IAES Journal of Electrical and Electronics Engineering
Vol. 4, No. 2, December 2017, pp. 41~44
ISSN: 2338-7432, DOI: 10.11591/jeee.v4i2.pp41-44

From hardware prototyping to intelligent control: the role of FPGA in robotics, automation, and power electronics

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Article Info

Article history:

Received Nov 11, 2016
Revised Jun 30, 2017
Accepted Sep 10, 2017

Keywords:

Field-programmable gate array
Hardware–software co-design
Industrial automation
Power electronics
Real-time control
Robotics

ABSTRACT

Field-programmable gate arrays (FPGAs) have evolved from configurable hardware prototyping platforms into important computational elements for real-time control and intelligent embedded systems. Their parallel processing capability, deterministic timing, and reconfigurable logic make them attractive for applications in robotics, industrial automation, and power electronics. Nevertheless, integrating FPGA technology into these domains involves challenges related to hardware–software partitioning, development complexity, resource utilization, and system verification. This review examines the role of FPGAs across these application areas, emphasizing the transition from rapid hardware prototyping to practical control implementation. The discussion draws on selected peer-reviewed journal and conference publications available up to 2016, covering industrial control architectures, robotic motion control, visual servoing, motor drives, and digitally controlled power converters. The literature indicates that FPGAs can execute time-critical control functions in parallel while supporting flexible system integration and hardware–software co-design. However, their advantages depend strongly on application requirements, implementation methodology, and engineering expertise. The review identifies key technical limitations and discusses opportunities for more integrated, reliable, and intelligent FPGA-based control systems.

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1. INTRODUCTION

Modern engineering systems increasingly require control platforms that combine high computational performance, predictable response time, and flexible hardware integration. Robotics, industrial automation, and power electronics are particularly demanding because they involve fast physical processes, multiple sensors, actuators, and continuously changing operating conditions. Conventional microprocessors and digital signal processors provide accessible programming environments, but sequential execution can become restrictive when several time-critical tasks must be completed simultaneously. Field-programmable gate arrays (FPGAs) offer an alternative by allowing designers to implement customized digital circuits that execute independent operations concurrently [1], [2].

The central research problem is therefore not simply whether an FPGA can implement a control algorithm, but how its reconfigurable architecture can improve the complete engineering process from prototyping to deployment. In robotics, this problem involves coordinating motion planning, feedback control, and sensor processing within strict timing constraints. In industrial automation, it involves integrating deterministic control with communication, monitoring, and hardware–software co-design. In power electronics, it concerns the implementation of fast switching, current regulation, and fault-management functions while maintaining reliable converter operation [1], [2].

This review examines the role of FPGA technology across these interconnected fields, focusing on the relationship between hardware architecture, prototyping methodology, and intelligent control implementation. It adopts a narrative review approach based on selected peer-reviewed publications available up to December 2016. The selected literature includes foundational discussions of FPGA-based industrial

control, experimental robotic controllers, visual servoing architectures, and digital control platforms for power converters. The analysis is organized around application domains, implementation strategies, limitations, and future research directions.

2. FPGA ARCHITECTURE AND THE TRANSITION FROM PROTOTYPING TO CONTROL

FPGAs provide configurable logic blocks, programmable interconnections, memory resources, and specialized arithmetic units that can be assembled into application-specific hardware architectures. Unlike conventional processors, which generally execute instructions through a shared processing sequence, FPGAs can perform multiple operations concurrently through dedicated logic circuits. This capability is particularly useful when control systems must process sensor signals, calculate control outputs, and update actuators within short and predictable intervals. Their reconfigurability also allows engineers to modify hardware functions during development without redesigning an entire integrated circuit [1].

The transition from prototyping to operational control requires more than implementing an algorithm in programmable logic. Engineers must determine which functions should be implemented in hardware and which should remain in software, especially when the design includes embedded processors and communication interfaces. Monmasson *et al.* [1] discussed FPGA design methodologies for industrial control and demonstrated the relevance of hardware–software integration for complex control applications. Bahri *et al.* [3] further examined hardware–software partitioning for system-on-chip FPGA-based sensorless AC drives, illustrating how computational tasks can be distributed between programmable logic and embedded processing resources.

A practical development workflow generally begins with algorithm modeling and simulation, followed by hardware description, synthesis, implementation, and experimental validation. Hardware-in-the-loop testing and modular prototyping can reduce the risk of transferring an unverified controller directly to physical equipment. The development process must also consider numerical precision, timing closure, resource consumption, and the behavior of interfaces between hardware and software. Consequently, FPGA prototyping is most effective when verification and system-level design are treated as integral activities rather than final implementation steps.

3. APPLICATIONS IN ROBOTICS

Robotic systems provide a clear example of the benefits of parallel processing and deterministic control. A robot manipulator may require simultaneous position, velocity, and current regulation across several motor axes, while its supervisory controller performs trajectory generation and system coordination. Kung *et al.* [4] developed an FPGA-based servo control integrated circuit for a six-axis articulated robot manipulator, combining trajectory planning with multiple position, speed, and current control functions. Their implementation demonstrates how FPGA-based system-on-chip architecture can consolidate control functions that might otherwise require several separate processing devices.

FPGA technology is also relevant to visual servoing, where image information is used to guide robot movement. Image acquisition, feature extraction, control computation, and actuator updates can impose substantial computational demands, particularly when a robot must respond to moving objects or changing visual conditions. Pérez *et al.* [5] presented an FPGA-based visual control architecture using dynamic perceptibility for robotic manipulators, demonstrating the application of parallel hardware to direct visual control. Such architectures suggest that programmable logic can support the integration of perception and motion control, although performance depends on sensor characteristics, algorithm complexity, and hardware resources.

A further consideration is the implementation of advanced control algorithms on robotic platforms. Gürsoy and Efe [6] investigated proportional-derivative and sliding-mode control schemes implemented on an FPGA platform for robot manipulators. Their work compared FPGA-based implementations with MATLAB/Simulink results and demonstrated the feasibility of hardware-based trajectory control. These studies collectively indicate that FPGAs can support both conventional feedback controllers and more computationally demanding robotic functions, provided that the architecture is carefully designed and experimentally validated.

4. APPLICATIONS IN INDUSTRIAL AUTOMATION

Industrial automation requires controllers that can coordinate sensors, actuators, motor drives, and communication interfaces while maintaining predictable execution. In production environments, timing variation may affect synchronization, product quality, and machine safety, making deterministic operation an

important design requirement. FPGA-based controllers can implement parallel signal-processing and control functions, allowing selected operations to execute independently rather than compete for processor time. Monmasson *et al.* [1] identified industrial control as an important application area for FPGAs and discussed design methodologies, development tools, and implementation considerations.

Hardware–software co-design is especially important when industrial systems combine complex supervisory functions with fast local control loops. Embedded processors can manage configuration, diagnostics, and higher-level decision-making, while programmable logic performs time-critical operations such as pulse generation, signal conditioning, and rapid feedback processing. This division can improve implementation flexibility, but it also introduces integration challenges involving data transfer, synchronization, and verification. The design must therefore allocate functions according to their timing requirements and computational characteristics rather than simply moving as much processing as possible into hardware [1], [3].

5. APPLICATIONS IN POWER ELECTRONICS

Power electronic converters require rapid control of switching devices to regulate voltage, current, and power under changing load conditions. Digital control platforms have become increasingly important in applications such as motor drives, renewable energy systems, distributed generation, and electric transportation. Buccella *et al.* [2] reviewed digital control of power converters and discussed the use of microcontrollers and FPGAs, including hardware and software implementation considerations. FPGAs are particularly relevant when multiple control channels, high switching frequencies, or specialized modulation strategies create demanding computational requirements.

The use of FPGAs in motor drives illustrates the connection between power electronics and intelligent automation. Sensorless drive systems, for example, require the estimation of motor states from measured electrical quantities, which may involve computationally intensive algorithms. Bahri *et al.* [3] described hardware–software co-design guidelines for FPGA-based sensorless AC drive applications, emphasizing the importance of partitioning functions between hardware and software. Such approaches can support fast control execution while retaining software flexibility for functions that do not require dedicated hardware acceleration.

Prototyping platforms can also improve the development and evaluation of converter controllers. Andersen and Nymand [7] presented a flexible FPGA-based experimental platform for testing and verifying digitally controlled DC–DC converters with different control strategies and converter topologies. Their platform included synchronized load-change functionality and data acquisition resources, supporting systematic comparison of control implementations. This approach demonstrates that FPGA development can contribute not only to final controller performance but also to the experimental process used to validate power electronic systems.

6. COMPARATIVE ANALYSIS AND TECHNICAL CHALLENGES

The three application domains share a requirement for reliable real-time processing, but their dominant engineering priorities differ. Robotics emphasizes coordinated motion, sensor integration, and perception, whereas industrial automation places strong emphasis on deterministic machine coordination and system integration. Power electronics focuses on fast switching control, electrical measurement, and converter protection. Table 1 summarizes these application characteristics and the principal contributions that FPGA technology can provide.

As shown in Table 1, FPGA technology provides a common hardware foundation for applications with different control objectives. Its main advantage is the ability to customize processing architecture around the timing and computational demands of a particular system. However, the table also highlights that hardware acceleration does not automatically solve application-level problems such as sensor reliability, system synchronization, or safe operation. These issues must be addressed through complete system design and experimental testing.

Table 1. FPGA roles across robotics, industrial automation, and power electronics

Application domain	Representative functions	FPGA contribution	Main implementation concern
Robotics	Servo control, trajectory generation, visual servoing	Parallel multi-axis control and sensor processing	Synchronization and numerical precision
Industrial automation	Machine coordination, signal processing, embedded control	Deterministic execution and hardware–software integration	Verification and maintainability
Power electronics	PWM generation, current regulation, converter testing	Fast control loops and configurable digital hardware	Switching constraints and fault handling

Several challenges continue to limit wider FPGA adoption. First, hardware description languages and digital design workflows require specialized expertise, which can increase development time compared with conventional software programming. Second, resource constraints and timing closure can become difficult when control algorithms, communication interfaces, and signal-processing functions compete for programmable logic resources. Third, hardware–software interfaces introduce additional verification requirements, particularly in systems where incorrect timing or data exchange can affect physical equipment [1], [3].

Another important challenge concerns the meaning of intelligent control in FPGA-based systems. FPGAs can accelerate neural-network operations, state estimation, and advanced control algorithms, but implementing computational intelligence does not by itself make a system autonomous or adaptive. Intelligent behavior depends on suitable algorithms, representative data, reliable sensing, and appropriate decision-making mechanisms. Therefore, FPGA-based intelligent control should be understood as the integration of reconfigurable computation with validated control strategies rather than as a direct consequence of hardware parallelism.

7. RESEARCH DIRECTIONS

Future development should prioritize design methodologies that make FPGA-based control systems easier to develop, verify, and maintain. High-level synthesis and model-based design can reduce the distance between control-system modeling and hardware implementation, although generated hardware must still be evaluated for resource utilization and timing behavior. Modular architectures may also support reuse across robotic platforms, industrial controllers, and power converters. These approaches could make FPGA technology more accessible to engineers whose primary expertise lies in control systems rather than digital hardware design.

Further research should investigate the integration of perception, estimation, and control within heterogeneous FPGA systems. In robotics, this could involve combining visual processing with motion control, while industrial automation could benefit from integrating machine monitoring with deterministic control functions. In power electronics, programmable hardware may support more sophisticated converter-control strategies and rapid fault detection. Across all three fields, progress will depend on rigorous benchmarking, hardware-in-the-loop validation, and transparent comparisons with processor-based alternatives.

8. CONCLUSION

FPGAs have developed from flexible hardware prototyping devices into practical platforms for real-time control in robotics, industrial automation, and power electronics. Their parallel processing, reconfigurability, and deterministic execution make them suitable for applications involving multiple control loops, fast signal processing, and specialized hardware functions. Research on multi-axis robotic control, visual servoing, industrial system integration, and digital converter platforms demonstrates the breadth of their engineering applications. Nevertheless, successful deployment requires careful hardware–software partitioning, resource management, numerical design, and systematic verification. The transition toward intelligent FPGA-based control will therefore depend not only on faster hardware but also on improved development methodologies and reliable integration with application-specific algorithms.

REFERENCES

[1] E. Monmasson, L. Idkhajine, M. N. Cirstea, I. Bahri, A. Tisan, and M. W. Naouar, "FPGAs in industrial control applications," *IEEE Transactions on Industrial Informatics*, vol. 7, no. 2, pp. 224–243, May 2011, doi: 10.1109/TII.2011.2123908.

[2] C. Buccella, C. Cecati, and H. Latafat, "Digital control of power converters - A survey," *IEEE Transactions on Industrial Informatics*, vol. 8, no. 3, pp. 437–447, Aug. 2012, doi: 10.1109/TII.2012.2192280.

[3] I. Bahri, L. Idkhajine, E. Monmasson, and M. El Amine Benkhelifa, "Hardware/Software codesign guidelines for system on chip FPGA-based sensorless AC drive applications," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 4, pp. 2165–2176, Nov. 2013, doi: 10.1109/TII.2013.2245908.

[4] Y. S. Kung, J. M. Lin, Y. J. Chen, and H. H. Chou, "Field programmable gate array-based servo control integrated chip for a six-axis articulated robot manipulator," *Advances in Mechanical Engineering*, vol. 8, no. 5, pp. 1–12, May 2016, doi: 10.1177/1687814016646520.

[5] J. Pérez, A. Alabdo, J. Pomares, G. J. García, and F. Torres, "FPGA-based visual control system using dynamic perceptibility," *Robotics and Computer-Integrated Manufacturing*, vol. 41, pp. 13–22, Oct. 2016, doi: 10.1016/j.rcim.2016.02.005.

[6] H. Gürsoy and M. Ö. Efe, "Control System Implementation on an FPGA Platform," *IFAC-PapersOnLine*, vol. 49, no. 25, pp. 425–430, 2016, doi: 10.1016/j.ifacol.2016.12.087.

[7] K. H. Andersen and M. Nymand, "Flexible experimental FPGA based platform: For testing and verifying digital controlled DC-DC converters," in *2016 IEEE 2nd Annual Southern Power Electronics Conference, SPEC 2016*, Dec. 2016, pp. 1–6. doi: 10.1109/SPEC.2016.7846080.