Key Technologies Enabling Automotive By-Wire Systems

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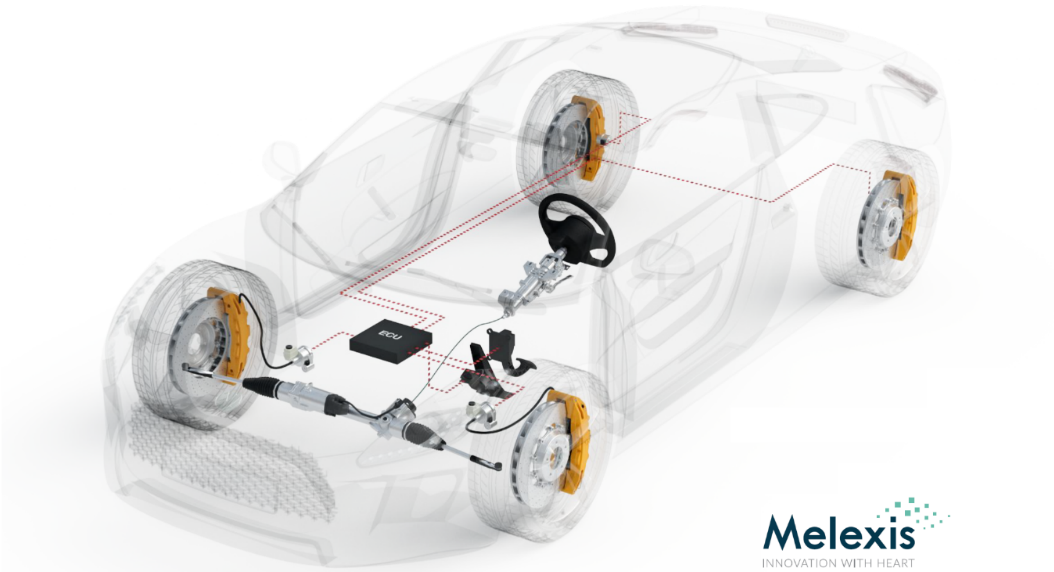
July 2025



The automotive industry has long been dominated by mechanical and hydraulic engineering, from suspension and cooling to the engine and controls, the overwhelming majority of vehicle systems feature mechanical and hydraulic control and operation. While electronic components have been incorporated into vehicles since the 1930s, mainly in the form of engine starters, lighting, and optional radios, the overall mechanical nature of vehicles persisted. Yet in recent decades, the scope and application of electronic systems in vehicles have expanded. Countless mechanical pumps and vacuum-controlled systems have been replaced with solenoids, solid-state relays, and piezoceramics. Likewise, electronic sensors and displays have long superseded feedback systems, such as mechanical gauges. Despite this shift, core functions like steering and braking have remained predominantly mechanical and hydraulic, with electronic components playing only an auxiliary role.

However, this is starting to change: the convergence of automotive intelligence, vehicle electrification and emissions regulations is prompting vehicle designers to revolutionize mechanical-hydraulic systems by transitioning them into electro-mechanical systems. This shift is driven by the goals of improving functionality and safety, enhancing precision, simplifying integration, reducing complexity of the overall system, and reducing emissions and energy consumption. As a result, the automotive industry is increasingly prioritizing the development of next-generation "by-wire" systems, which offer superior support for emerging vehicle functionality compared to traditional mechanical-hydraulic systems.

The Shift Towards By-Wire Systems

A by-wire system, in essence, replaces traditional mechanical linkages with electronic control mechanisms. This represents a significant departure in the design and operation of vehicles, wherein essential functions such as throttle, braking, and steering are no longer reliant on physical connections such as steering columns, cables, or hydraulic lines. Instead, sensors, motorized actuators, and control units manage these functions.

Throttle-by-wire, for instance, replaces the mechanical connection between the accelerator pedal and the throttle valve, using position sensors to gauge pedal position and transmit signals to the engine control unit (ECU) for electronic power adjustment instead. While the lack of mechanical linkage can cause concern for some, the concept has a successful track record. The Concorde, introduced in 1969, was a groundbreaking aircraft in many regards, but it was also the first commercial airliner to use fly-by-wire technology [1]. Implementing throttle-by-wire technology in the automotive industry began with BMW's 7 series lineup in mid-1980s [2]. Since then, it has been a common feature for essentially all modern vehicles.

By-wire systems offer several advantages, including finer control, greater efficiency, enhanced safety features, and compatibility with emerging technologies like autonomous driving. However, they come with their own set of unique challenges, such as ensuring reliability and the advanced integration and redundancy requirements.

Brake-by-Wire and Steer-by-Wire

Although by-wire operation has become commonplace in vehicles, with technologies like throttles, engines, and some gearboxes being controlled electronically, the transition has been slower for two main vehicle systems – namely braking and steering. But thit is rapidly changing.

Significant advantages

Brake-by-wire systems use sensors to monitor brake pedal position or pressure and control the braking force either by driving electro-hydraulic or electro-mechanical brake actuators (calipers).

Brake-by-wire enables the seamless integration of autonomous driver-assistance systems (ADAS) and autonomous driving capabilities [4], while also facilitating regenerative braking in electric vehicles (EVs). This feature allows the vehicles' powertrain motors to generate a braking force which inverts the current flow, allowing the battery pack to be recharged during braking.

Steer-by-wire systems completely eliminate the mechanical steering column which directly links the steering wheel to the wheels. Instead, the system relies on electronic sensors to identify steering inputs, which are then communicated to actuators that drive the wheels.

Steer-by-wire offer several advantages over traditional mechanical steering systems. It facilitates the simpler integration of advanced functionalities, such as lane-keeping assistance, collision avoidance, adjustable steering ratios and autonomous driving capability, while also alleviating certain packaging limitations and enabling the utilization of in-wheel motors that would present difficulties with a conventional steering rack and allowing innovative vehicle designs by eliminating the need for a physical steering column, opening up interior space and design possibilities.

Due to the complexity and costs involved, these systems have long remained mechanical. But with the advenance of car automation, electrification and the implementation of new sensor and actuator technolgies, many of the longstanding barriers have been removed and steer-by-wire and brake-by-wire systems are becoming key elements for the next generation of EVs.

Emissions reduction

Hydraulic systems are affected by fluid contamination and leakage, they require regular maintenance and fluid replacement to ensure safe operation. Brake-by-wire and steer-by-wire in combination with the implementation of purely electro-mechanical actuators allow the complete removal of

[1] https://www.heritageconcorde.com/fly-by-wire
[2] https://www.pistonheads.com/news/ph-features/ph-origins-electronic-throttle-control/38098

hydraulic assistance. This represents a new paradigm in the car industry and enables “dry” braking and steering systems, which reduce the amount of fluids in the car, eliminating the associated emissions and maintenance requirements.

With the implementation of emissions regulations and the introduction of electric cars, the exhaust emissions of fine particulate matter PM10 and PM2.5 (smaller than 10μm and 2.5μm respectively) have significantly dropped in the last two decades. However, the emissions due to brake and tire wear have slowly but continuously increased and they became the main source for vehicle particulate matter emissions. Figure 1 shows an estimation from the Air Quality Expert Group of the evolution of fine dust emissions (PM10) in the United Kingdom from 2000 to 2030 [2]. This will need to improve: the Euro 7 regulation has specifically put limits to the brake particle emissions and plans to determine limits for tire abrasion [1].

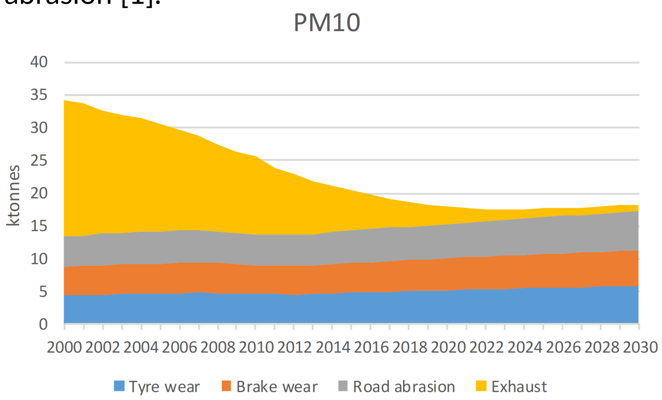


Figure 1 – UK emissions of PM10 from road transport (Source: Air Quality Expert Group UK [2])

Brake-by-wire technology can provide a faster application and release of braking torque, which, in combination with precise speed sensors and automotive intelligence, enables the minimization of brake and tire wear emissios in several ways: the usage of regenerative braking can be maximized, the braking torque can be optimized to minimize tire wear and the application of throttle and brakes at the same time can be completely avoided.

Sensor Requirements

In safety-critical systems, electronic components must adhere to several essential technical requirements. These components need to feature inherent precision, reliability, and the ability to withstand the challenging conditions found in vehicles, such as vibration, temperature fluctuations, and electromagnetic interference (EMI). The sensors must also be simple to integrate and able to work alongside other sensor types, as heterogeneous redundancy has become a core element of the functional safety architecture governing by-wire systems for failsafe operation [3].

In comparison to a conventional braking system, a brake-by-wire system requires both more areas of sensing and higher redundancy at each point in the system, as it lacks the mechanical backup (Figure 2). To guarantee safe operation, it is common to deploy several sensing channels, making sensor integration and flexibility a key design consideration for engineers. System control and feedback is gathered through brake pedal position and force sensors, along with additional sensors installed on the calipers and brake fluid circuits. Due to the temperature ranges, vibration and noise (EMI) associated with these areas of a vehicle, sensor accuracy and reliability are key at each point in the system, demanding the deployment of redundant high-quality sensors.

In a steer-by-wire system, supplementary sensors are necessary to track the position of the rack and verify that the movement aligns with the indicated demand from the steering angle sensor (Figure 4). Once again, reliability is crucial and multiple sensing technologies are deployed to enable heterogeneous redundant system operation.

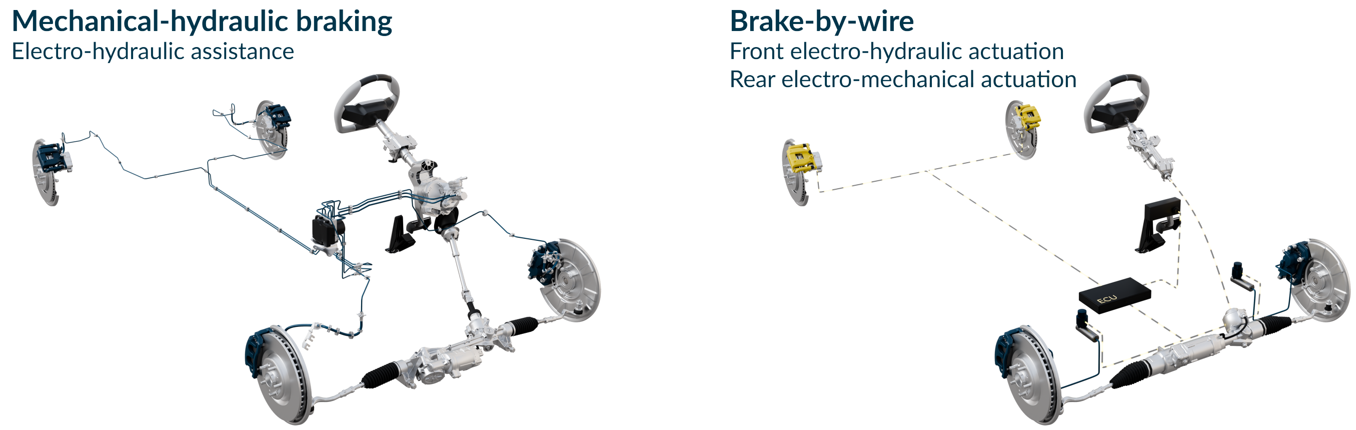


Figure 2 – Evolution from mechanical-hydraulic to brake-by-wire braking systems (Source: Melexis)

Melexis Sensors for By-Wire Systems

With a longstanding association with the automotive industry, Melexis has been supplying a diverse range of sensing technologies for a considerable period of time. Its product range includes cutting-edge magnetic and inductive sensors specifically designed for next-generation by-wire systems.

Magnetic Sensors

Melexis magnetic sensors like MLX90423, MLX90424 and MLX90427 leverage Melexis proprietary Triaxis® technology and have been specifically designed for advanced automotive brake-by-wire and steer-by-wire applications. In contrast to conventional Hall sensors that solely detect magnetic flux density perpendicular to the surface of the Hall element, Triaxis® sensors have the ability to detect all three magnetic flux components due to the presence of the integrated magnetic concentrator (IMC). This technology enables the sensor to accurately decode the absolute position of any moving magnet, whether it is moving in a rotary or linear displacement (Figure 3).

Triaxis® sensors like MLX90423 and MLX90427 are ISO 26262 ASIL-C qualified [3] and can withstand stray-fields up to 5mT, which makes them an excellent choice for electric vehicles or systems with close proximity to other magnetic sensors. They are also available in TSSOP-16 Dual-Die packaging, providing additional built-in redundancy and enabling the implementation of ASIL-D systems. A product like the MLX90424 integrates two Triaxis® MLX90423 sensors and one MLX92292 low-power Latch and Switch wake-up sensor in a single package, providing the ultimative sensing solution for brake-by-wire applications.

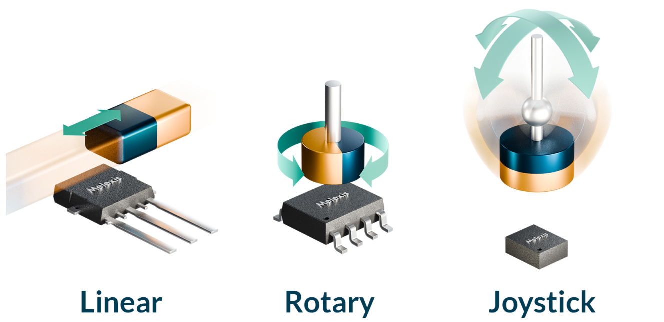


Figure 3 – Triaxis® solutions can be used to detect linear, rotational or "joystick" movement (Source: Melexis)

Beyond the sensing elements, the Triaxis® ICs provide a number of key features which are designed to further simplify the development of advanced by-wire systems. The multiple output modes Analog, SPI, PWM and SENT, including SPC capability in ICs like MLX90377 and MLX90376, support applications with a multi-sensor bus architecture and ensure compatibility with different system configurations, enabling smooth integration into various automotive platforms.

Furthermore, by including a gateway (input pin) in ICs like MLX90372, the sensor can measure external signals from sources like pressure sensors, force-sensitive resistors, or NTC temperature sensors. This feature enhances integration possibilities, reducing wire count and simplifying system design.

Figure 4 – Evolution from mecanical to steer-by-wire steering systems (Source: Melexis)

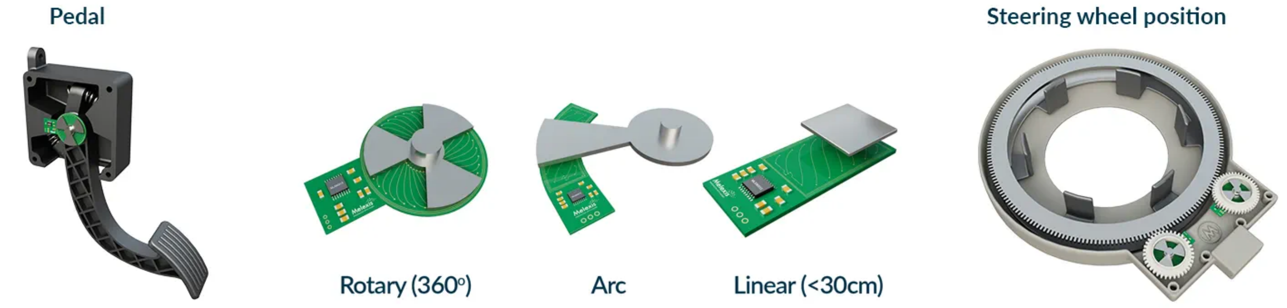


Figure 5 – MLX90513 three movement types (central) accompanied by a brake-by-wire pedal (left) and a steering wheel position application (right) (Source: Melexis)

Inductive Sensors

Melexis inductive sensing ICs like the MLX90513 are immune to magnetic stray fields (ISO 11452-8 [5]), enabling their deployment in environments with high electromagnetic interference (EMI) and in combination with magnetic sensors such as the MLX90423 or MLX90427. This makes them perfect for the heterogeneous setups required in safety-critical by-wire systems.

Designed for automotive and industrial applications and, relying on more than 15 years of inductive sensors experience at Melexis, the MLX90513 is a robust interface allowing to sense absolute rotary and linear motion or position (Figure 5). The inductive sensor operates by using inductive coupling between a transmitting coil, the target, and three receiver coils. When the on-chip LC oscillator generates an electromagnetic field through the transmitting coil, this electromagnetic field induces a target (rotor) angle dependent voltage in the three receiving coils.

The MLX90513 internal signal processing units capture and process the three signals, resulting in precise positional information with a maximum error of $\pm 0.1\%$ full scale. The coils that receive signals are positioned relative to each other based on the number of poles on the metallic target (rotor) above them. Usually, these coils are made as tracks on a printed circuit board allowing for simple custom design and elegant integration into brake-by-wire and steer-by-wire systems.

Similar to its magnetic counterparts, the MLX90513 is ISO 26262 ASIL-C qualified [3] and offers four output modes (SENT/SPC, PWM and Analog) to accommodate multi-sensor bus setups and facilitate the seamless integration into automotive platforms.

Conclusion

The automotive landscape is undergoing a profound transformation, with steer-by-wire and brake-by-wire technologies emerging as a cornerstone for the next generation of vehicles. These safety-critical systems offer distinct advantages over traditional mechanical and hydraulic setups, enabling enhanced functionality, superior control, and significant steps towards a more sustainable, clean, and intelligent mobility future.

However, the successful implementation of these advanced systems rely on highly-precise, reliable, and intelligently integrated sensing solutions. This is where Melexis excels with a portfolio of cutting-edge robust Triaxis® magnetic sensors as well as stray-field immune inductive sensors, which are specifically engineered to meet the stringent demands of automotive by-wire applications.

Melexis sensors offer unparalleled precision, a wide operational temperature range (40°C to 160°C), and exceptional immunity to electromagnetic interference and stray fields, ensuring robust performance in the most challenging automotive environments. Beyond their technical prowess, Melexis solutions are designed to simplify complex system designs through features like built-in redundancy (e.g., TSSOP-16 Dual-Die packaging for ASIL-D systems), multiple output modes (Analog, SPI, PWM, SENT, SPC), and the ability to integrate external signals via input pins. This holistic approach empowers automotive OEMs and Tier 1s to streamline development cycles and reduce overall system complexity and cost.

As the industry moves rapidly towards electrification and higher levels of autonomous driving, the functionality and safety provided by advanced by-wire systems will be paramount to winning over consumers. High-quality position sensors are not merely components; they are critical enablers that ensure the safety, performance, and innovative design of future vehicles.

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