Silicon Mobility

FPCU (Field Programmable Control Unit) New semiconductor architecture to boost HEV and EV systems

White Paper

Khaled Douzane
VP Product
Silicon Mobility

- Version 1.1 / May 2017 -

Contents

Company Information & Contact
Silicon Mobility
Les Aqueducs - Bâtiment 2
535 route des Lucioles
06560 Sophia Antipolis
France
Tel : +33 4 84 79 10 20
www.silicon-mobility.com
contact@silicon-mobility.com

I. Automotive electrification trend

Automotive is living a digitalizing revolution. The industry experiences the same revolution which has turned mobile phones into smartphones. Cars are becoming electrified, autonomous, connected and part of the diverse mobility service impacting the automotive industry at all levels.

The value of semiconductors inside cars is drastically increasing. With the advent of internal combustion engine downsizing and hybridization of the powertrain, the average cost of electronic inside a modern car is about 30% of the total cost of the car. With the continued penetration of car electrification and hybridization together with the perspective of the integration of more active ADAS systems, car to car communication systems, and ultimately autonomous driving functionality, this ratio is expected to reach an average of 50% of the total cost of the car in the 2020's years.

The effects of this revolution go beyond and radically change the face of the traditional supply chain relationship between OEMs, automotive Tiers 1 and their Tiers 2 or IDM. The emerging OEMs manufacturing pure electric vehicles are deeply changing the rules by dealing directly with technologies providers, along with Tech Giant such Waymo or Apple, and mobility services providers (ZipCar, Uber, Lift). All are investing heavily in powertrain electrification, real-time emission control, autonomous car and vehicle-to-vehicle, infrastructure or cloud communication and forcing traditional OEMs to react.

Among these major trends, vehicle electrification is already impacting on a global scale. Due to international sustainability policies, car manufacturers are encouraged to reduce CO_2 emissions. As a result, cars are using more and more electric power to assist the traditional internal combustion engine or even to drive the car alone. Solutions go from several flavours of hybridization (micro, mild or full) to plug-ins or pure electric vehicles. Integration of electric motors into powertrain systems are being widely adopted into newly manufactured cars. Already 30% of yearly manufactured cars integrate an electric motor (mostly into micro-hybrid / stop-start solutions). With an estimated steady 28% adoption rate, by 2025, nearly 80% of vehicles will include at least one electric motor in this mix of micro/MHEV/FHEV/EV cars.

From market leaders, via German premium brands to new OEMs, the future of vehicles is through electrification. Winner of this race will be judged by the market on two key factors: vehicle range and battery charging speed. The challenge is quite easy in its formulation: how to improve vehicle range and battery charging time?

II. Seeking the best technology

The answer is far more complex as it involves several elements within an electrified powertrain system. OEMs and Tiers 1 are already playing on several factors and investigating / testing new technologies or ideas to find the best solution: battery technology (Lithium-ion, Solid state, Aluminum-ion, etc), electric motor design (3, 6 or 8 phases Permanent Magnet Synchronous Motor), electric motor power (24V, 48V, 700V, etc), electric motor positioning in the car (front belt, gearbox, transmission, axle, wheel), power transistors (MOSFET, IGBT, GaN, SiC, etc). Amazingly, no adequate solution has been offered by traditional semiconductor vendors to control these new systems efficiently. Tiers 1 and OEMs are forced to reuse microcontrollers originally designed for internal combustion engine control and are facing unbreakable limits with such architecture.

In response to this need, Silicon Mobility is introducing a brand new semiconductor architecture, the Field Programmable Control Unit (FPCU), designed for automotive powertrain control application surpassing the actual limitations. This white paper presents the current stakes in control systems for electrification applications, the limitations of the conventional microcontrollers' architecture and details the new FPCU architecture and how it benefits users and system integrators.

III. Control systems in electrification applications

Hybridization has introduced a huge diversity of powertrain systems within the classical Gasoline vs Diesel world. Micro Hybrid (stop-start system), Mild Hybrid (stop-start, torque assist, electric drive at low-speed, regenerative breaking), Full Hybrid (full electric drive, torque assist, regenerative breaking), Plug-ins Full Hybrid and pure Electric Vehicles, are now proposed multiplying the number of powertrain architectures. Mild Hybrid Electric Vehicles (MHEV), for example, allow the electric motor to be placed at 6 different places inside a powertrain system: on the front belt, on the crank, on the transmission, in the gearbox, on the axle or in wheels.

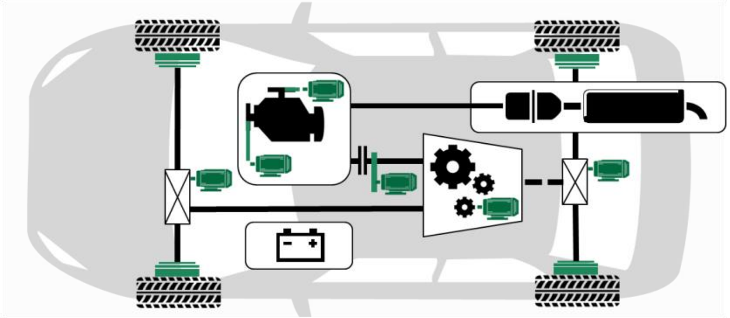

Figure 1: Possible localization of electric motor in MHEV

If the Micro-Hybrid system has only an inverter control of the eMotor, all flavours of hybridization from Mild-Hybrid to full electric vehicle include a dedicated battery ranging from 48V to 700V. The couple "eMotor – Battery" equipping electrified vehicle needs 3 different controllers dedicated to energy usage, conversion and storage: an Inverter Control to drive the eMotor, a DC/DC Control to convert high voltage to standard 12V and an AC/DC Control for battery charging which convert from the power outlet.

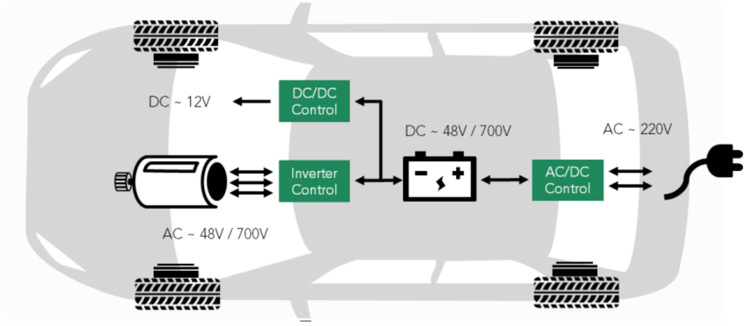

Figure 2: Key control systems in electrification

Quality of control is measured in terms of the ability of the control to maximize the energy transferred by reducing losses in conversion such heat dissipation, vibration and noise. For example, the inverter control of an eMotor will be represented by the following figures:

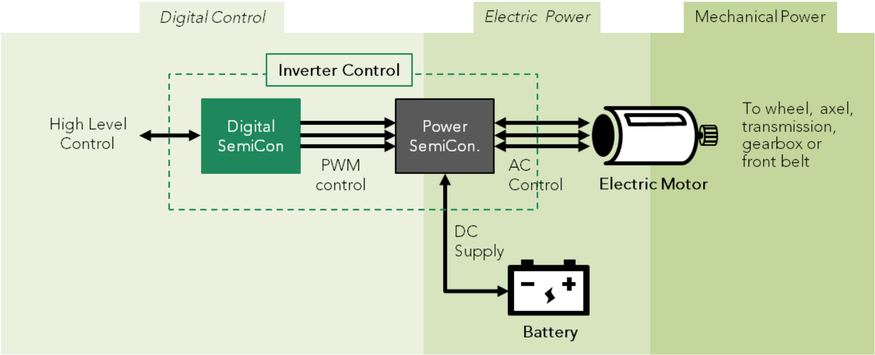

Figure 3: Inverter control high level schematic

Inverter control is composed of two kinds of principal semiconductors: power transistors (MOSFET or IGBT), and a digital control processor. The digital control switches transistors to convert the direct current out of the battery into several phases of alternative current to drive the magnets of the eMotor and make the rotor turn. The transistors are driven using digital signals which commute accordingly to pulse width modulations (PWM). PWM patterns are results of a complex algorithm executed into the digital control processor, which translate a high level of control commands like speed regulation or torque set point.

Among the different factors that directly affect the performance and efficiency of a DC/DC, an AC/DC charger or an inverter, the control method (power transistor architecture and technology), the switching frequency (real-time control, speed of PWM and transistors switching) and the digital processing and control method (algorithm executed into the digital controller) are the major ones.

With the emerging of GaN/SiC transistors, complex control methods with higher switching frequency, higher than hundreds of KHz for a Field oriented Control of an inverter and up to several MHz in some DC/DC or AC/DC applications, are required to improve energy efficiency conversion, system size and heat. The switching time is then required to be in the range or below 1 µs.

IV. Conventional solutions are a mismatch.

Currently, Tiers 1 and OEMs face huge limitations making it impossible to reach such a high frequency with conventional digital control processors. Conventional semiconductor solutions are microcontrollers (MCUs) which rely on multiple proprietary CPU and integrate complex timer-based micro-CPU to handle real-time control of actuators and sensors. These conventional architectures result in a sequential and centralized data processing. They are adapted to complex system control where the maximum response time is within the range of a few milliseconds as is required for internal combustion engines. Needless to say, using products built to sustain a response time of 1ms to control an engine requiring a switching time of 1µs is a mismatch!

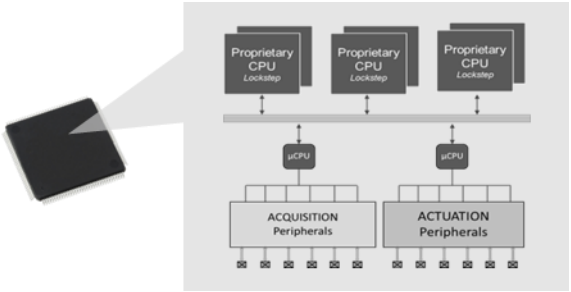

Figure 4: Conventional Architecture

For the next generation of electrification control systems, these microcontrollers face huge software bottleneck issues. A multicore MCU dedicating one of its CPU to the execution of the control loop may barely achieve a PWM inverter control frequency in the range of 10 to 20KHz in the best case scenario. In the defence of this MCU devices, they are simply not done to execute control loop in the range of 1µs, limited that they are by their inherent sequential data processing capabilities of theirs integrated DSP or FPU that just cannot deliver the sufficient data throughput.

MCUs rely only on embedded CPU or fast timers which are sequential processing based. Actual CPU loads directly influence processing time of events, requiring strong engineering effortsto fine-tune timings with a real-time O/S. Fixed response times whatever the occurrence of the event or the number of events to process is impossible to demonstrate in such architectures.

MCUs need to run very fast to execute the control loop at its fastest speed. Advanced MCUs will run at 350MHz with a fully loaded CPU, resulting in maximum power consumption of the chip and maximum heat generation which directly leads to another big issue for heat sensitive systems like embedded inverters attached to electric motors. Not only are these solutions slow but they also produce undesireable collateral issues.

V. Removing bottleneck software with FPCU

Silicon Mobility has taken an approach in complete rupture with conventional systems: combining a flexible and parallel hardware architecture for the real-time processing and control of sensors and actuators, coupled to a standard CPU. All this is surrounded and complemented with an integrated ASIL-D-functional safety architecture to form a single semiconductor.

The flexible and parallel architecture relies on tightly coupled autonomous actuation/acquisition peripherals and a programmable logic fabric interconnected with parallel data paths. The programmable logic has been designed accordingly to automotive constraints, safety requirements and HEV/EV applications requirements.

The resulting architecture is far more powerful and flexible than a conventional safety MCU and much more adequate than a generic FPGA or any other kind of hybrid CPU/FPGA architecture with respect to the targeted applications. Silicon Mobility has defined this new architecture as a Field Programmable Control Unit, or FPCU.

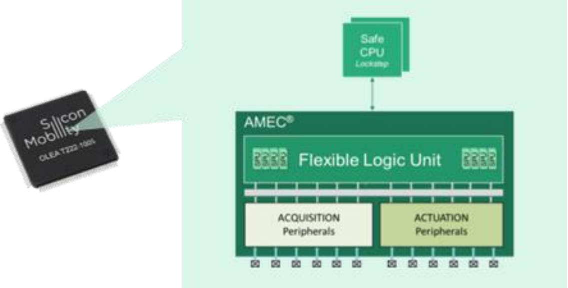

Figure 5: FPCU Architecture

The first production release of FPCU is Silicon Mobility's semiconductor solution: OLEA® T222. In OLEA®: the programmable logic fabric is named Flexible Logic Unit (FLU). The FLU is linked to generic and registers-based configurable peripherals, so called Powertrain-ready-Peripherals (PrP) to form a dedicated interface for actuators/sensors control and local data processing. This interface is named AMEC® for Advanced Motor Event Control.

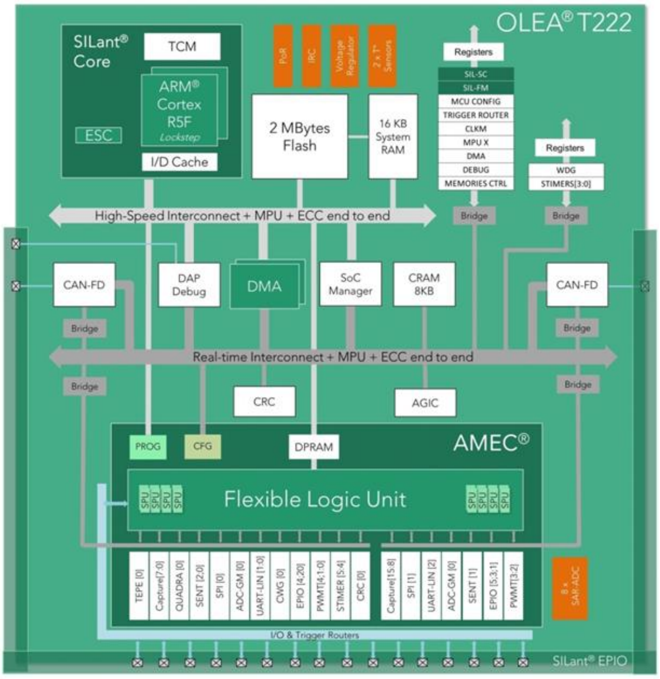

Figure 6: Detailed block diagram of OLEA T222

With FPCU architectures, the programmable logic fabric hosts the hard real-time processing algorithms and locally processes incoming data from sensors to update actuators without going back to the CPU. CPU is off-loaded and can be used for slower response time functions, releasing it from the timing tuning challenge. In the case of OLEA® T222, the AMEC® is able to process in parallel all data coming from sensors in a fixed response time whatever the number of events to process or their occurrence. The architecture is fully deterministic.

The following figure shows a detailed view of AMEC® inside OLEA® T222. The Flexible Logic Unit integrates several Signal Processing Units (24-bit MAC) which multiply computation power on complex algorithm. (To learn more about AMEC® features and capability, please contact Silicon Mobility).

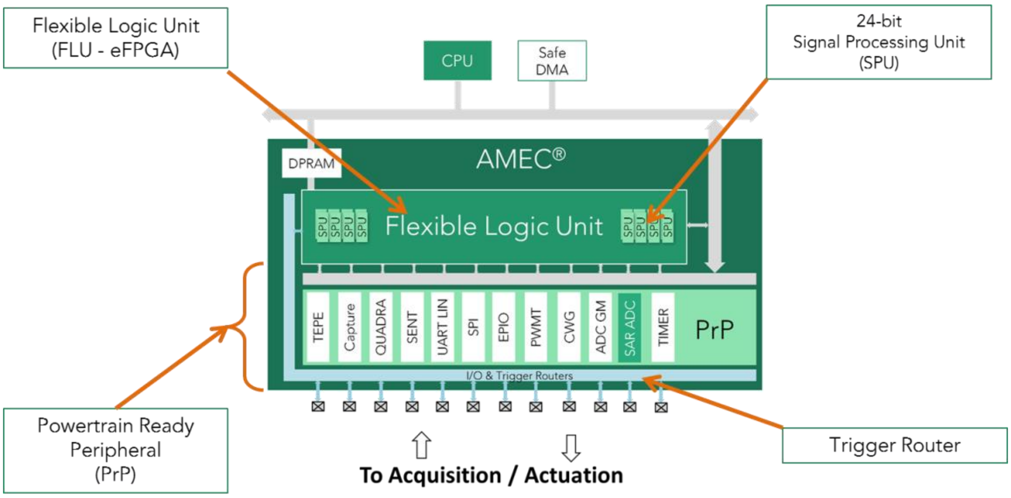

Figure 7: AMEC® block diagram

The Trigger Router is used to route in parallel all inputs (from the PrP, EPIOs and the FLU) to any of its outputs either linked to the PrP, the FLU inputs or towards off chip devices.

With OLEA® T222 FPCU architecture, software bottlenecks are removed. OEM's test-benches have demonstrated an acceleration of 40x on data processing compared to a reference automotive MCU. Complex control loops as a Field Oriented Control for PMSM electric motor are accelerated by a factor of 20x.

A direct consequence of executing complex algorithms in hardware instead of software is the reduction of the device's power consumption. OLEA T222 has been measured as consuming 180x less than the automotive reference MCU. The FLU does not need to run at 350MHz to be efficient, and even if it did, only a small specific hardware function inside the FLU would be activated, not the whole CPU.

The FPCU architecture is fully deterministic and integrates functional safety mechanisms that cover fault at system level. As a result, the Fault Reaction Time (FRT) to address hazard that might arise for inverter, DC/DC or AC/DC control is a matter of nanoseconds instead of several hundreds of μs, if not ms, for solution based on conventional semiconductor solutions.

VI. FLU : A Robust Design

From the start, Silicon Mobility has imagined, designed and developed the FLU to overcome FPGA weaknesses in regards to reliability and safety requirements for automotive applications.

FPGA are known to be easily affected by Single Event Upset (SEU) because the matrix configuration and user data are stored into SRAM cells which are very sensitive to ionization. To manage SEU, users need to design special functions in addition to their application because no specific active safety mechanisms are implemented by default into FPGAs. For safety critical design, an external monitoring MCU is even required. Moreover, the size of FPGA's matrix makes them long and costly to load and to test. It is often necessary to test matrix with a user's specific test program to assess full coverage.

In contrast, FLU is robust by design. No SRAM cells are used in FLU's matrix. The technology implemented is based on the usage of latch cells and configuration is stored into Non Volatile Memory cells (eFlash). All memory cells are protected. The eFlash storing the matrix configuration integrates Error Code Correction (ECC) while an automatic, continuous and in operation Control Redundancy Checking (CRC) on latch cells is integrated to check any non-desired programming change. The Fault Reaction Time is drastically reduced, below 3.5µs in the worst case, between fault occurrence and fault correction.

FLU is designed according to automotive design rules and not like a FPGA dedicated to consumer applications. The physical implementation of the matrix follows all semiconductor recommendation rules for a stringent automotive grade. FLU implementation is hardened from the rest of the device for maximum reliability. Finally, there is no need for specific users' test programs, because a Built-in Design For Test (DFT) with Automatic Test Pattern Generator (ATPG) is integrated. The entire matrix is tested at manufacturing and ready to be used.

FLU is not a standalone programmable area as in an eFPGA. It is tightly coupled with SILant®, the safety mechanisms available in OLEA®. This white paper will not detail the SILant® technology (another dedicated paper will be soon available on this topic), but it is important to know that FLU is paired with the ESC (Events Sequence Control), clock monitoring and EPIO modules which allow the implementation of robust designs. In case of detection of a faulty FLU user-cell, FLU could be either reset or isolated from the rest of the device (more detailed are available in OLEA® Safety Manual).

Furthermore, FLU can host safety mechanisms as it has direct interfaces with the SILant® Fault Manager in OLEA®. It allows the support of application specific safety monitoring function and/or application specific fault correction mechanisms.

VII. Case study example: 6 phases WRSM with safety critical design

The following case study shows a very challenging design, impossible to implement with a conventional MCU. It is an inverter control of a six phases Wounded Rotor Synchronous Motor (WRSM) with a Hall Effect sensor for position measurement and a Field oriented Control method (FoC). The design is safety critical and comply the highest safety integrity level. OLEA® T222 is able to run the FoC control loop to command PWM switches at 100 KHz without any CPU intervention.

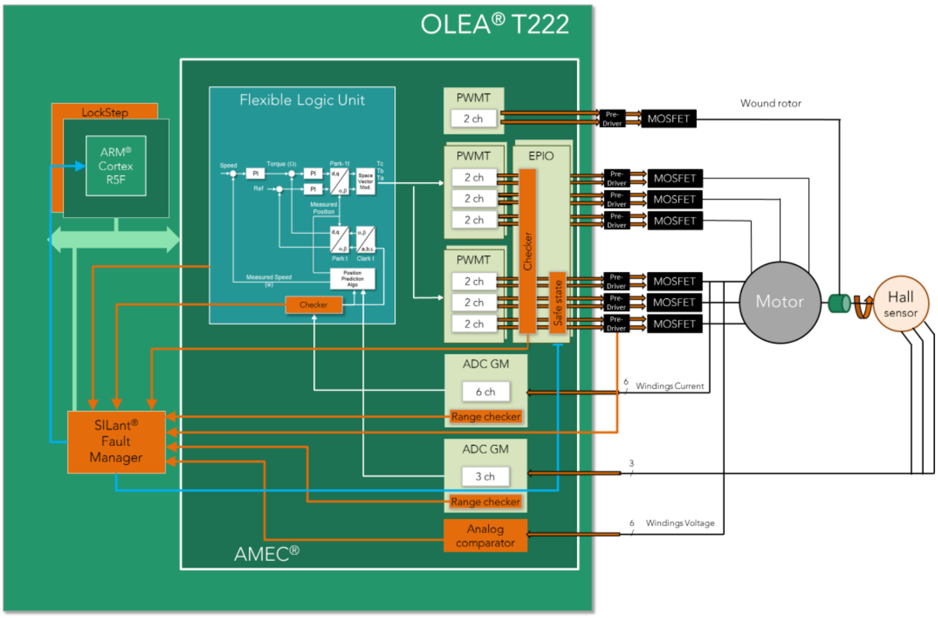

Figure 8: Safe Control of a 6 phases WRSM using OLEA®

The Field oriented Control algorithm is hosted inside the FLU and drives the PWM of the AMEC®. One PWM is used for controlling the wounded rotor excitation signal. 6 PWMT are used (2 channels each) to drive each motor phase. Current out of the power transistor is measured and fed back into the Field oriented Control as well as the position measure out of the Hall-Effect based sensor using the embedded SAR ADCs.

Several embedded safety mechanisms and methods are used in this example:

- PWMT driving the motor phases are duplicated (redundancy) and outputs are compared transparently.
- ADC integrates range checkers monitoring any measure value that would go beyond a defined range.
- Analog comparators are used to detect any short-circuit or over-current
- In FLU, a position estimator is implemented to compare, in real-time, the measured and the estimated position to check any discrepancy.

If an error is detected by any of these mechanisms, the SILant® Fault Manager collects it and automatically applies a safety response (defined by users) adapted to the detected failure. For example, it can automatically activate resets or switch outputs to safe states to prevent from any system damage in less than 500ns.

VIII. Conclusion

This white paper has introduced the FPCU, a new semiconductor architecture, with OLEA® T222 as the first element of the family to fully remove HEV software bottlenecks that HEV system designers experience with conventional solutions. FPCU brings software and hardware flexibility to safety critical applications where real-time processing and control performance are not achievable traditionally with conventional multicore microcontrollers as described in this document. Besides the performance increase, FPCUs as OLEA® T222 bring several additional system benefits:

- The FPCU architecture changes the digital control loop design rules. New digital control-loop and algorithm could be considered to favour the system electronic/electric downsizing and endurance increase.
- Improve quality, reduce of billof material, ECU size and complexity by the removal of external DSP, FPGA or glue-logic,
- Ideal solution for platform approach to support any type of actuators and sensors with possibility to add pre or post signalling adaptation.
- Hardware update is possible by software reducing the cost of versioning and upgrade.

Along with OLEA® T222 FPCU, Silicon Mobility has developed OLEA® COMPOSER, a seamless design and calibration framework from model based description on industry's standard development and EDA tools. OLEA® Composer provides a single design framework for both Hardware and Software programming of the FPCU. If FPCU architecture is unique, designing an application on it does not mean changing its tooling or design methodology. From model design, via virtual prototyping to hardware in the loop simulation, OLEA® COMPOSER brings toolboxes and plug-ins that automate code generation for CPU and FLU (C code and HDL code generation from MATLAB) and automatically handle variables and parameters for validation and calibration phases in CPU or FLU memory. A separate white paper (soon available) will describe Automotive V-Model development cycle on OLEA® T222 FPCU using OLEA® COMPOSER.

Several uses case demonstrations of OLEA® T222 FPCU are available from Silicon Mobility. Please ask Silicon Mobility for evaluation board and starter kits to get hands on OLEA® T222 and discovers the benefits of FPCU to your system.

Table of figures

Glossary

AC: Alternative Current
ADAS: Advanced Driver Assistance Systems
CPU: Control Processor Unit
DC: Direct Current
EV: Electric Vehicle
FHEV: Full Hybrid Electric Vehicle
FLU: Flexible Logic Unit
FPCU: Field Programmable Controller Unit
FPGA: Filed Programmable Gate Array
HEV: Hybrid Electric Vehicle
IDM: Independent Device Manufacturer
MAC: Multiplier-Accumulator
MCU: MicroController Unit
MHEV: Mild-Hybrid Electric Vehicle
OEM: Original Equipment Manufacturer
PHEV: Plugins Hybrid Electric Vehicle
PWM: Pulse Width Modulation
SEU: Single Event Upset
SPU: Signal Processor Unit
SRAM: Static Random Access Memory
WRSM: Wounded Rotor Synchronous Motor