All-Electric Airplane with the elimination of the engine driven hydraulic systems, some new thinking is required in the actuation system arena.

One thought is to replace the hydraulic actuator with an electric actuator and this idea is very close to becoming a reality. Recent advances in the use of rare earth magnetic materials, such as samariam-cobalt, and in high-speed, high-power electronic switching devices have led to a class of brushless DC motors with electronic commutation schemes which are light enough, powerful enough, and reliable enough to perform the flight control actuation task. The electric actuator offers several benefits: improved maintainability, reduced logistics, better redundancy management, greater reliability, and in most cases reduced life cycle costs. Electric actuation also offers the controls designer an alternate methodology in primary actuation. There are certainly instances where envelope and structural or other physical constraints may be more easily overcome with use of electric actuators rather than hydraulic actuators. In addition, the use of electric actuators can add a dimension of dissimilar redundancy to the survivability aspect of aircraft design.

ELECTRIC ACTUATOR LABORATORY TESTING

Several successful electric actuation laboratory demonstrations have been conducted:

- The Air Force Flight Dynamics Laboratory (FDL) sponsored development of an electric rotary hinge line actuator by AiResearch [5].
- NASA sponsored several Space Shuttle improvement programs which concluded that electrically actuated flight control systems potentially improve efficiency and save weight. The Johnson Space Center developed a Space Shuttle Orbiter prototype electro-mechanical actuator system and sponsored Delco in the development of the motor for it [6].
- Honeywell, with support from Inland Motors, successfully developed a Space Shuttle Orbiter inboard elevon electric actuator. This actuator has been tested in the Orbiter Flight Control Laboratory by Rockwell [7].

The promising studies and successful laboratory demonstrations have carried development to the point where demonstration by actual flight test is the next logical step. There are several very promising flight test demonstrations in work including two at Lockheed-Georgia: A C-141 aileron electric actuator system and the High Technology Test Bed (HTTB), a highly modified C-130 with five all-electric flight control systems [8,9].

THE C-141 AILERON ELECTRIC ACTUATION SYSTEM

The C-141 program came about as the result of a "seed-money" Independent Research and Development (IR&D) program for study of All-Electric Airplane flight control implications. The conclusion was reached that it was time for flight test demonstration of electric primary flight control actuation systems. Discussion with the Air Force Flight Dynamics Laboratory, Control Techniques Group and Sundstrand Corporation resulted in the formulation of a plan to develop and flight test such a system. Flightworthy hardware has been developed by Sundstrand and Lockheed-Georgia, delivered to the Air Force Flight Dynamics Laboratory, and test flown by the 4950th Test Wing. Flight test results were almost exactly as expected indicating a bright future for electric actuation systems.

The C-141A used in the flight test program is shown in Figure 2 and the general arrangement of the hybrid hydromechanical/electromechanical C-141 roll control system is shown in Figure 3. A block diagram of the electric actuator system is shown in Figure 4.

Figure 2. 4950th Test Wing C-141A

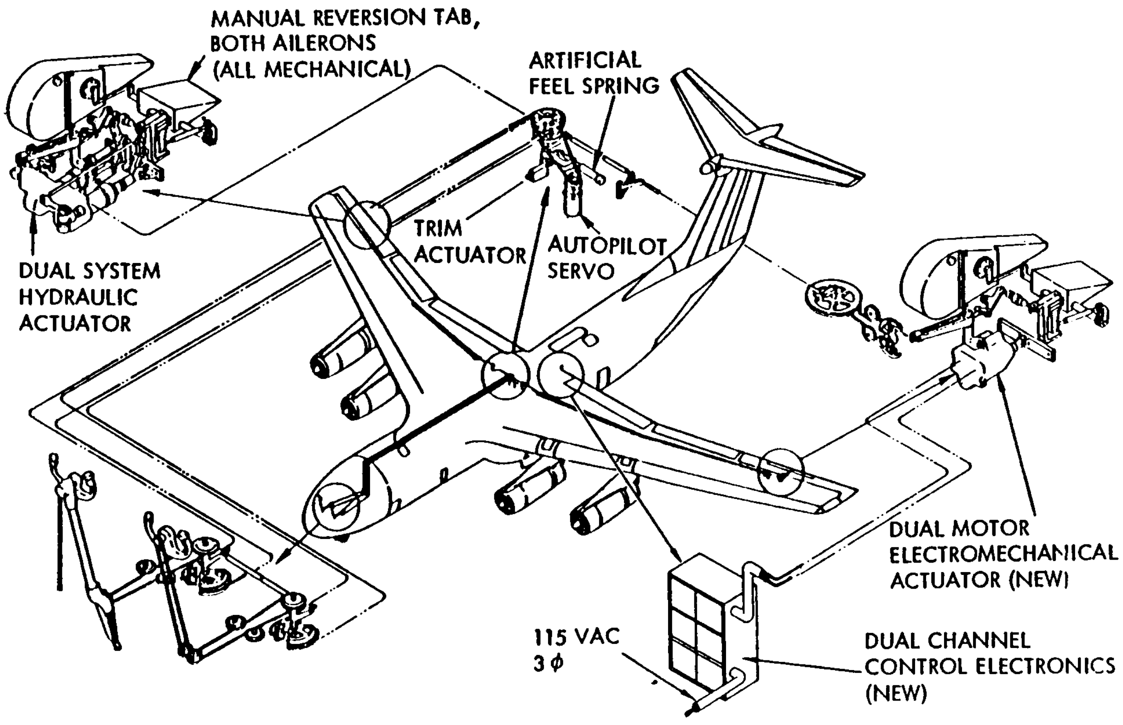

Figure 3. Modified C-141 with One Electrically Actuated Aileron

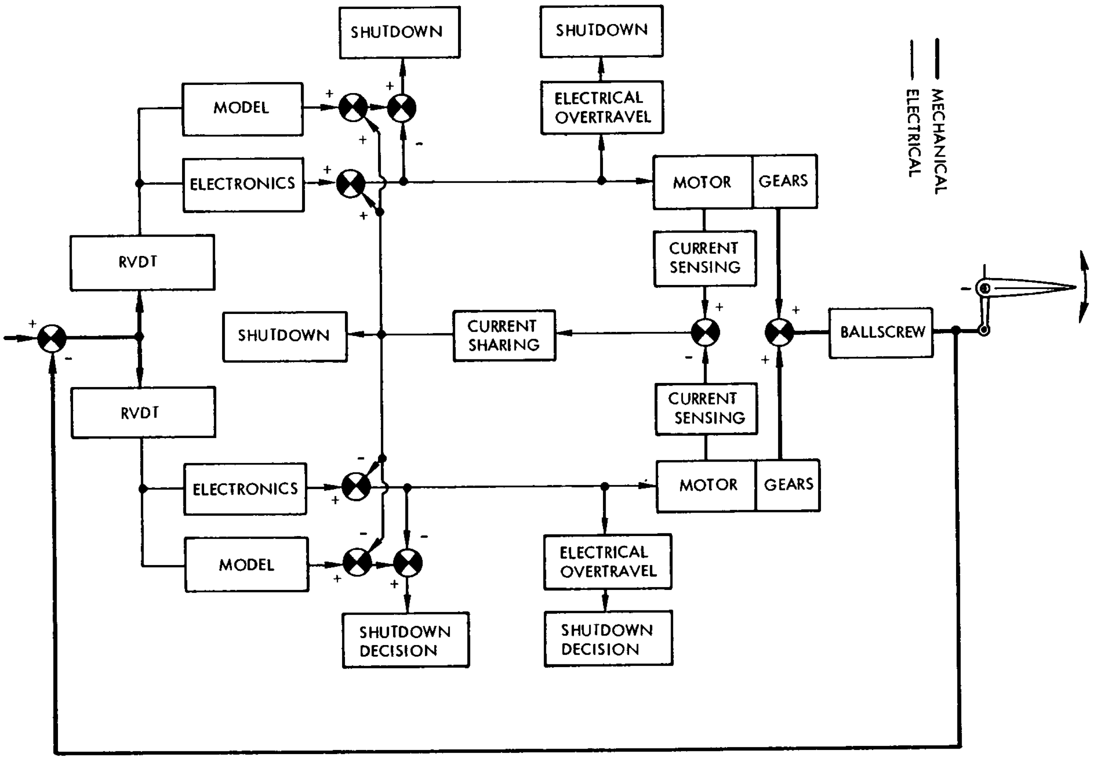

Figure 4. Dual Channel Electric Actuation System

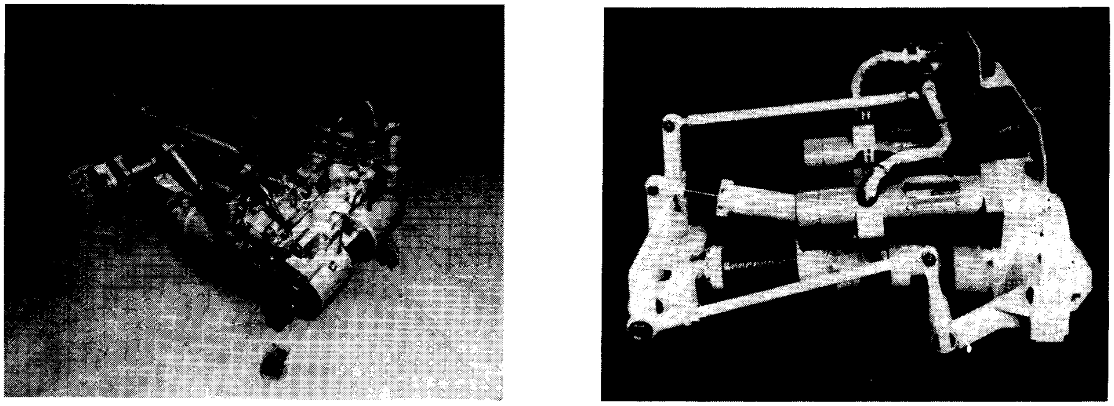

Figure 5. C-141 Hydraulic and Electric Aileron Actuators

The C-141 aileron electric actuation system is designed and fabricated as two separate but equal load sharing subsystems or channels. During normal system operation, the two channels together operate the C-141 aileron. The channels are electrically and physically separated to the greatest practical extent to minimize the possibility that a single electrical or mechanical fault will cause loss of the system.

A photographic comparison of the C-141 electric actuator vs the hydraulic actuator appears as Figure 5. A performance comparison is tabulated in Figure 6.

	ELECTRIC	HYDRAULIC
o MAX OUTPUT FORCE	19,050 LBS	19,050 LBS
o NO LOAD RATE	4.65 IN/SEC	4.65 IN/SEC
o STROKE	+3.35 IN, -2.08 IN	+3.35 IN, 2-08 IN
o FREQUENCY RESPONSE	4Hz (1ST ORDER)	4Hz (1ST ORDER)
o MAX FREEPLAY	.010 INCH	.095 IN
o WEIGHT ①	60 LBS	58 LBS
o STIFFNESS	6.0 X 10^5 LB/IN	5.6 X 10^5 LB/IN
o LIFE CYCLE COST ②	$21.7M	$25.6M

① WEIGHT SHOWN REPRESENTS THE ACTUAL WEIGHT OF THE PROTOTYPE "HOGOUT" COMPONENTS AND INCLUDES THE STEEL YOKE ADAPTER REQUIRED FOR A "DROP-IN" REPLACEMENT INSTALLATION. A PRODUCTION VERSION IS ESTIMATED TO WEIGH 35 LBS.

② BASED ON 100 AIRCRAFT, FOR 20 YEARS, FLOWN 1000 HOURS/YEAR, IN MILLIONS OF 1983 DOLLARS, REFERENCE 10.

Figure 6.′ Performance Comparison

The flight test program was highly successful. The system was totally compatible with the aircraft:

- System operation was smooth and trouble free;
- No EMI problems (either emission or interference);
- An extensive and successful ground vibration test was undertaken to investigate resonance tendencies;
- In-flight flutter checks revealed no tendency for flutter;
- There were no thermal problems. The electric actuator ran a few degrees cooler than the hydraulic actuator in the other wing;
- Power consumption in the air during the extensive system exercises was considerably less than expected (12.5 amps max actual);
- Aircraft roll rate performance was identical to a standard C-141 as was the ability to accurately maneuver to, and hold, a bank angle;
- Pilot comment was 100% favorable indicating the electric system performance was identical to its hydraulic counterpart.

Figure 7 presents a sample of the flight test data collected. Left (electric) aileron position data may be directly compared to right (hydraulic) aileron position data. Maximum aileron travel is 25° up, 15° down. Note that on the first aileron pulse, the electric aileron slows as it approaches end of travel and this is reflected in a rounding of the wave form at the top.

This is due to electrical snubbing incorporated into the electric actuator system circuitry to slow the actuator as it nears its mechanical stops.

This did not result in any differences in airplane handling qualities and probably would not be incorporated into a production design.

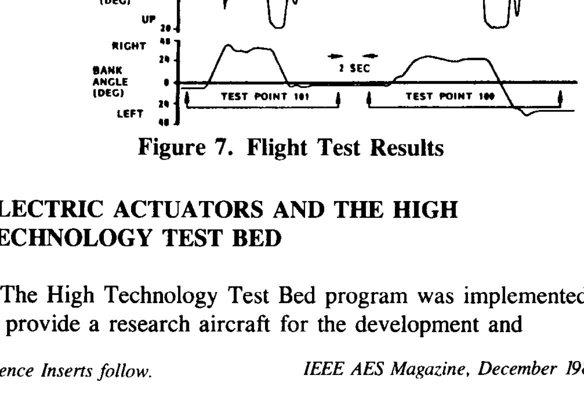

Figure 7. Flight Test Results

ELECTRIC ACTUATORS AND THE HIGH TECHNOLOGY TEST BED

The High Technology Test Bed program was implemented to provide a research aircraft for the development and

Foreign Technology and Conference Inserts follow.

evaluation of aerodynamic, avionic, and flight control system concepts which relate to the following technology areas:

- Advanced Assault STOL Capability
- Aircraft Survivability
- Advanced Flight Station
- Integrated Controls and Avionics

The HTTB is basically a stretched C-130 aircraft and is shown in Figure 8. The program provides participating suppliers with useful design, maintainability, and reliability data for new technologies and a means by which improved hardware and systems can be evaluated. Testing in this environment will bring about a more rapid maturing of the technologies required for the design and development of future commercial and military aircraft.

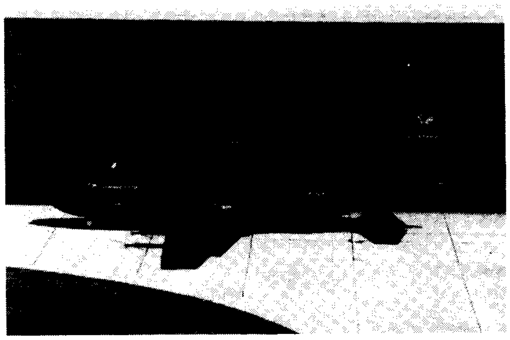

Figure 8. The Lockheed-Georgia High Technology Test Bed

The near-term goal of the HTTB demonstration program is the development of short take-off and landing (STOL) capability. The accomplishment of this near-term goal entails substantial flight control system modification, including the incorporation of rudder tab, elevator tabs, and pitch, roll and yaw stability augmentation systems (SAS). These all new systems are controlled by a triplex, MIL-STD-1750A based, digital flight control computer (DFCC) with DFCC commands transmitted by redundant MIL-STD-1553B data buses. The systems feature "smart" electric actuators developed by Sundstrand and DFCCs built by Sperry. The DFCCs compute the control laws, manage the system operational status (failure and redundancy management), and output the appropriate position and mode control commands to the electromechanical actuation systems.

Each actuator is locally controlled by its own microprocessor based control electronics assembly (CEA), which performs commutation control of the motor, positional control of the output shaft, power up confidence testing, and continuous monitoring of the actuator's health: so-called "smart" actuation systems. Figure 9 is a block diagram of the all-electric actuation system including the DFCC interface. Figure 10 is a photograph of the linear electric tab actuator, the rotary SAS actuator and a control electronics assembly (CEA).

The tab surfaces replace the C-130 trim tab surfaces and have two primary functions:

- The tabs are geared to the primary control surfaces in order to generate aerodynamic control force to augment the force output of the primary hydraulic actuator. The greater force requirement comes from the expanded operational envelope of the HTTB over a standard C-130.
- In addition, the tab systems have enough control power to permit safe operation and return of the aircraft in the event the HTTB should lose all hydraulic power. Therefore the electric tab systems provide a backup to the hydraulic systems. The rudder tab has dual, linear, ballscrew drive actuators operating in an Active/Active fashion and the rudder tab system is a Fail-Faired system. Each of the four elevator tab surfaces has a single linear ballscrew drive actuator and the elevator tab systems are Fail-Locked.

The stability augmentation system (SAS) mechanization is similar to the tabs. The actuator output positions the hydraulic primary actuator control valve and augmentation is provided by the primary control surfaces. The dual rotary actuators operate as an Active/On-line pair and the SAS is Fail-Operate/Fail-Safe.

A test of the systems' health is performed during pre-flight built-in tests, which are implemented and monitored by the DFCC. Preflight built-in tests include static and dynamic control checks to confirm correct actuator operation. The power up confidence test implemented within each actuator's remote terminal complements the flight control system self test performed by the DFCC during the preflight checks.

IN CONCLUSION

And so we are almost there. The problem has been analyzed, the laboratory experiments have proved to be successful, and flight test programs are underway. Soon an aircraft will take to the air with no mechanical or hydraulic components within its flight control systems. Flight control will be all electric by means of electrical input signals (fly-by-wire) which are processed by redundant digital computers communicating with "smart" electric actuation systems.

Mr. D. T. Glass-Hooper who wrote on "The Electric Control of Large Aeroplanes" some 70 years ago would be pleased.

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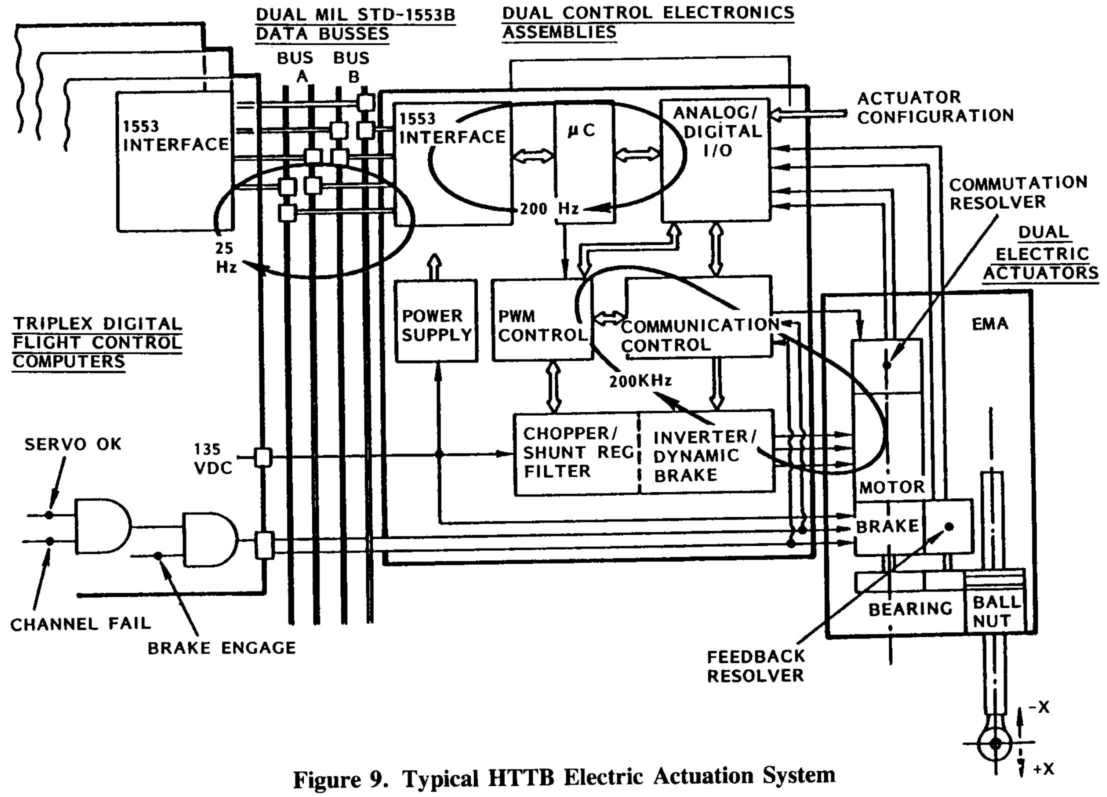

Figure 9. Typical HTTB Electric Actuation System

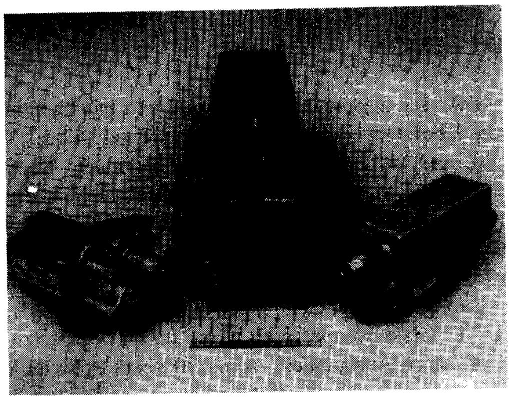

Figure 10. HTTB Electric Actuators and Controller

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