New Actuators for Aircraft, Space and Military Applications

F. Claeyssen[1], P. Jänker[2], R. LeLetty[1], O. Sosniki[1], A. Pages[1], G. Magnac[1], M. Christmann[2], G. Dodds[3]
(1) CEDRAT TECHNOLOGIES, MEYLAN, FR ; (2) EADS, MUNICH, DE; (3) EADS, Filton, UK

Abstract:
Actuation is used in all vehicles (aircraft, spacecraft, ground vehicles, etc) to control the position and/or attitude of the vehicle, and also to deploy or retract equipment, particularly for embedded optic instruments (cameras, telescopes). As such, the actuation is a safety critical system, particularly when humans could be catastrophically affected by failures within the system. Applications for actuation are flight controls, landing gear, rotors, suspension, antennae steering, valves, scanning, positioning using hydraulic, electromechanical, magnetic and piezo actuators. In aircraft there is a common goal to reduce the number of hydraulic actuators in vehicles and eventually to replace them completely by electric actuators. The interest for smart suspensions is pushing magnetorheological fluids (MRF) actuators. In UAV, MAV and microsatellites, actuators key drivers are often miniaturisation and low power. Embedded optic & space instruments are leading to improved piezo actuators and motors.

Keywords: actuation, smart materials, piezoelectric, noise & vibration reduction, space qualification, aerostructures, UAV, MAV

Introduction

Actuation is more and more used in all air, space and defense vehicles (Aircraft, helicopters, spacecraft, ground vehicles, robots, MAVs, UAVs …) to position parts (ex mirrors in telescopes), deploy or retract equipment (ex antennas) and to control the position and/or attitude of the vehicle (ex flaps in helicopters). Actuation is very often a safety critical system. In a satellite with an embedded observation telescope, the mission can be lost for example if just milligrams of dust due to an actuator contaminating the optics. The case is even more critical in aircraft as humans could be catastrophically affected by failures within the system.

In spacecraft, space robots, unmanned areal vehicles, small actuators are strongly demanded on one hand because they allow the structures to become 'smarter' or 'adaptronic'. On the other hand, the added mass and failure risks they induce are not acceptable, which strongly pushes the actuator technologies to improve. These needs lead to a competition between two types of technologies: On one side, there is the conventional electromagnetic actuation, including the Electro Mechanical Actuators (EMA) and Direct-drive electro-magnetic actuators. On the other side there are the smart materials actuators. Both types are making progress and showing advantages and limits, which are discussed through recent developments in the section 'Smart actuators for space and defense'.

State-of-the-art actuation systems of aircraft or rotorcraft are currently based on hydraulics. Future flight control system architectures will be based on "More Electric" or even "All Electric" concepts promising benefits mainly in terms of efficiency and weight and reduction of maintenance. Electric actuation is gaining considerable momentum competing with conventional hydraulic systems. However, the big challenge in designing electromechanical actuation systems is to achieve both quantifyable improvements and compliance with the stringent requirements in terms of environment, operational reliability and safety.

This review paper illustrates ongoing research activities by two application cases: aircraft flap actuation system for secondary flight control, and swash plate actuation system for rotorcraft primary flight control.

The paper explains the basic design methodologies which are rigorously based on safety and performance. It sketches common techniques in aerospace for actuation systems designs.

Smart actuators for space and defense

EMAs are the most commonly used actuators in space applications. They are based on a rotary electric motor and gears to transform the motion from rotary to linear. They offer a high force-to-mass ratio and holding torque at zero speed. However they may have some limitations such as in positioning accuracy. For example, the CHECAM screw/nut autofocus mechanism for Mars MSL [1] is a COTS Micos translation stage based on a Phytron 2-phase stepper motor and a leadscrew. Its mass is 272gr. Its stroke is 15mm with a positioning precision of 5μm after qualification. Because it was not initially designed for a space application, several problems were met during the project and were solved by customization: Backlash of 30μm in the leadscrew, variation of the resistive torque from the nut with temperature and lifetime. At the opposite extreme, a High Precision Linear Actuator [2] has been specifically designed by Sener and ESA for space, targeting Antenna reflector trimming. Their idea is to perform the speed reduction and the movement transformation in only one gear, using a harmonic drive. Its mass is 1.7kg. Stroke is 15mm with accuracy better than 10μm. Although the objectives were achieved, limitations in controllability were found: Step advances are sometime in the opposite direction to the commanded one. The Glory Solar Array Drive [3] is based on Moog motors and Harmonic Drives. The difficulties met were a 30% loss of torque due to storage and stress corrosion inside the Harmonic drive. To remove the previous micro-positioning limitation, JPL designed and tested a new linear ballscrew actuator for SIM, based on a direct drive DC motor and a precision piezo brake [4]. Motor control commutation using feedback from a precision linear encoder on the ballscrew output produced an incremental step size of 20 nm over a range of 120mm, yielding a resolution of 1/(6x10^6).

Direct-drive electro-magnetic actuators are used especially when compactness and/or high positioning resolutions are wanted. For example, a Limited Angle Torque (LAT) actuator has been designed by Cedrat for ESA for precise pointing in 2009. The angular stroke is 13° realized with full controllability, high resolution and no micro vibration. This is achieved thanks to a specific no-cogging rotary actuator based on Lorentz forces, leading to a controllable torque of 0.25Nm and a torque resolution better than 1/10 000 [5]. The main limits are a small driving torque compared to BLDC and no holding torque at zero speed. Also for precise pointing, a new approach in space consists of using multi-dof electro-magnetic bearings to provide a nano-positioning resolution [6,7]. Other magnetic actuator applications can be found in optical instruments and small equipment: Cedrat is developing for CSEM and ESA, replacing ETEL, the 30mm-stroke Voice Coil Motor for the Corner Cube of the IASI spectrometer [8,9] for METOP as well as small launch lock mechanisms (latches) for CNES.

Smart material actuators are the alternative and a more innovative approach for making high performance actuators, being often initiated by space, defence and aircraft governmental agencies, such as DARPA [10] or NASA. Smart materials are active materials that mechanically respond under a non-mechanical excitation (Electric, magnetic, thermal, …).

A first family of smart materials actuators is the Induced Strain Actuators (ISA), which use the strain of the smart materials to cause the actuator motion. Because of their analog nature, they naturally offer a high resolution on limited stroke.

Among them, Electro Active Polymers (EAP) [11] are spectacular because of giant strains (from 1% to 100% depending of their types), comparable to human muscles (that have 25% active deformation). So EAP are often considered as future artificial muscles for robots and have led to the appearance of many suppliers [12]. In practice, only a few space applications have emerged. The famous dust-wiper based on EAP [13] considered by NASA for the Nanorovers seems not used in targeted MUSES-CN mission. Conversely a good success from JPL is the shape control of a 35-meter-diameter membrane reflector for antennas using PVDF [14]. However the life time of such polymers exposed to the sun is questionable.

Shape Memory Alloys (SMA) offer high strains (4-8%) with high forces, driven by temperature changes. These SMA may compete with EAP. For example, a new dust-wiper based on SMA has passed evaluation tests for the MEIGA Mars project [15]. Other recent interesting SMA applications are an experimental mechanism embedded on the Nanosat Aggiesat1 [16] and the concept of a deployable truss [17].

Magnetostrictive & Magnetic Shape Memory (MSM) materials offer H-field-induced strains over 0.1% but suffer from a mass penalty due to the need coil. However NASA has developed a high load magnetostrictive valve [18] and a hybrid piezo-MSM pointing mechanism is envisaged [19].

Piezo Induced Strain Actuators for embedded space and defense applications are generally based on low-voltage multilayer PZT piezo ceramics, also called MLA. As a major limit, these exhibit strains of only 0.1% @ 150V with generally much more force than required. Stroke amplification was wanted by space applications leading to the APA™ from Cedrat presenting a strain of 1% to 10% and qualified to their space requirements [20]. New gains of 50% for dynamic stroke [21] are indentified taking care of new non-linear effects. Recent applications of piezo actuators by Cedrat for space and defense are presented in [22]. They cover micro-positioning, pointing, scanning, damping [23] and are used in various optical instruments, cameras and defense equipment. Double stage amplification is a way to remove piezo strain limits: A new 12mm-high actuator, based on APAs generates a stroke of 2.5mm with force of 1.7N [24]. This piezo actuator exhibits a spectacular strain of more than 20%. Therefore it is considered as a new ‘piezo muscle’, competing with EAP for robotics. The main limit of this type of actuator is its low stiffness, which reduces the system bandwidth.

A second family of smart materials actuators is the Piezo motors. These are based on the accumulation of small steps produced by piezo actuators under quasi static, harmonic or transient excitation. By this method, the stroke limitation of piezo ISA can be removed.

A Piezo Motor from PI is selected for the LISA Caging mechanism, to perform a smooth actuation. This is well achieved but tests by RUAG have identified some difficulties [25]. For example, the motor generates wear debris, which is a typical limitation of most piezo motors. A piezo motor from Piezomotor is used for a tilt mechanism in LISA [26]. The new small piezo motor, SPA, from Cedrat [27] is also involved in space applications.

Magneto Rheological Fluids are fluids which also solidify under the influence of magnetic fields. They are considered in space and defense for making damped latches as well as controllable suspensions and landing gears [28].

Novel actuators for aviation – technical challenges of EMA

One peculiarity of electromechanical actuators (EMAs) compared to well established and field proven hydraulic actuators is that the mechanical jam of an electromechanical actuator has to be considered as a credible failure. The probability of occurrence of these failures is greater than 10-8 per flight hour. This is due to the fact that EMA operation relies on mechanical components not being certified as critical parts – and thus not being trusted never to fail – e.g. ball screws or roller screws, respectively. In a conventional rotorcraft swashplate actuation arrangement comprising three actuators, the jamming of any one of those actuators would be catastrophic. Therefore the system has to be designed jam-tolerant – either by conceiving an appropriate actuator arrangement or by providing highly available, jam-tolerant actuators.

It is common practice in aerospace to apply techniques of redundancy to solve the problem to satisfy the safety requirements [29,30]. For proper fault isolation one may also have to apply additional safety devices, e.g. power-off brakes and disconnect devices.

Application examples

Swashplate actuation system

The swashplate system of a helicopter provides lift, pitch and roll control for primary flight control. The loss of any of these control functions is classified catastrophic mandating a very robust and fault-tolerant design of the 3-degree-of-freedom swash plate actuation system. When using EMAs, the system must be fail-operative regarding major mechanical failures, and dual-fail-operative for all other failure modes whose probability is not extremely remote [31]. Figure 1 shows an exemplary swashplate assembly. The upper part including the rotor blades, the pitch links (red), the rotor hub (centre) and the inner part of the swash is rotating while the outer part of the swashplate and the actuators (rods below the swash plate) are static. The swash plate can translate along the rotor hub axis and tilt around two axis perpendicular to it.

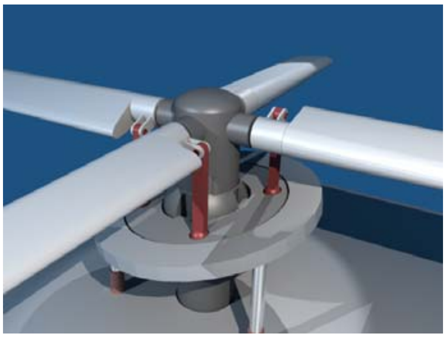


Figure 1 : Schematic of a helicopter swashplate

Trailing edge flap actuation system

The high lift system of large transport aircraft comprises leading edge slats and trailing edge flaps, which are deployed during take-off and final approach, providing additional lift to get or stay airborne at low speeds.

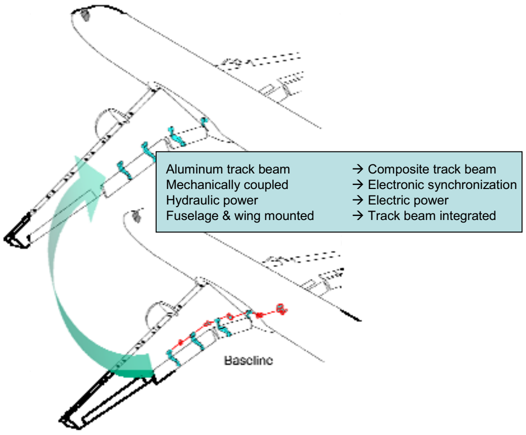


Figure 2 : Schematic of distributed support structure integrated electric flap actuation system

Symmetric flap actuation on both wings is paramount for safe flight and is traditionally assured by coupling all flap surface actuators to a torque shaft system, which extends along the rear spar of both wings and is driven by a centralized hydraulic, electric or hybrid motor. The actuators are located at or near special flap support structures which transmit the lift produced by the movable flap surfaces to the wing.

In an alternative approach offering improved operational flexibility and an increase in fault tolerance, a distributed electrical flap drive system has been developed that is integrated with the flap support structures [32, 33, 34]. A schematic of this new approach as well as the key changes with respect to conventional technology is displayed in Figure 2.

Actuation system techniques

Fault tolerant actuator arrangements

One peculiarity of EMAs is the lack of field experience for safety critical flight control applications with the consequence that actuator free wheel or jam failures have to be considered as credible failures. This necessitates designing redundancy into actuation systems of such safety critical applications. There are in principal two different ways to address this issue:

⇒ Control surface redundancy might contribute to the resolution of safety requirements. For example, many large transport aircraft have split elevators and ailerons so that one jammed surface might still allow controlled and safe return and landing. However a surface free wheel may still result in a flutter condition (unstable aerodynamic effects causing an oscillation of the surface with virtually no damping) and structural failure.

⇒ Actuator redundancy: Redundant actuators ensure continued safe operation of the control surface (primary flight control) or the system can be transferred into a safe state after detection of a failure (e.g. high lift devices, horizontal stabilizer trim)

For the helicopter swashplate application example there is no control surface redundancy and thus the actuator redundancy approach has to be applied. As there is no safe static state of the swash plate the actuation system has to ensure continued safe operation in all three degrees of freedom after any credible failure on an actuator. A set of possible actuation arrangements emerging from a top-down approach is shown in Figure 3 – Serial, Parallel, and Grouped positioning of the actuators. They all rely on the basic idea to provide jam tolerance by means of redundant actuators, whereas their operation philosophies differ substantially.

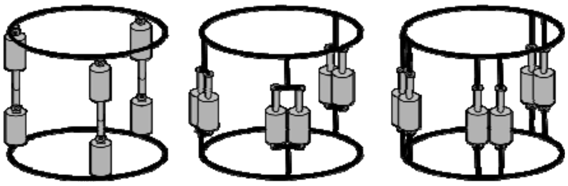


Figure 3 Serial, Parallel, and Grouped concept

The failure management of all three concepts relies on the fact that each actuator is capable of compensating the performance of a faulted adjacent actuator. As to the Serial and Parallel arrangement, the mechanical jam of a single actuator can be tolerated. However, a free wheeling actuator would result in the free wheel of one of the three legs and in consequence in the loss of control of the entire flight control system. To avoid this scenario an additional power-off brake is required as a safety device blocking the screw of the affected actuator.

Since each of the six EMAs of the Grouped concept has its own attachment point at the swashplate, a free wheel could be compensated, whereas a mechanical jam would be catastrophic. Thus each actuator must be equipped with a disconnect device mechanically converting the jam into a free wheel.

For the trailing edge flap actuation example a safe system state is one with the flap system stopped and held in a defined and symmetric position. In this configuration the aircraft can continue to fly (although in a restricted envelope) and make a safe landing – probably at increased speed and/or angle of attack. However the probability of entering this degraded or inoperative state may not exceed 10^{-5} per flight hour, requiring some redundancy in the electrical components. Thus the resulting system and system architecture looks quite different from the aforementioned example (Figure 4 and Figure 5).

The mechanical drive train is designed as dual load path. Only the primary load path (blue in Figure 5) is can operate the flap whereas the secondary load path (green) is only designed to stop it in a given position through a purpose built power-off brake.

Using a conventional actuator topology, any failure of the motor, the associated power stage and control electronics, the feedback sensors or the brakes (failure to disengage when commanded) would result in the flap being inoperative and stopped with a total probability exceeding 10^{-5} per FH. For the example application this problem is addressed by a fault-tolerant electric motor and power stage, and by applying redundant control channels and feedback sensors. The brakes feature two solenoids and associated power stages which can both independently disengage the brakes. To provide an absolute position signal that is not lost after a power interrupt, a two-channel geared multi-turn angular position transducer is applied.

It should be noted that on top of providing redundant components, the system also has to be capable to localize and isolate a failure for continued safe operation. After a second failure a safe transfer to the inoperative state is acceptable – but this still means that e.g. a false sensor reading has to be identified as such.

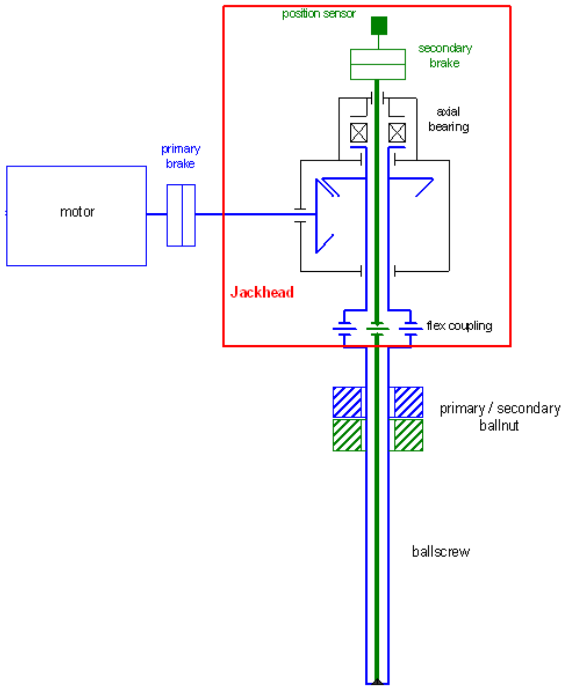


Figure 4 : Principal actuator arrangement for one support station of the trailing edge flap system

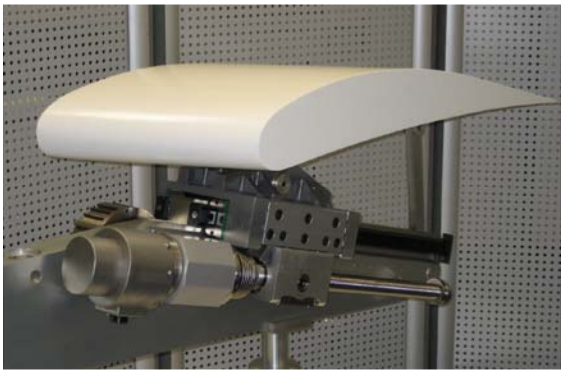
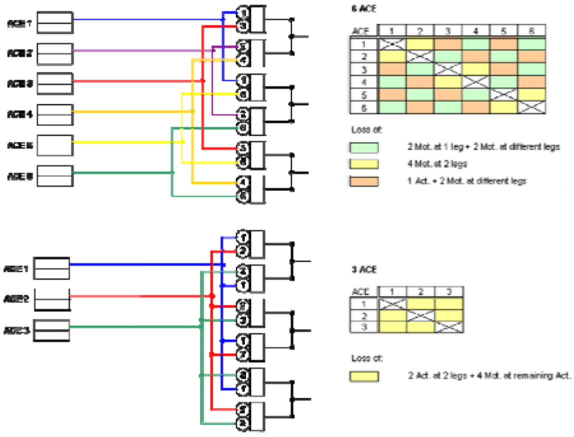


Figure 5 : Trailing edge flap actuator prototype

Optimizing redundancy

The required number of redundant components in safety critical actuation systems can easily be determined by combining the quantified failure modes of mechanical and electrical components with simple Markov models.

As to the helicopter swash plate, this analysis indicates the need for at least two electric motors per actuator, i.e. at least 12 electric motors for the actuator arrangements displayed in Figure 3. Each of them needs its associated power stage. A straightforward approach would require the same amount of Actuator Control Electronics (ACEs) each providing two lanes (command and monitor) to facilitate failure detection, i.e. 24 computer lanes in total, with the corresponding negative implications on weight, cost and MTBF (mean time between failures). However, the command functions can be integrated in a reduced number of ACEs while still complying with the safety requirements. The reduction potential is assessed by means of a permutation analysis. Figure 6 shows two examples for the Serial and the Parallel concept (identical control architecture) with the vertical rectangles and the adjacent circles representing actuators and motors.



6 ACE

ACE	1	2	3	4	5	6
1	☒	🟨	🟧	🟩	🟧	🟩
2	🟨	☒	🟩	🟧	🟩	🟧
3	🟧	🟩	☒	🟨	🟧	🟩
4	🟩	🟧	🟨	☒	🟩	🟧
5	🟧	🟩	🟧	🟩	☒	🟨
6	🟩	🟧	🟩	🟧	🟨	☒

Loss of:

🟩 2 Mot. at 1 leg + 2 Mot. at different legs
🟨 4 Mot. at 2 legs
🟧 1 Act. + 2 Mot. at different legs

3 ACE

ACE	1	2	3
1	☒	🟨	🟨
2	🟨	☒	🟨
3	🟨	🟨	☒

Loss of:

🟨 2 Act. at 2 legs + 4 Mot. at remaining Act.

Figure 6 : ACE permutation

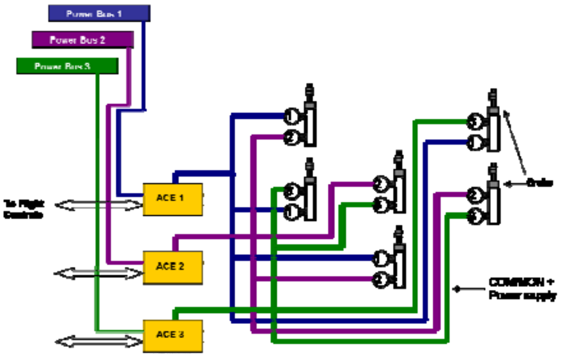


Figure 7 : System architecture of Serial concept

Using six ACEs, three different degraded modes are possible after the failure of two ACEs. Reducing the number to a total of only three ACEs and applying the proper mapping of ACEs to electric motors, just one scenario has to be taken into account. Even though component losses are more severe than for the events relying on more controllers, safety requirements can still be met – and at a better system MTBF due to lower parts count.

Design load assessments considering the relevant failure cases of all concepts reveal that a reduced number of ACEs results in significantly increased motor and actuator loads for some of the variants and permutation mappings, whereas it does not have any effect on the design loads for others. Thus, the benefits in terms of mass and cost reduction achieved by the reduced number of ACEs can be fully exploited for the latter. Whereas for the first group of system architectures, these benefits have to be traded against the increased design loads of power electronics, motors and actuators and their implications. An exemplary system architecture for the Serial arrangement is shown in Figure 7. It is apparent that the utilization of a reduced number of ACEs is reasonable for this design variant. Relying on the shown permutation, the system is capable of surviving even two arbitrary component failures (except a jam).

In the trailing edge flap application example, a different approach was used to reduce the negative impact of providing redundancy on actuation system weight. The technology of internally redundant electrical motors and motor drive electronics was applied there [35, 32, 33]. In this case the electric motor can continue to operate in a degraded performance mode after a fault in the motor itself or in the power stage.

Safety analysis

In order to quantitatively prove compliance with the certification specifications, safety analysis in terms of a Fault Tree Analysis (FTA) has to be performed. For the helicopter swashplate application example a combination of FTA and Markov models according to the standard EN 61025 can beneficially be applied to simplify the fault trees significantly. All actuators being identical in terms of components and operation, it is sufficient to model a single actuator and to insert a Markov model above acting as a multiplicator.

The safety analysis proves the required system availability to be achieved, and identifies the weak spots within the architecture. For each of the investigated swashplate actuation system concepts, the particular safety device, i.e. the power-off brake or the disconnect device, respectively, turns out to be by far the most critical component. Two main requirements emerge from the analysis.

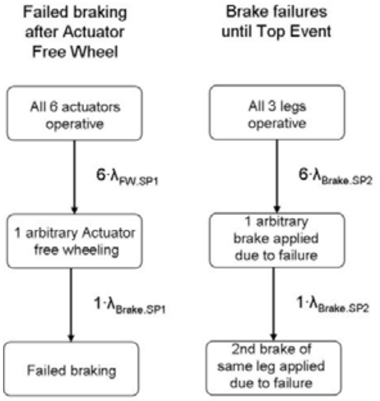


Figure 8 : Markov model for safety device requirements

First, the respective safety device may not fail in case it is needed. For instance, the power-off brake of one actuator in the Serial arrangement may not fail to engage if both motors of this actuator failed. Second, the safety device must not unintentionally be activated. E.g. two unintended brake engagements at the same leg of the Serial concept would be catastrophic. Figure 8 shows the according Markov models for the described scenarios.

Conclusion

Because of very stringent requirements, space and defense are still driving the development of high performance actuators. Conventional actuators like EMAs based on harmonic drives and direct drive magnetic actuators continue to improve. Smart materials actuators such as piezo-ISA are considered to be mature, and are being used more and more in small equipments. Other smart material actuators are still only marginally used.

"More Electric" and "All Electric" concepts are emerging which promise higher efficiency and lower system weight as well as cost benefits. Key elements for these concepts are high performing EMA systems having high level of safety and reliability.

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