Electronics Take Off

Real-time testing of modern actuation systems at Moog

Modern aviation actuation applications are trending towards electric actuation technologies as an alternative to hydraulic systems. These advances have introduced complex electronics and embedded software into an industry that has been historically mechanical in nature. This change is prompting developers of these systems to seek more effective testing strategies to ensure high reliability, performance and safety in operation. Real-time testing has played a key role in the development of complex, modern actuation systems.

Moog is using dSPACE real-time testing solutions in a wide range of applications, from control electronics for traditional hydraulic actuators to real-time simulators for qualifying safety-critical flight software in redundant electric actuation systems.

Moog has been a key supplier to the aerospace industry for the last 60 years and has grown from being a high-technology component manufacturer to a leading supplier of integrated flight control actuation systems. Moog's reliable flight control systems and specialized control products can be found across the aircraft marketplace throughout the world.

Moog Aircraft Group's offerings are wide-ranging, from integrated flight control systems, such as primary and secondary flight controls, high lift, and maneuvering leading edge systems, to critical control applications such as engine control, active vibration control, weapon bays, navigation and guidance. Moog supplies products as integrated system solutions and as individual components. Moog's development capabilities include critical control products such as flight control computers and software, cockpit controls, control electronics and power drives, actuators, sensors and related components. Supporting and keeping pace with an evolving wide range of products that are critical to aircraft operation requires a modern, advanced development environment that can support demanding design and testing needs.

Evolution of Aircraft Flight Control Actuation

Flight control actuation systems are critical to enabling the flight of modern high-performance aircraft. Right from the start of the first human flight, these systems have always received specific attention. Early aircraft included mechanically linked direct pilot control, where pilot control effort moved the control surfaces. Gradually, as aircraft evolved and control surface loads increased, hydraulic power was added to assist the pilot inputs. In these systems, hydraulics linked to pilot inputs augment the control of flight surfaces. Over time, systems evolved to full hydraulic actuation to move flight surfaces. These actuation systems position the control surfaces in response to mechanical inputs from the pilot controls.

A major leap from the mechanical-hydraulic systems was the introduction of fly-by-wire actuation systems. In these systems, pilot controls pro-

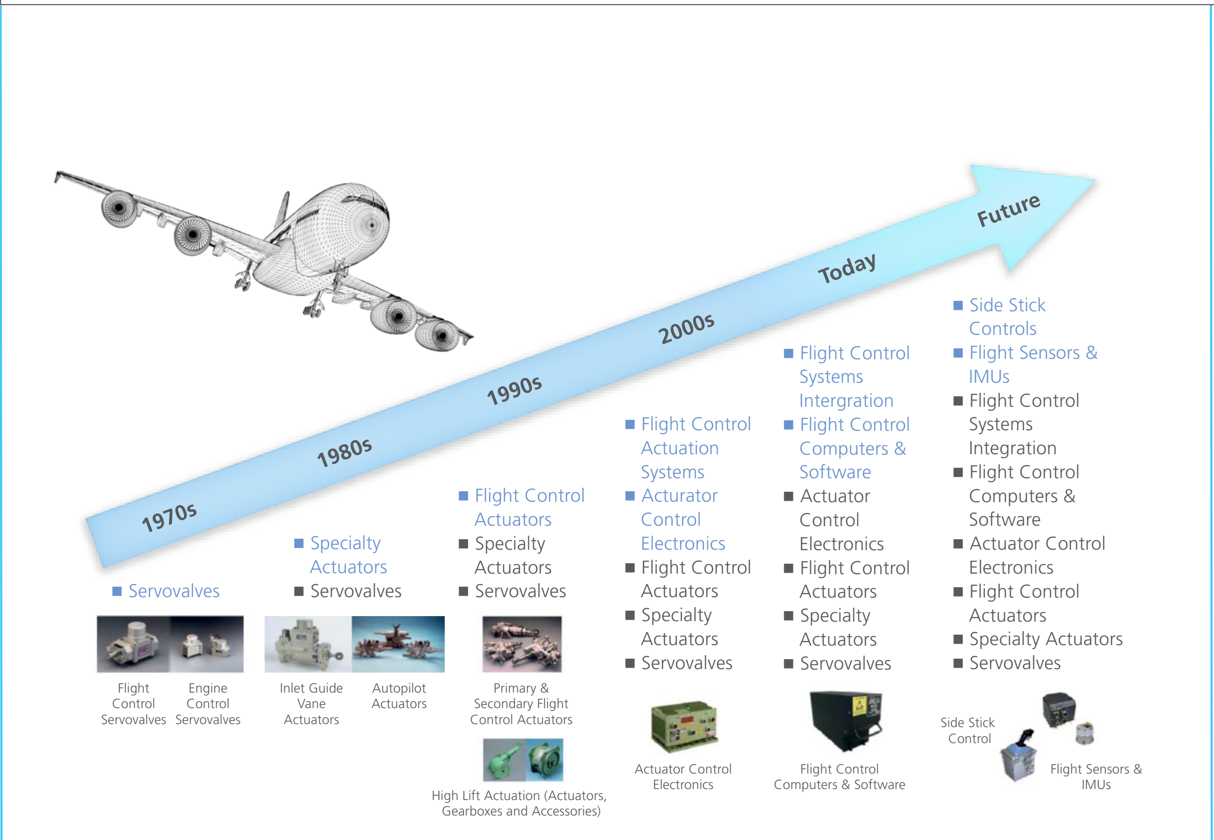

Figure 1: Moog evolution from component supplier to integrated systems supplier.

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> *David Cook, Moog*

vide inputs not directly to the flight controls, but rather to the flight control computer, which then controls hydraulic actuators with electrical signals. This was a major transition, and this type of actuation can be found in many modern aircraft currently in operation.

Further progress with actuation systems is the transition to power-by-wire technology. Power-by-wire systems are controlled and powered electrically. Pilot controls provide inputs to the flight control computer, which controls the electrically powered actuator. The command signals to the actuation systems are sent directly as electrical signals or as communication messages over a communication bus such as ARINC 429, MIL-STD-1553, IEEE 1394b, etc. Actuator controllers position the actuator in response to the commands from the flight control computer.

In addition to the above product evolution, two critical changes at the technical and business level have also had a big impact on actuation systems. The first is the aerospace industry's move toward procurement of integrated actuation systems, including controllers and actuators, from a single supplier. This results in the transfer of integration responsibilities to the supplier. As a result, suppliers have had to transform themselves from component suppliers to major systems suppliers with high-level system engineering expertise.

The second is the move towards modular distributed systems, wherein the actuator controllers are mounted directly on the actuators. This move has resulted in more electronics and software content in products that have historically been all mechanical. These changes, in addition to advances in actuator technology, have resulted in products such as electromechanical actuators (EMAs), electrohydrostatic actuators (EHAs), electric backup hydraulic actuators (EBHAs), and hydraulic actuators with integral control electronics. The use of electric-powered actuators located in unpressurized aircraft bays has also required actuator suppliers to develop expertise in high-altitude, high-power electronic control systems. These trends have increased system and component complexity tremendously and imposed the need for sophisticated development processes and testing capabilities.

Development Process for Modern Actuation Systems

As described previously, the evolution from actuation devices to entire systems poses additional challenges to the development process. In particular, there are challenges in the areas of requirements management,

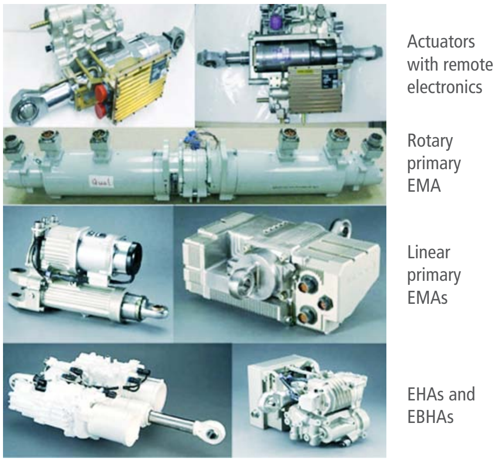


Figure 3: Aircraft actuation systems.

systems analysis and design, system integration, and system verification and validation. A summary of some of the challenges associated with actuation system development are described below.

As system complexity increases, good requirements management and traceability become even more important. In this process, it is important to break down the high-level requirements into specifics for particular components and to allocate requirements to development teams appropriately. Proper requirement allocation and flowdown are essential to ensure that the system components provide all the necessary functionality to meet the requirements of the integrated system.

Requirement traceability is also a key tool in ensuring that all system and component requirements are properly verified.

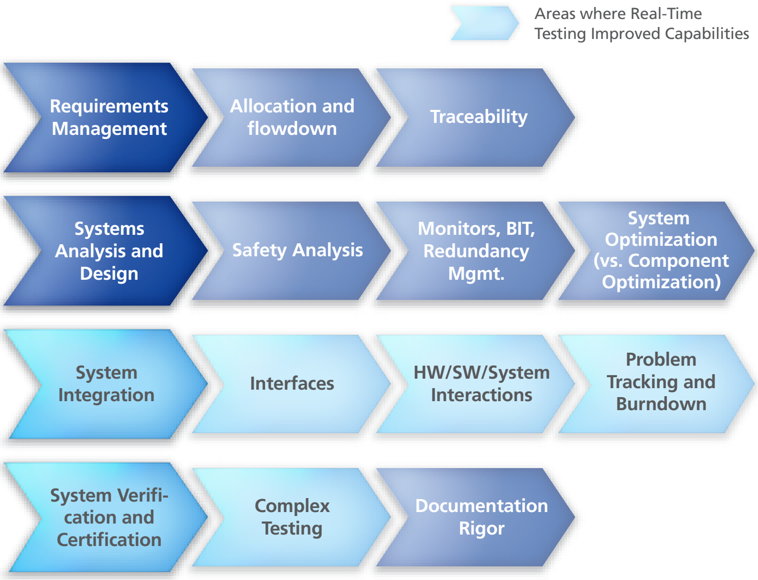
System complexity also makes system-level analysis and design more challenging. Effective system design is required to ensure that the components of the system operate in a safe manner. This often requires system monitors to detect faults, built-in tests (BITs) to determine system health, and logic to manage the operation of redundant system elements. In the design and analysis process, discipline must be maintained to ensure the focus remains on optimizing the system versus optimizing the various system components.

As system complexity increases, additional effort is required to ensure that the components function properly when integrated at the system level. System-level integration involves defining and testing how the system components will be integrated into the overall actuation system and how the actuation system will integrate with various other aircraft systems. The hardware and software components must interact to perform the necessary system functions while ensuring system safety. System integration involves managing system interactions throughout the design process and culminates with integrating the actual system in a lab environment.

Although system integration is required to get the system to an operational state, test activities must also be performed to ensure that the system does not have any unwanted or unsafe behavior.

When system problems are found, they must be analyzed, tracked, and resolved to ensure that the system operates in a safe manner and that system requirements can be satisfied.

Figure 2: Process challenges in actuation system development.



Once a system is assembled and integrated, verification activities must be performed to ensure that the system meets its specified requirements. For some projects, certification activities are required to support FAA or EASA type certification of the aircraft. Certification typically involves adherence to DO-178 for software and DO-254 for complex electronic hardware. All aircraft actuation system projects require extensive testing to verify system performance and safety in the intended operational environment.

As system complexity increases, the required testing also becomes more complex. Component-centered testing is not sufficient for verifying system requirements. Complex lab facilities are necessary to provide system stimulus and to measure system responses in order to verify the system behavior. The entire verification and certification process requires rigorous documentation to ensure that the right system is tested in the right way, and to the right requirements.

> “Moog has utilized dSPACE real-time test systems since 1991 for developments for commercial aircraft, business jets, unmanned aerial vehicles, and more.”
>
> *David Cook, Moog*

Role of Real-Time Testing / Benefits

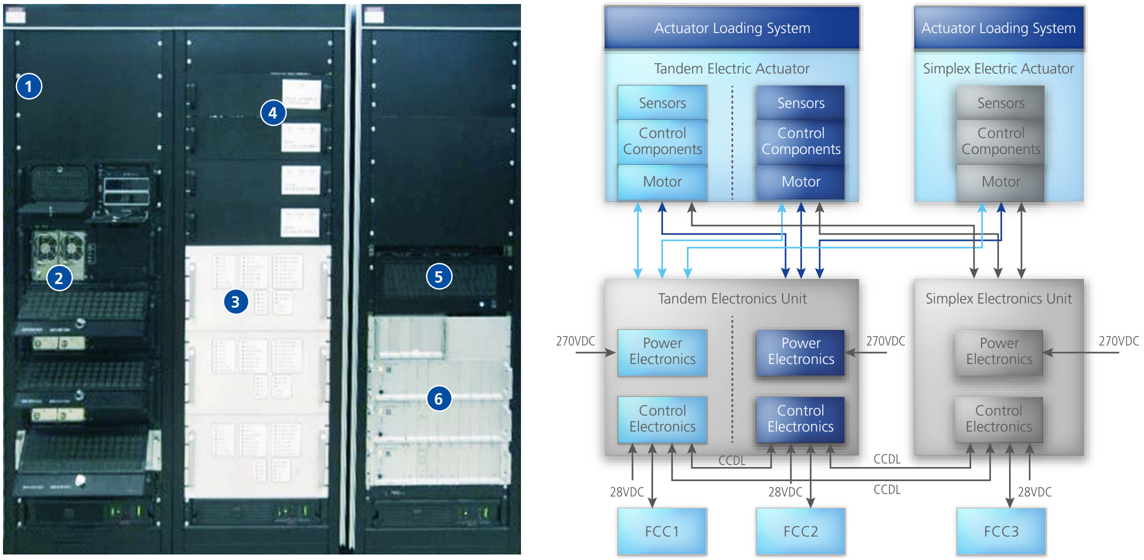
Of the mentioned challenge areas, system integration and system verification have the potential to benefit from the use of automated real-time test systems. Because of this, Moog uses these systems in a variety of roles throughout the development process. Some examples of applications with real-time systems are shown in the table below.

Model-based real-time simulation systems have helped increase the flexibility of Moog’s test systems. Moog utilizes real-time test systems to emulate controllers when testing actuators, to emulate actuators when testing control software, and to test integrated systems by emulating the system inputs and measuring the system responses. Additionally, the automated testing capabilities enable complex test sequences to be executed in a repeatable and deterministic fashion. This makes it possible to quickly run regression tests for system modifications and variants. The automation and deterministic real-time systems also enable the creation of difficult test conditions in lab environments. In particular, this allows more complete and thorough failure mode and effects testing (FMET). For example, the simulation of actuator failure conditions allow the testing of actuator-related fault detection algorithms without costly test hardware. These features improve the overall testing capability and result in significant cost savings. Moog has utilized the benefits of the real-time test systems offered by dSPACE since 1991. First applications of the dSPACE test systems were for actuator products for a large commercial aircraft. Since then, Moog has utilized dSPACE real-time systems on a variety of projects and in a variety of roles. Moog currently has 20-30 test systems that are still being used for new applications. dSPACE real-time test systems have been used for aircraft programs, including V-22, F-117, B-2, X-35, F-35, A400M, KC-46, 787, A350 and various other UAV, biz jet, and commercial aircraft programs.

Testing Role	Application	Example
Actuator Controller Emulation	■ Actuator acceptance testing ■ Actuator qualification testing	■ Emulation of FCC actuator control laws for actuator acceptance and qualification testing.
Test System Control	■ Various forms of testing	■ Control of dynamic loading system for actuator or system testing
Controller Prototyping	■ Component development testing ■ Actuator development testing	■ Providing control loops for valve testing. ■ Control prototyping for actuator R&D.
Actuator Simulation	■ Component development testing ■ Software and system integration and verification testing	■ Actuator simulation for component level testing (EHA pumps) ■ Simulation of mechanical and electrical elements for system or software testing
External System Simulation	■ System and software integration and verification testing	■ Simulation of flight control computer for integration and verification testing

Figure 4: Real-time testing role and benefits.

Figure 5: Aircraft with Moog actuation systems tested with dSPACE.



① Bays for Control Electronics
② Computers with Real-Time Hardware
③ Break-out Boxes (Pull-Out Bays)
④ Failure Insertion Units
⑤ Real-Time Computer for Control of Test Lab
⑥ I/O Signal Conditioning

Figure 6: Left: System software workstation for electric actuation system.
Right: Use of the workstation for testing a triple redundant, electric-powered actuation system.

Application Examples:

The following are three examples of applications where Moog has employed dSPACE-based real-time test systems in the development of complex actuation systems.

1. System Software Workstation for Electric Actuation System

The first test system (figure 6) is used for testing a triple redundant, electric-powered actuation system. The test system provides testing capabilities for software verification, as well as for testing the integrated system. It serves as a hardware-in-the-loop platform for software testing, and provides measurement, control, and data acquisition for integrated system testing. For software testing, the system provides real-time simulation of power electronics and actuators of the triplex system.

The test system contains seven DS1005 processor boards in a multiprocessor configuration installed across five rack-mounted chassis. The hardware also includes three IEEE 1394 buses with fault injection capability, and three proprietary CCDL buses. High-performance motor models are executed at a rate that exceeds 30 kHz to provide real-time feedback to the motor control software. There are just over 780 I/O channels in this system.

The simulator functionality is used for software testing and for system testing with difficult-to-implement faults. Automation allows running these tests in batch mode, unattended or with remote monitoring. By simulating the plant, it is possible to conduct software testing in a representative closed-loop environment. The high fidelity simulation in this test station also reduces the time required in the system lab for problem resolution. Utilizing an automated software test environment has reduced software verification time from two weeks to two days per system configuration.

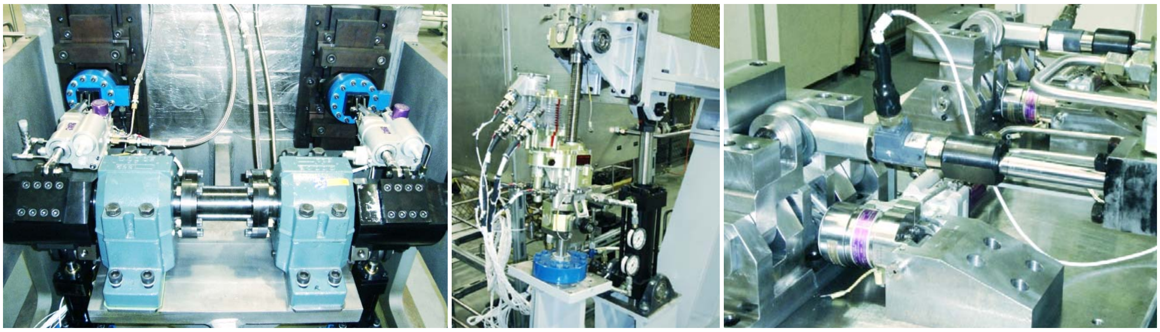


Figure 7: Actuator test rigs for testing commercial flight control systems (left: rudder actuator test rig; middle: HSTA test rig; right: spoiler actuator test rig).

2. System Software Workstation for Commercial Flight Control System

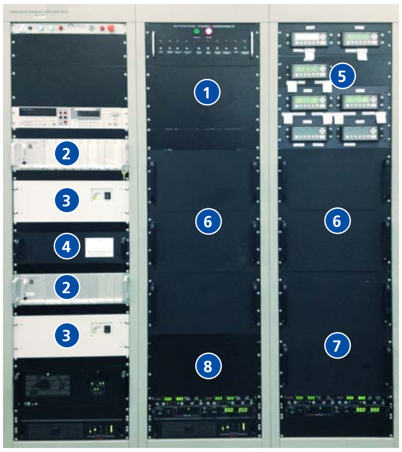
The second example (figures 7-9) is a test system for a flight control system used on a commercial aircraft. Similar to the previous application, this test system also provides a single platform for testing the integrated system and for software verification. It provides capabilities to test with real components, simulate individual components, or simulate the entire system. This system also includes the ability to use real pilot controls or to simulate control inputs for repeatable testing. The test lab includes a variety of actuation hardware and associated actuator test rigs. Various actuator rigs are connected to the test system. The test system provides control and monitoring of actuator test rigs. Examples of the test hardware and test rigs are shown below.

The flight control system in this application also includes controls for the high-lift surfaces on the aircraft. The high-lift test rig, as shown below, includes hardware for one wing. The other wing is simulated with a load motor and real-time control. By doing this, it is possible to reduce the required lab space for test equipment. This setup allows complex failure scenarios to be tested that are difficult to achieve with real hardware.

This system is comprised of two PX20 chassis, with seven DS1005 processors in multiprocessor configuration, 16 Tx/Rx channels of ARINC 429, relays to switch between simulated or real hardware, and almost 400 I/O channels.

The system provides fault injection capability and the ability to use various test rigs in the test environment individually or as a system. Automated testing allows for formal verification of software and system requirements. This representative closed-loop environment provides an effective development and certification platform for the integrated system and the embedded software.

Figure 8: Left: Pilot control station with representative controls and related flight control hardware.
Right: High lift test rig for commercial flight control systems.



1. Motor Control for High Lift Sim
2. Simulator I/O Conditioning
3. dSPACE PX20 Expansion Boxes
4. Relay Controller
5. Load Control for Test Rigs
6. FIU/Switch Relays
7. Simulator Loads
8. ARINC Interconnect

Figure 9: Test system hardware for commercial flight control systems.

3. Virtual Electro-Hydraulic Actuator (EHA) for Pump Testing

This system (figure 10) provided a unique test capability for use in the development of pumps for flight control EHAs. Intermittent duty, reversing motion and loads, and high accelerations are some of the unique demands that flight control EHAs impose on hydraulic pumps. Derivation of pump duty cycles from actuator level duty cycles can have significant uncertainty. Therefore, for risk mitigation testing of a new EHA pump, a virtual EHA was modeled and realized in a test system for pump life testing. The system provided a test environment that was representative of what the pump would see during operation in the actuator. Use of a real-time test system with virtual EHA removed many of the uncertainties associated with pump characteristics over life and provided accurate and meaningful test results. ▪

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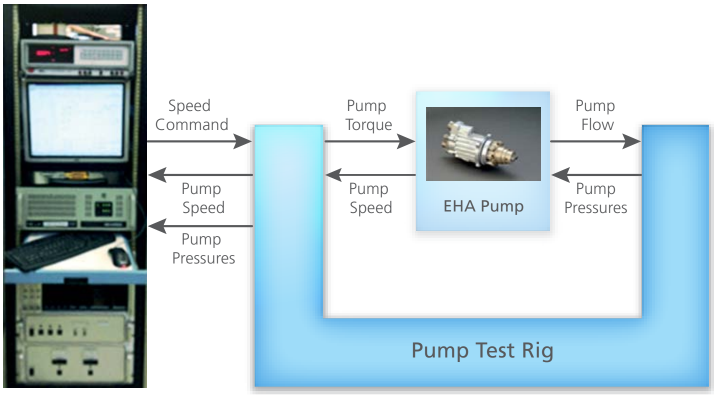
Figure 10: Test environment for electrohydrostatic pumps.



Summary

Modern actuation system complexity has increased tremendously with the integration of electronics and software with actuation devices. The move to electric-powered actuators has made motor control technology essential to the development of modern actuation systems. These advances pose additional challenges to those developing modern flight control actuation systems. Real-time test systems, based on dSPACE technology, have provided unique test capabilities that have enabled Moog to meet the demanding test requirements associated with the development of modern complex actuation and flight control systems.

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