Low Power, Secure, and Deterministic Multi-Axis 100+ kRPM Motor Control Solutions

WP0201 White Paper

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Motors used to be large in size, power hungry, expensive, noisy, and unsafe. Substantial progress has been made to reduce and tackle these concerns and increase the use in several applications such as medical, automotive, defense and security, surveillance, factory and home automation, and industrial applications.

Historically, microcontrollers (MCUs), microprocessors (MPUs), and digital signal processors (DSPs) have been used for motor control. Regardless of the progress made with implementations using these hardware platforms, the following are the limitations:

- Non determinism
- Limited performance and difficult scalability
- Reliability in extreme operating conditions
- Power consumption
- Tamper, cloning, and overbuilding risks
- Longevity of supply

Microsemi® IGLOO2® field programmable gate array (FPGA) attributes combined with an innovative, flexible implementation and a comprehensive motor control eco-system solve these issues and offer cost optimized ready-to-deploy solutions that are easy-to-use, adaptable, customizable, and have short design cycles. Moreover, as the IGLOO2 FPGA is field programmable, these solutions offer flexibility for the system architect to integrate additional functions, protocols, voltage/level shifters, thus reducing the bill of materials (BoM) and the overall cost.

This paper is organized into the following sections:

- "Introduction to BLDC Motors and their Use"—Provides a quick overview of the brushless DC electric motors (BLDC)
- "Limitations of MCU, MPU, and DSP-Based Motor Control Solutions"—Focuses on the drawbacks of microcontroller and application processor-based solutions and contrasts these with Microsemi FPGA-based implementation and features
- "Microsemi Motor Control Eco-System"—Introduces the eco-system and the enablers to integrate, customize, and validate the motor control solution
- "Conclusion"—Provides a summary and overview of future enhancements

Introduction to BLDC Motors and their Use

BLDC motors are special type of DC motors with permanent magnet in which brushes are not used for commutation. Instead, electronic switches are used to control magnitude and direction of current in motor windings. To accomplish this in a controlled manner, a rotor speed and position feedback mechanism and electronic controller are required. The BLDC motors are adopted as they have the following properties:

- High efficiency
- High reliability
- High speed
- Low noise operation
- Low electromagnetic interference (EMI)
- Low maintenance cost
- Quick cooling
- Longevity, as there is no friction of brushes

The above attributes and advantages drove the adoption of BLDC motors in many applications and areas like automation, military, medical and other appliance. Table 1 lists a sub-set of some of these applications. The wide spread adoption of the various models makes it imperative to design low cost, reliable, efficient, and flexible controllers taking into account the actual requirements of each application.

Table 1 • **Examples of Applications using BLDC Motors**

Market	Systems/Application
Medical	Gear pumps for precision volume dosing Hand-held high efficiency portable infusion pumps Quiet respirators Surgical and dental hand tools Ventilation, blood pumps, diagnostic lab equipments
Industrial	Centrifuges Computer numerical control (CNC) machine tools, sewing machines Servo robotic positioning actuators Fuel valve control actuators Solar array deployment Control moment gyroscopes Traction control Heating, ventilating, and air conditioning (HVAC) blowers and compressors Gas turbines Flywheels
Defense	Articulation of weapon system guidance platforms Electronic fuel injection (EFI) for unmanned aerial vehicles (UAVs) Unmanned recon robots Surveillance cameras crane control Stabilization platform
Aerospace	Thrust vector control (TVC) actuators Fuel valve actuators Control moment gyroscopes Solar array deployment Servo robotic positioning actuators Seat actuation

Limitations of MCU, MPU, and DSP-Based Motor Control Solutions

In this section, the limitations of the MCU, MPU, DSP-based motor control solutions are explained and contrasted with the advantages offered by Microsemi IGLOO2 FPGA-based implementation.

Non Determinism

All microcontrollers and microprocessors allow for a variety of interrupts and schemes, structures, and priorities for these interrupts. While masking of interrupts is available in some of the architectures, there are limitations associated with the masking. Some of the unmasked interrupts are deemed critical, of higher priority, and have preemption associated with them. This leads to actual interruption of the motor control algorithm till the execution of the service routines associated with these interrupts (ISRs) is completed. The length in time and the priority of execution of the ISRs is not bounded and vary widely, leading to the nondeterminism of the execution of the motor control loop.

The performance of FPGA-based implementation is deterministic and bounded. The synchronous nature of these implementations add additional assurance that the timing is clock frequency-based and does not vary. Moreover, when Time Division Multiplexing (TDM) is adopted for multi-axis controllers, there is fairness as each motor has the same time slot length, thus being deterministic.

Low Performance and Tedious Scalability

There are several dimensions associated with the performance and scalability attributes. At a practical and high level, motor control designers consider one or several of the following:

- Motor control algorithm execution time and pulse width modulation (PWM) switching frequency
- Adaptability to run the motors from low to high RPM
- Capability of handling more than one motor
- Capability of handling different types of motors in TDM mode

Even with the most advanced MCUs (with dedicated PWM peripherals), the motor control implementations suffer at least in two areas and show severe limitations as soon as the algorithm execution time and switching frequency increase to hundreds of kHz. Several papers suggested the use of an FPGA to help coping with either performance limitations or additional motors [AAP2006, Miller2013]. Applications microprocessors (MPUs) have more horse power and can achieve higher speed, but like the MCUs, their efficiency is limited when it comes to controlling multiple motors or motors of dissimilar nature. Additionally, the motor control algorithms are cumbersome and difficult to fully validate when more than one motor type is involved.

Similarly, DSP architectures and offerings, while more suited to run complex mathematical functions (floating point), were used instead of MPUs/CPUs when speed and complex motor constructions were involved. However, DSP-based implementations have high harmonic distortion due to the switching losses. In contrast, FPGAs allow higher efficiency and parallelism in the implementation of the critical control algorithm and reduces the aforementioned loss by 50%. For more information, refer to "References" on page 11.

The execution time of motor control algorithm is crucial for high-speed motors that demand high switching frequency of the order of hundreds of kHz. For efficient motor operation, it is mandatory to execute the control algorithm at the rate of switching frequency. Even though it is possible to run the motor by updating controller output once in multiple PWM switchings (which is the case with micro-controllers), it may not lead to best performance of the motor in terms of torque ripple and harmonics. When it comes to controlling multiple motors with a single control loop, MCUs, MPU, and DSPs are obliged to reduce the switching frequency or to update the PWM after multiple switchings. The parallel computational capability of FPGA allows high frequency operation of multiple motors without compromising on performance and efficiency.

Figure 1 shows a comparison of high-speed motor torque ripple of IGLOO2 FPGAs and MCUs.

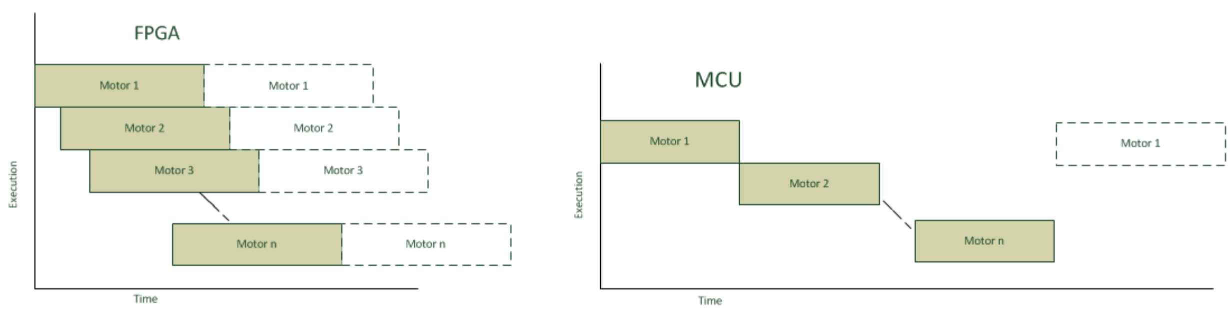

Figure 1: IGLOO2 FPGAs vs MCUs – Comparison of High-speed Motor Torque Ripple

Table 2 shows the impact of torque ripple as a function of number of motors.

Table 2 • **Impact on Torque Ripple as Function of Number of Motors**

Number of motors	Torque ripple with MCU/MPU/DSPs	Torque ripple with FPGA
1	5%	<4%
2	6%	<4%
3	8%	<4%
4	10%	<4%
5	13%	<4%

IGLOO2-based implementation is not only capable of running multiple BLDC Motors at 100+ kRPM each, but also capable of controlling a combination of BLDC, stepper, and induction motors within a small footprint and ultra-low power IGLOO2 FPGA such as M2GL005 or the smallest 5K LUT device. Moreover, the Microsemi solution offers bidirectional rotation with precise speed control and capabilities to adjust on-the-fly the speed of each of the motors to run as low as 3 RPM to as high as 100 kRPM at constant load and inertia. For more information, refer to "Microsemi Motor Control Eco-System" on page 6.

Reliability and Resiliency

There are multiple facets to reliability. One of these facets is related to the non-degradation of the operation of the controller under extreme temperature (above and beyond the “industrial” temperature range (-40° C to 85° C junction) combined or not with voltage fluctuations (over and undershoot). Another facet is related to operation under harsh conditions such as a radiation environment (medical scanners, nuclear plants, avionic engine control, guidance systems in nuclear sub-marines or missiles, solar panel control in LEO satellites, and so on). A third facet of the reliability is the longevity of operation of the controllers, when the motor life period is long (with or without maintenance). One more reliability related aspect has to deal with the wear out of the motors due to torque ripple and harmonics as a result of inefficient motor control. A fourth attribute is related to the actual power consumption of the motor control implementation as for the space-limited or compact systems the heat and the thermal management could become a concern. Mirosemi IGLOO2 exhibits the lowest static, typically around 6mA, and low dynamic power (the device can operate at 1 V, 1.1 V, and 1.2 V). Additionally, the temperature impact on the standby current is limited to five times the typical figure at highest temperature. This low total power dissipation removes the need for thermal mitigation concerns and cost.

The availability of military grade MCUs, DSPs, and application processors is limited. This has led several motor control system houses to either deploy a lot of money, time, and effort to up screen the existing processor offer. Others have opted to seek the help of up-screen houses and pay a hefty premium to ensure a supply of up-screened micro-controllers and processors (as yields are limited). Moreover, the specification/datasheet of the up-screened devices show a severe degradation in many areas such as performance, resiliency (life time), EMI, tighter operating voltage range, etc. These tighter and degraded specifications impact the performance and scalability discussed in the previous section.

All Microsemi FPGAs are ruggedized by design and are available in military temperature range with firm specifications and datasheet. Some of the Microsemi IGLOO2 devices are even available in automotive temperature range, namely from –55° C to 125° C, for high volume applications.

Last but not the least, MCUs, MPUs, and DSPs are vulnerable to single event upset (SEU) effects. The flash-based Microsemi FPGA configuration is differentiated because it is non-volatile and is immune to SEU effects. The retention time and the life time specification shows that Microsemi FPGAs can operate 20 years without any maintenance (or configuration re-fresh).

Tamper, Cloning, and Overbuilding Risks

MCUs, DSPs, and the large majority of application processors do not offer secure boot, let alone secure application code authentication. Several techniques have been deployed to tamper with either the boot or the application codes giving control to the intruders. This may lead to a malfunction of the motor and may cause disruption or cause life threats. The limited offer of application processors with secure boot is overpriced, which makes it difficult for cost sensitive or high volume applications. Additionally, if a malicious competitor gets access to the application code, the intellectual property could be cloned and the business of the system house is at risk.

Microsemi IGLOO2 FPGAs are the highest secure programmable devices in the market today. They offer the most advanced anti-tamper services and resources. Several defense, intelligence, industrial, and communication applications with stringent security requirements adopted the IGLOO2 as roots of trust. Several government certifications have been granted for IGLOO2.

Longevity of Supply and Market Dynamics

Regardless of the efforts of several microcontroller and processor vendors to provide longevity for their products, the market dynamics made the track record of most of these vendors follow the trends below:

- Proprietary architectures and associated eco-systems were the foundation of strategic loyalty or partnership between providers and customers. Because of economics and longer time to market, these proprietary architectures disappeared from the market and the roadmaps. ARM-based architectures are being heavily adopted making the differentiation less defensible and the customer loyalty a myth of the past.
- The ARM-based offering has made porting of old libraries and application codes easier and less costly lowering the risk of “firmware veto” to adopt new generation products.
- The time between two new generations from all of these vendors is shorter and shorter, stimulated by aggressive competition and steeper erosion of the ASPs. As a consequence, the market demand and adoption is swayed towards new generations (faster, richer, and cheaper). A corollary consequence is that the commercial “life cycle” of new families is shorter than previous families. In other words, the ramp to decline of the volumes of new generations is shorter. To be fair and complete, volumes of newer generations ramp faster and are definitely higher at peak, but they decline faster as well.
- Microcontroller and processor companies' financial pressures drove them to shift their support to new products and lower the support/sustainment costs of older products. This reduces even further the appetite of customers to re-use, let alone to adopt older products.

However, FPGA vendors have proven track record of longer commercial lives of their products, even though this has seen products discontinuation notification from some static random-access memory (SRAM) FPGA vendors in recent years. Microsemi has by far the highest longevity of supply of its products. On average, Microsemi FPGAs have been recommended for new designs for close to 20 years and their supply is available for more than 25 years.

Microsemi Motor Control Eco-System

Microsemi offers the most comprehensive FPGA-based eco-system for BLDC, stepper, and induction motor control designers. The following sections describe some of the elements of the eco-system.

Design Files and GUI for Customization

The reference design to control BLDC in sensorless mode (supporting stepper motor with micro-stepping as well) is readily available on the Microsemi website [MMC2015]. The easy-to-use graphical user interface (GUI) allows users to quickly configure the motor control parameters, and provides interface to start/stop the motor, set motor speed, change direction on the fly, and so on. Additionally, the GUI helps users to graphically visualize internal parameters through plotting functions as shown in Figure 2. The reference design can be used to control any BLDC (as well as stepper) motor by simply configuring the parameters without modifying the design or running through Libero® System-on-Chip (SoC) toolset.

Users have access to fully validated and ready-to-use solution. Users do not need to be motor control experts nor FPGA designers.

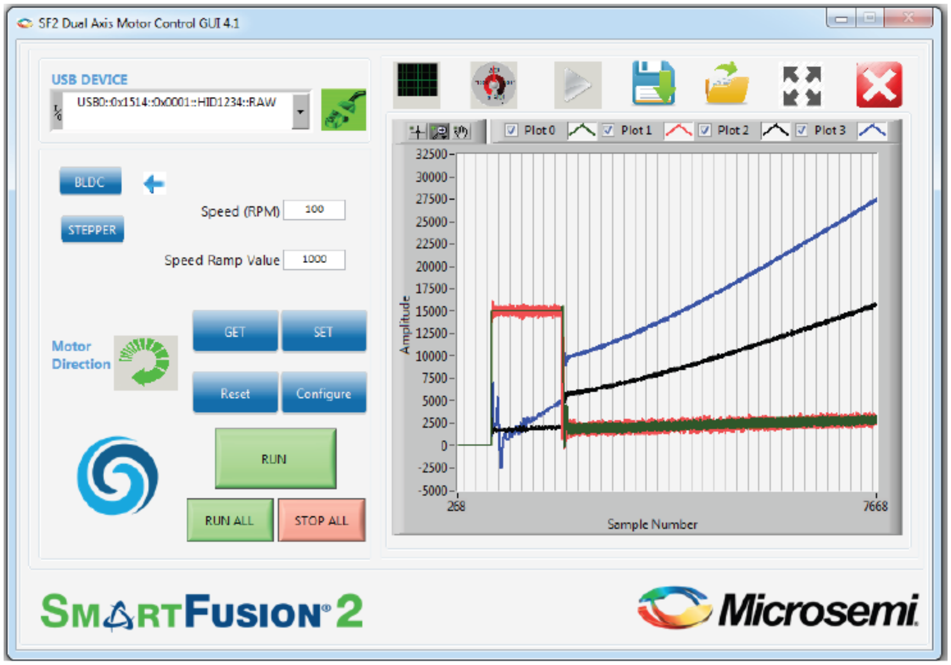

Figure 2: Real-time Graphical Display of Internal Parameters

Design Resources - Vault and List of IPs

For customers looking to develop their own motor control solution or customize parts of the implementation proposed in the previous section, Microsemi provides a motor control vault (MCV) including modular IP blocks with easy-to-use drag and drop interface. The MCV includes, among others, the following IP cores:

- PI controller
- ADC interface
- Phase PWM with dead time and delay time
- FOC transformations
- Space vector modulation
- Position and speed estimator
- Stepper micro-step generation
- Encoder interface
- Hall sensor interface

All these IPs have been developed through a process that eases DO-254 certification and were validated not only logically, but also on actual silicon. This is important for safety critical motor control applications.

High Performance and Safety-Aware Algorithms

Figure 3 shows the block diagram of the algorithm.

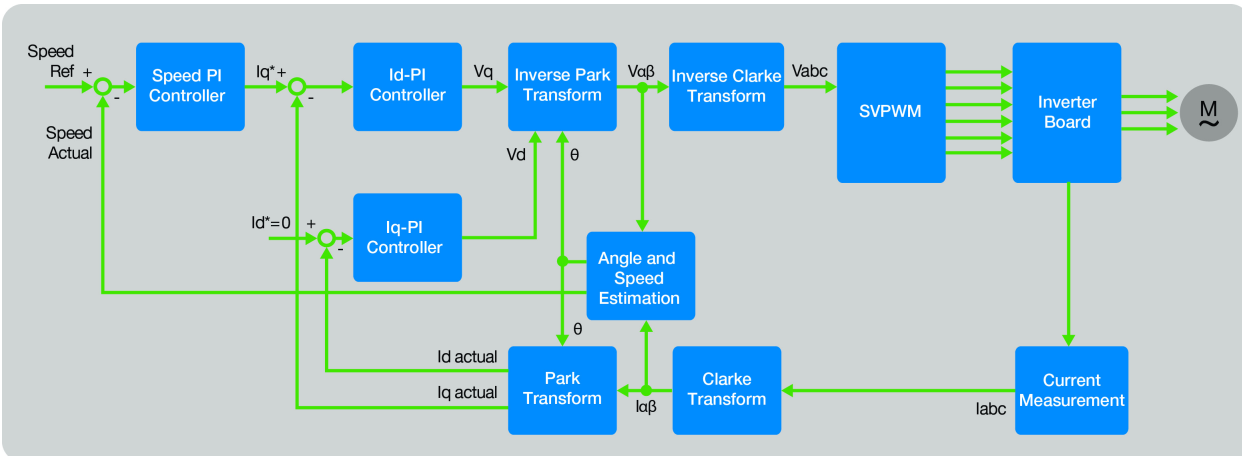

Figure 3: Microsemi Modular Sensorless BLDC Motor Control Block Diagram

Microsemi motor control algorithm has embedded safety features that detects rotor slip due to overload and attempts to restart the motor for a predetermined number of times. Additionally, the approach also features overcurrent and fault shut-downs within single system clock cycle.

The design uses coordinate rotation digital computer (CORDIC) with sine-cosine required for field oriented control (FOC) of motors. The design is optimized to make sure not only the least FPGA resources are used but also to execute full motor control algorithm within a short period. Currently, the full cycle is executed in as short as 1 µs for sensorless operation. This low latency enables to switch at very high frequencies and reduce the ripple in motor current and torque.

The design offers several features to allow bidirectional operation, dynamic and accurate speed control with the lowest in the industry torque ripple when several motors are used.

Hardware Kits

Microsemi offers out-of-the-box ready to use motor control starter kit, shown in Figure 4. This kit can be used to evaluate reference design and also to customize the design for specific customer application. The kit can be used to control BLDC and stepper motors and has following features:

- Capable of controlling motors up to 48 V and 8 A with switching frequency up to 500 kHz
- Analog-to-digital converter (ADC) with 12-bit resolution and 1 MSPS sampling rate
- Single ended/differential encoder interface
- HALL sensor interface
- High-speed USB, 10/100/1000 Ethernet, universal asynchronous receiver/transmitter (UART)
- Compact size and uses a single power supply

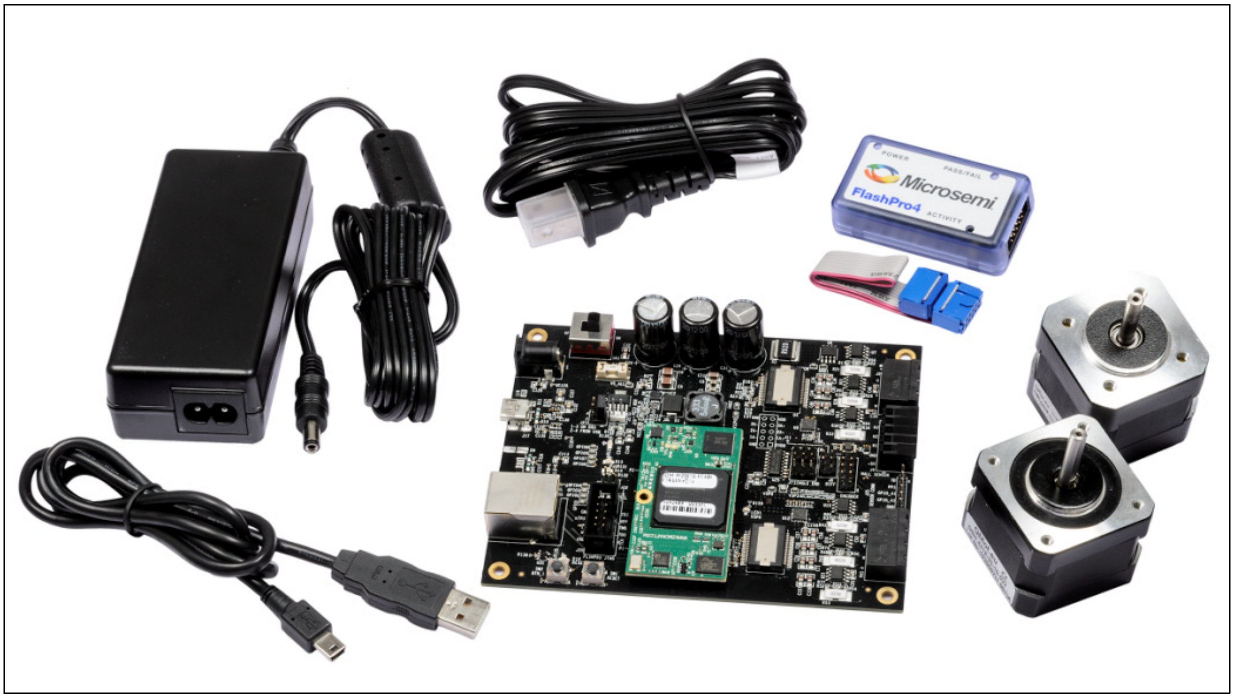

Figure 4: Microsemi Dual-Axis Motor Control Kit

Design Services and Expert Technical Support

Microsemi believes that expert support is as valuable as the innovative solution it brings to customers. The investments Microsemi made in developing the internal expertise were made not only to bring up innovative solutions, but also to enable customers access this expert support team. The team is capable of helping customers reach their design goals in a shorter time and covers various areas such as customization, tweaking of parameters or IPs, timing and power optimization. The team has expertise to assist from system-level down to the actual hardware implementation of the algorithm or tools settings.

This removes any tools related learning time or cost for customers not familiar with Microsemi Libero SoC FPGA design toolset. For users who want to acquire knowledge and expertise using these tools, Microsemi offers free remote and on-site training sessions. Users can access new revisions of the solutions by signing a maintenance contract.

Conclusion

The innovative implementation proposed in this paper achieves several design goals at the same time, namely, safety, flexible performance, scalability, and cost. Combined with the inherent benefits of the Microsemi nonvolatile IGLOO2 FPGAs such as security, low power, SEU immunity, and longevity of supply, it is a unique offer that allows motor control designers not only to achieve their schedules, but also to differentiate their solutions against their competitors. The reference solution provided does not require expertise neither in motor control, nor in the Microsemi toolset.

Table 3,Table 4, Table 5, and Table 6 provide a summary of the various attributes considered in the comparative study presented in "Limitations of MCU, MPU, and DSP-Based Motor Control Solutions" on page 3. While throughout the paper, the focus was on contrasting Microsemi IGLOO2-based BLDC motor control solution against MCU, MPU, and DSP-based implementations, the tables below consider SRAM FPGAs-based alternative. The ruggedized non-volatile Microsemi FPGAs have various advantages when compared to SRAM FPGAs in particular in areas such as reliability, security, power consumption live at power up, and total cost of operation and ownership. The authors spent quality time checking the various documents from various vendors, and when no reference was found, "Not documented" is mentioned for fairness.Future work is focused on additional valuable on-the-fly features, support of the largest number of motors and additional dissimilar motors (BLDC, stepper, and induction motors).

Table 3 • **Determinism, Performance and Scalability – Platforms Comparative Summary**

		MCUs	MPUs	DSPs	SRAM FPGAs	Microsemi FPGAs
Determinism		No	No	No	Yes	Yes
Scalability	Number of motors	Limited to 1	Limited to 2 or 3	Limited to 2 or 3	Not documented	8+
	Mix of motor types	No	No	No	Not documented	BLDC, stepper
	Dynamic speed control	Very limited	Limited	Limited	Limited	Yes
Performance	TDM impact	Very high	Very high	High	High	Very low
	Torque ripple	High	Medium to high	Medium to high	Medium	Very low
	Harmonics	High	Medium to high	Medium	Low to medium	Very low

Table 4 • **Reliability, Safety, and Security Risks – Platforms Comparative Summary**

		MCUs	MPUs	DSPs	SRAM FPGAs	Microsemi FPGAs
Reliability	Extreme temperature	Industrial temperature	Industrial temperature	Industrial temperature	Mil temperature (limited to old products)	Mil and automotive temperature range
	SEU susceptibility	Yes	Yes	Yes	Yes	No
Safety	Rotor slip detection	Not documented	Not documented	Not documented	Not documented	Yes
	Overcurrent and fault shut-downs	Not documented	Not documented	Not documented	Not documented	Yes
	Dynamic speed control	Very limited	Limited	Limited	Limited	Yes
Security and Risks	Tamper risk	High	High	Very high	Very high	No risk
	Cloning risk	Very high	Very high	Very high	Very high	No risk
	Overbuilding risk	Very high	Very high	Very high	Very high	No risk

Table 5 • **Longevity of Supply and Total Cost of Ownership (TCO) – Platforms Comparative Summary**

		MCUs	**MPUs**	**DSPs**	**SRAM FPGAs**	**Microsemi FPGAs**
Longevity of supply		Medium	Medium	Medium	Medium to high	20+ years
Total cost of ownership	Acquisition cost	Low	Medium	Low to medium	Low to medium	Medium
	Maintenance cost	Low to medium	Medium	Medium	Low	Low to none
	Soft cost	High	Medium	Medium	Low to medium	Low
	Obsolescence cost	Low to high	Low to medium	Low to medium	High	Very low

Table 6 • **Motor Control Specific Eco-systems – Platforms Comparative Summary**

		MCUs	**MPUs**	**DSPs**	**SRAM FPGAs**	**Microsemi FPGAs**
Moto control eco-system	IDE	Limited	Rich	Per platform	Rich	Rich
	Motor control IPs or firmware libraries	Limited	Rich	Rich	Limited	Very rich
	DO-254 or DO-178	No	No	No	No	Yes
	Motor control kits	Yes	Yes	Yes	Limited (through partners)	Yes (dual and 6-axis)
Learning curve		Relatively short	Long	Long	Medium to long	Short
Expertise required		Some level	High	High	High	Very basic

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