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Doctoral Dissertation

Doctoral Program in Computer and Control Engineering (37th cycle)

Reconfigurable Accelerators Design Methods for High Reliability Space Applications

By

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Politecnico di Torino

2025

Abstract

The continuous scaling of semiconductor technology has led to significant improvements in performance, energy efficiency, and integration density, enabling the development of increasingly powerful and flexible computing architectures. Among these, Field-Programmable Gate Arrays (FPGAs) have gained prominence due to their ability to provide high-performance, reconfigurable solutions tailored to specific applications. Their versatility makes them particularly well-suited for space systems, where custom, mission-adapted hardware is essential. However, the harsh radiation environment of space poses significant reliability challenges, as FPGAs are highly susceptible to radiation-induced effects. To ensure the robustness of FPGA-based designs in space, it is necessary to develop methodologies that enhance their resilience while maintaining performance and resource efficiency.

This dissertation proposes a comprehensive set of tools and techniques to improve the reliability of FPGA-based accelerators operating in radiation environments. The research covers multiple levels of abstraction, from low-level design methodologies to system-level fault mitigation strategies. First, placement and routing techniques are explored to optimize fault tolerance, leading to the development of a CAD tool that enhances the fault resilience of reconfigurable designs. Additionally, a novel Total Ionizing Dose (TID) estimation tool is introduced to provide more accurate predictions for radiation-aware design. Specifically, the tool performs dose estimation for interplanetary missions considering the effective spacecraft trajectory combined with solar activity prediction, providing a powerful means to characterize spacecrafts sensitivity related to their mission profile.

To evaluate and mitigate radiation-induced errors, an analysis framework is developed to assess Single Event Effects (SEEs) in FPGA-based design, aiming at performing a mission-tailored estimation of system Mean Time to Failure. The dissertation also focuses on AI-oriented accelerators, particularly systolic arrays, which

are becoming increasingly relevant in space computing due to their efficiency in executing deep neural networks. Through detailed reliability analysis, new fault detection and mitigation techniques are introduced, leveraging data mapping strategies to minimize susceptibility to faults.

The culmination of this research is the development of the Reconfigurable Platform for AI Resilience within RISC-V Ecosystem (RePAIR), an integrated fault detection and recovery system that combines a RISC-V processor with a Tensor Processing Unit (TPU) to enable resilient AI acceleration. By leveraging Dynamic Partial Reconfiguration (DPR), the platform can recover from faults with minimal downtime, ensuring efficient and reliable execution of deep learning workloads in space environments.

The findings of this dissertation highlight the critical role of fault-tolerant design methodologies in ensuring the reliability of FPGA-based accelerators for space applications. By addressing challenges across multiple levels of abstraction—ranging from placement and routing optimizations to AI-specific fault mitigation strategies—this work provides a robust foundation for enhancing the resilience of reconfigurable computing in radiation-prone environments. The development of the RePAIR platform further demonstrates the feasibility of integrating AI acceleration with dynamic fault recovery, paving the way for future advancements in resilient space computing. Building on these contributions, future research should explore adaptive machine-learning techniques for real-time fault prediction and mitigation, as well as extend the applicability of radiation-hardened design approaches to emerging FPGA architectures. Additionally, further validation through radiation tests and collaborations with space agencies will be crucial in refining these techniques for next-generation space missions.