Thought Leadership Article

Electromechanical Actuators Require Smart and Integrated Driver Solutions to Empower the Intelligence at the Edge

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Abstract

To empower intelligence at the edge, smart and highly integrated driver solutions are required for electromechanical actuators. Those smart edge devices merge actuator as well as sensor functions to allow for better real-time decision-making at the machine level and to provide in situ feedback information back to higher control levels, the cloud, or AI productivity solutions. This article discusses smart driver solutions and technologies where the analog and the digital intersect—at the Intelligent Edge.

Introduction

In our quest to empower more intelligence at the edge, physical edge devices such as electromechanical actuators call for more smartness to benefit from better real-time decision-making at the machine. These actuators provide smart, valuable, and rich sensor-like feedback. Such edge devices are key to Industry 4.0 and beyond. They control robots as well as manipulate and automate factory processes—transforming digital information into physical motion while offering a high level of intelligence and self-awareness.[1] While the actuators manipulate things, sensors are used to measure and quantify real-world parameters—they transfer from physical back to digital values. Thereby, actuators and sensors are mostly still considered to be separate devices or components.

Stepper motors and solenoids represent a large portion of those electromechanical actuators and are found on every factory floor, in automotive applications, in lab automation, and more. The global multibillion USD stepper motor and solenoid market continues to grow and is driven by lab and medical applications, industrial applications, and automotive applications. These applications demand an increasing focus on higher degrees of automation and miniaturization of the actuators and driver electronics. Traditional driver solutions are not tailored to these new requirements, and they lack sensing capabilities.

The latest silicon cDriver™ solutions, which consist of a smart controller and driver, enable intelligent actuators at the edge by merging sensor and actuator functions into single integrated components to be used inside embedded motion control solutions.[2,3] System parameters and state variables that are only available directly in or at the electromechanical actuator are measured and evaluated in place (for example, temperature, solenoid reaction time, and motor load value).

This fusion of sensor capabilities with the actuator yields a paradigm change for electromechanical actuators. They advance from simple power conversion systems to self-aware sensors that perfectly control the actuator and provide in situ data back to higher control levels, the cloud, or AI productivity solutions. The electromechanical unit becomes the sensor.

Electromechanical Actuators—Short Overview

Stepper motors and solenoids are used in a wide range of automotive, industrial, and healthcare applications. Both share a lot of similarities: copper coils are energized with a current resulting in mechanical movement.

Two-phase stepper motors are typically controlled by two current sources that induce 90° phase-shifted sine- and cosine-shaped currents into the two phases of the stepper motor. The currents through the coils of the stepper motor (the stator) define the orientation of a magnetic field. The rotor aligns like a compass needle in the field of the stator coil. By electrically controlling the rotation of the magnetic field, the rotor rotates through alignment in the magnetic field. Figure 1 shows the stator/rotor arrangement of a standard hybrid stepper motor and some example stepper motor types.

Figure 1. A hybrid stepper motor with 50 pole pairs (left) and different types of stepper motors (right).

Solenoids are comparable to stepper motors. A coil is energized with a current to result in mechanical movement. The moving part is not a rotating magnetic but a metal plunger resulting in linear movement. From a control perspective, there are two types of solenoid valves: on/off (switching) and proportional valves. Switching solenoids are used to realize the on/off function of pneumatic or hydraulic valves. When the coil is energized, a magnetic field is generated and the metal plunger moves in the direction of the magnetic field. While the initial current (hit current) is quite high to move the plunger, only a reduced current is required to hold the plunger in place (hold current). When the coil is de-energized the magnetic field disappears and the plunger is free to move back by an external force (spring, gravity). Figure 2 shows the typical current profile when driving a switching valve. The small dip during the current ramp-up phase (energization time) is due to the back electromotive force (BEMF) generated by the plunger movement. When the excitation time is over, the current can be reduced to a hold level to hold the plunger in place as long as needed. Proportional valves can hold the plunger in any position by controlling the energy flow and by adjusting the solenoid current. They are normally used in a closed-loop control system to control a specific system variable; for example, pressure, air, or fluid flow.

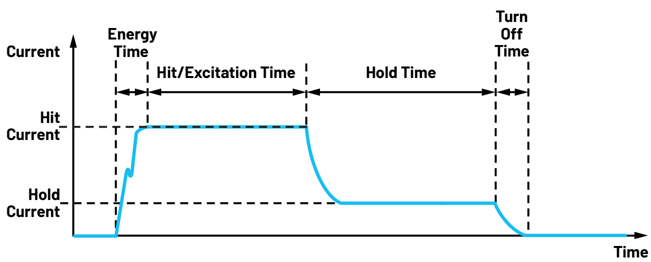

Figure 2. A switching valve's current waveform.

Why Do We Need a New Approach to Controlling Electromechanical Actuators?

Driver IC solutions available in the market today are not really tailored for solenoid drive applications and efficient and economic implementation. They lack embedded control sequencers, application-specific functions, diagnostic functions, and protection. Whenever advanced control features (driver sequencer, dithering, fast demagnetization, current measurement) or advanced diagnostic functions (detection of plunger movement[4], on/off status detection, inductance measurement, open load detection) are required the system complexity increases significantly due to the additional external workarounds and circuits needed.[5,6,7,8] The designer designs every single block (digital controller, current sensing, signal conditioning, power stages, protections) and has those interconnected. Occupation of real estate/board space, long design time, application reliability, long bill of materials (BOM), and lack of flexibility are some of the problems that designers must still face.

Let's look at several global trends that result in additional requirements and needs for embedded control and driver solutions for electromechanical actuators.

Evolution of Miniature Actuators

Ongoing miniaturization makes electromechanical actuators cost- and space-effective components in medical devices, the chemical industry, lab automation, semiconductor manufacturing, food and beverage sectors, and industrial and automotive applications. Examples of miniaturized valves and manifolds and hybrid solutions (stepper motor + solenoids) are shown in Figure 3. Sizes go down to just a few millimeters in diameter. While the benefits of miniature actuators are expected to boost the growth, these markets call for additional requirements such as a longer effective lifetime, durability and reliability, small-scale embedded controller and driver solutions due to space constraints, and simplified handling and control.

Figure 3. Miniature solenoid, manifold, and hybrid manifold examples (image source: with permission by Lee Hydraulische Miniaturkomponenten GmbH/The Lee Company).

Enhanced Diagnostics

Electromechanical actuators are prone to degradation during long-term operation and may show other failure scenarios on the electrical side (coil problems, residual coil power, overheating, insulation failures) and on the mechanical side (partial valve closure or opening, manual override, pressure differences, dirt gathering, damaged valve mechanics, grease dry-out). These challenges affect the performance, lifetime, and operational availability of those actuators and the systems they are used in. This results in a critical demand for digitization: detailed and high quality diagnostic feedback on local system parameters for monitoring the health state of the actuator and its control electronics, for better decisions at the local machine level to react to changes and to communicate diagnostic information preprocessed or as raw data from the edge to the higher control levels. Feedback and diagnostics beyond simple driver error flags are required!

Energy Efficiency

The carbon footprint plays a major role today. Energy efficiency is driven by global environmental policies, cost, and application constraints. Energy is one of the most valuable global resources and the cost continues to grow. Thus, the power consumption of the actuators needs to be optimally controlled and reduced to a minimum. Another positive side effect is that solenoids or stepper motors stay cooler within the application when the power consumption is controlled efficiently. This reduces system cooling efforts and could make them usable in specific applications with hard requirements on temperature, for example in sensitive lab applications.

Time to Market

Development times need to be reduced in the same way as system complexity is growing. Highly integrated, proven, and ready-to-use building blocks and subsystems help reduce or hide the overall complexity, help reduce design risks, and thereby keep time-to-market cycles on a reasonable level.[9] System design is dominated more and more by communication interfaces and a software-centric view. Thus, active system components and building blocks are selected by the flexibility and capabilities of their communication and control interfaces.

Total Cost of Ownership

The overall costs associated with a product's whole lifecycle are commonly understood as the total cost of ownership (TCO). This does not just cover development costs or other nonrecurring engineering costs, but all direct and indirect types of running expenses: energy costs (energy efficiency), maintenance costs, operational availability, and supply chain risks. While energy costs are directly measurable, maintenance costs can be estimated upfront. In market segments with long product lifetimes such as industrial and medical applications, the TCO needs to be considered and reduced to a minimum.

Impacts of a Sensor-Actuator Fusion in cDriver

With reference to the different global trends discussed, the integration of sensor-like capabilities into cDrivers for electromechanical actuators is required. Multichip and monolithic chip-level solutions continue to emerge that not only contain the analog driver part but will also be dominated and defined by their enhanced digital functions, their sensing capabilities and decision-making, and their communication interface. This sensor-actuator fusion satisfies many needs and brings a broad range of advantages to solenoid- and stepper motor-based applications.

Evolution of Miniature Actuators: Compact Embedded Hardware Solutions

Miniature valves, manifolds, and multiaxis stepper motor applications benefit from highly integrated and embedded hardware solutions to drive and control them. If the controller and driver electronics can be the same way small and compact, the overall actuator subsystem offers competitive size reduction for space-constrained applications.

A typical embedded hardware solution for a single solenoid, a manifold, or a multiaxis stepper system consists of a bus interface for communication, a microcontroller unit (MCU) for the application control, and one or more controller/driver units as shown in Figure 4.

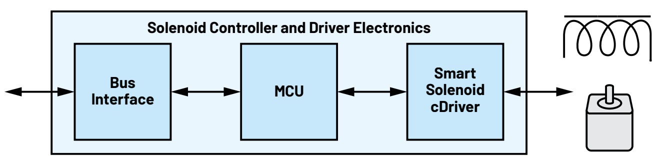

Figure 4. Typical solenoid or stepper motor controller and driver solution/high level.

The communication interface and MCU depend on the application and the overall system architecture and are typically only required once per unit. Contrary, the actuator controller/driver stage may be required multiple times for a manifold/multiaxis system and thus offers the highest potential for optimization. Typical driver implementations for solenoids also offer extended features but expose a large BOM and require much space for all the components.[5,6,7,8]

Fully integrating those extended control and sensing functions into a single component reduces the required board space to an absolute minimum. Solutions using integrated current sensing eliminate large external sense resistors and additional shunt amps for example. Low $R_{DS(ON)}$ integrated driver stages allow for best efficiency and reduce thermal losses, which again has a positive impact on the required cooling area or in critical application environments.

Figure 5 shows typical manifold examples. Space savings and BOM reductions allow for ultracompact solutions and cost savings for components, PCBs, and housing materials inside those applications.

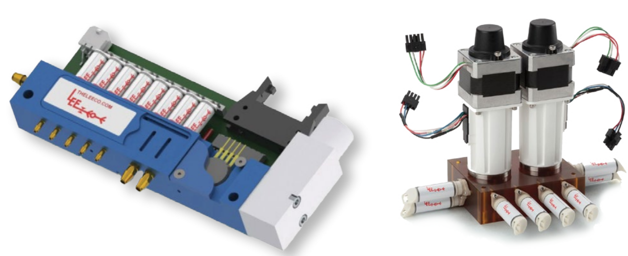

Figure 5. Example manifolds (image source: with permission by Lee Hydraulische Miniaturkomponenten GmbH/The Lee Company).

Like solenoids, the driver part is also dominating stepper motor solutions. Highly integrated stepper cDrivers allow for extreme space savings while offering superior quality control. Besides their diagnosis and feedback capabilities they come with an integrated motion controller plus the power stage[10,11] as well as fully integrated current sensing.[12,13]

Reto Himmler, Principal Electronics Engineer at Hombrechtikon Systems Engineering AG, Switzerland, confirms: "We are using ADI Trinamic™ stepper motor drivers for more than a decade now due to the industry-leading features. The TMC5240[13] is the part we were waiting for! The higher motor current, the small form factor, and the integrated current sensing help to save the rare board space in our lab automation equipment. The low dissipation caused by the low $R_{DS(ON)}$ gives more freedom for the mechanical design. The 8-point ramps are fine—even if the 6-point ramps of the existing products are already well suited for our applications."

Enhanced Diagnostics: Paving the Way to Predictive Maintenance and Self Awareness

Sensor-like data is available locally in smart cDrivers. But what can be done with this abundant set of information?

The parameters available with the smart cDriver solutions include driver temperature, information on coil resistance and temperature, coil inductance estimation, supply voltage, actual coil currents, and BEMF information. Smart integrated algorithms and functions allow for deriving system and application conditions and other system parameters like the solenoid's reaction and travel time, local current dip, open load detection, over current and short detection, detection of part closure and plunger movement, plunger displacement measurement, and real-time current monitoring. For stepper motors, the actual load information based on StallGuard™ and the level of the CoolStep™ current reduction can be read out as well.[14,15] For many applications, the StallGuard load value is extremely valuable information as long-term drifts may indicate degradation in the mechanics and gears or defective mechanical end stops within the application. The StallGuard value is directly related to load conditions on the motor shaft and can vary in the application and over time depending on motor acceleration or external forces. The StallGuard value even allows the detection of a physical motor stall before it happens. This is then useable for sensorless end stop detection or calibration in the application.

The local sensing capabilities and diagnostics and the availability of this in situ feedback pave the way for predictive maintenance and self-awareness on three different levels that are shown in Figure 6:

- Locally inside a cDriver component
- On the application level in the local MCU of the embedded subsystem
- On higher levels like factory floor, plant control, or cloud

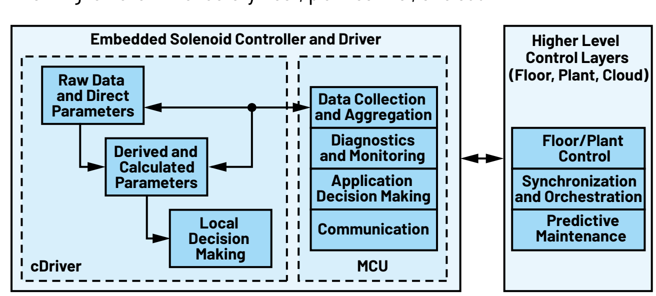

Figure 6. Sensor and diagnostic data availability and flow.

Better real-time decisions can be made directly inside the controller and driver electronics due to the local monitoring and self-diagnosis functions. These consist of configurable thermal protection limits, configurable short detection, and driver protection in case of faults, automatic hit to hold current switchover, immediate fault reporting; for example, when the solenoid's plunger gets stuck.

Using the local MCU, more elaborate functions can be implemented by interpreting the sensor-like data within the application's context. Real-time monitoring is possible via the serial interface of the cDriver. Diagnostic information and parameters are available as a stream of continuous feedback from the actuator and cDriver. This allows for more specific status monitoring, long-term failure identification, or even pattern detection. Reaction and travel time measurement, local dip search, plunger displacement, and load values: a drift of these parameters over time is a symptom of aging of the actuator and indicates the need for preventive maintenance during its operating life. Sensor data can be aggregated. Application statistics beyond simple fault detection can be preprocessed and put into the right format before being communicated via the communication bus interface such as IO-Link®, CANopen, or even Industrial Ethernet derivatives to the higher control layers.

On the higher control layers, the data streams from decentralized individual actuators, manifolds, or multiaxis systems. Or another possibility is that factory floor islands come together and offer additional options to improve control, monitor system health, simplify maintenance, or put them into context with metadata. For example, the knowledge of a manifold's reaction and travel times helps synchronize multiple valves or improve orchestrating of different solenoids and other actuators toward better interaction and throughput. Defective actuators can be identified and located.

Energy Efficiency: Superior Control Quality

Being able to measure the reaction and travel time of a solenoid and detecting the local dip of the current positively impact power consumption. It allows tuning control parameters like target current and slew rate to optimize the reaction and travel time. Moreover, it enables automatic switchover from hit to hold current at the optimal point in time instead of waiting for a static preconfigured hit time window. The energy that would unnecessarily be pumped into the solenoid's coil can be saved. This further improves the efficiency of the solenoid unit. This is particularly true in the case of bistable pulse solenoid valves (latched valves) in which the hold status is mechanically ensured (springs) so that the hold current is zero and only the excitation hit current contributes to the total power consumption.

In stepper motor applications, immense energy savings are possible as well using the ADI Trinamic CoolStep solution on top of the StallGuard load value.[14,15] CoolStep thereby offers a sensorless dynamic current level control taking the actual load on the motor shaft into account. With just a low load on the shaft, it is not required to power the motor with full nominal target current. The target current can be adjusted to the required minimum. When the load increases, the target current is adjusted the same way to allow for more motor torque. Even peak loads can be captured, and the target current can be boosted above the nominal current temporarily without damaging the motor. This drives a stepper motor at the minimum current and reduces the motor's energy consumption by up to 90%.

This improvement in energy efficiency also results in less heat dissipation and thermal stress, which results in a longer lifetime and improved reliability and functional availability of the solenoid valves[16] or stepper motors. Keeping the actuators cooler enables a broader range of applications and use cases; for example, in lab, chemical, or medical areas where temperature needs to be properly controlled to not reach critical limits.

Time to Market: Simplified Control/Ease of Use

cDriver components have an interface-centric architecture. The bidirectional nature of the interface allows acquisition of the sensor data and parameters available inside the cDrivers and configuration and adaptation of the control parameters to the application. The cDriver components are subsystems themselves and provide high end building blocks for solenoid and stepper motor control that are ready to use and widely configurable. Software development (for the solenoid or stepper motor part) is reduced to a minimum—it is basically not needed at all. One does not need to be an expert in solenoid or stepper motor control. Instead, the focus can be put on its own application-specific functions and the communication side. This communication-centric interface-focused way of thinking results in software-defined hardware and is not just a benefit for the system design or software engineer, but it also reduces the time to market and minimizes design risks.

Total Cost of Ownership

Smart and highly integrated cDriver components as discussed in this article help reduce the TCO. Cost savings are expected on three different levels: energy cost, maintenance cost, and unplanned expenses due to risk mitigation.

The functions to improve energy efficiency and reduce power consumption have a direct impact on the running expenses—saving energy is saving cost.

Measures for predictive maintenance based on the extensive diagnostic data and sensor-like feedback help reduce unplanned maintenance costs and simplify the maintenance process in general as points of failure can easily be localized. The continuous stream of feedback from the actuator subsystem(s) helps monitor system conditions and improves operational availability, which in turn prevents additional costs due to production downtimes.

Another important impact of the cDriver components' high integration that is not to underestimate is the immense reduction of the BOM as shown in the examples before. But it is not just the reduction of the BOM cost alone. Global supply chain challenges, fab capacities, and shortage of semiconductors and electronic components driven by trade wars or other global events compromise the ability to manufacture and ship products in time or at all. This is not just a risk but a matter of fact. Reducing the number of BOM components removes dependencies and prevents unplanned redesign of the controller and driver electronics and subsequent requalification efforts.

Conclusion

With a fusion of sensor and actuator, new cDriver components are enabling smart electromechanical actuators at the edge. cDriver components can do more than just switch a solenoid or spin a motor: they offer extensive diagnostic functions and thereby are a kind of sensor on their own. Preprocessed data make decisions locally and offer safety and monitoring functions. Such smart sensing actuators deliver additional value to the cyber-physical systems and factory floors of the future by solving mechanical challenges, hiding complexity, encapsulating sophisticated functions, providing abundant information to the higher control layers for further processing, and reducing cost and power consumption. This is a new level of digitization and a paradigm change in controlling electromechanical actuators at the edge. Guido Gandolfo, Product Line Manager for Motion Control at MEV Elektronik Service GmbH, Germany, says: "The new family of stepper motor drivers enables our customers to develop smaller and smarter products with higher efficiency in a shorter time. It is the next step in maintaining the state-of-the-art status of the ADI Trinamic drivers." MEV is a distributor with expertise in motion control and design-in support.

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About the Author

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