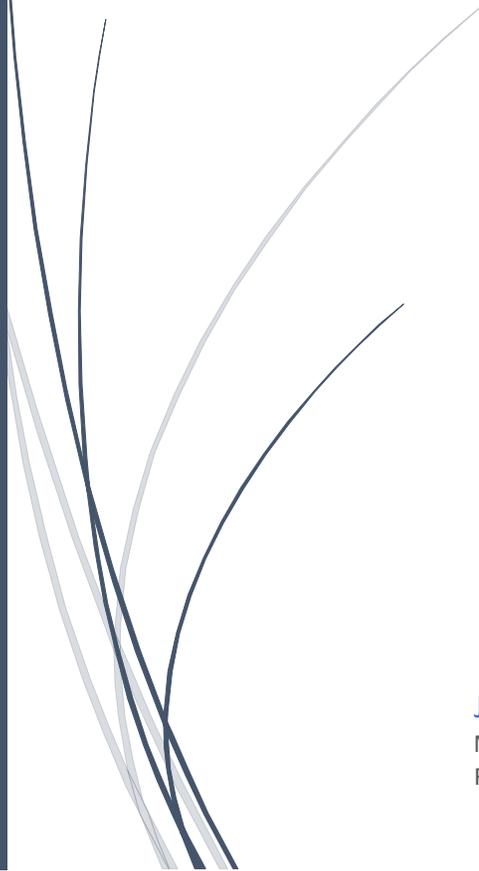




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FPGA Based Real Time Image Processing Architectures for Autonomous Navigation Systems



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Abstract

The rapid advancement of autonomous navigation systems across domains such as intelligent transportation, aerial robotics, and industrial automation has intensified the need for high-performance, real-time image processing solutions. Field-Programmable Gate Arrays (FPGAs) have emerged as a powerful platform to meet these demands, offering customizable, parallel, and energy-efficient architectures suitable for time-sensitive inference tasks. This chapter presents a comprehensive study on FPGA-based real-time image processing architectures tailored for autonomous navigation. It explores the integration of compact and deep learning models, discusses heterogeneous co-design methodologies combining High-Level Synthesis (HLS) with low-level RTL, and addresses key challenges related to timing closure, resource utilization, and memory constraints. The implementation of mixed-precision computing strategies, energy-proportional design techniques, and lightweight neural networks are emphasized as critical enablers for achieving low-latency and power-aware processing on edge devices. The chapter highlights emerging trends, current research gaps, and directions that will drive the evolution of reconfigurable architectures in intelligent autonomous systems. By aligning architectural optimization with real-time performance and energy efficiency, this work lays a robust foundation for scalable and deployable FPGA solutions in next-generation navigation platforms.

Keywords: FPGA, Real-Time Image Processing, Autonomous Navigation, Deep Learning Acceleration, Energy Efficiency, Hardware-Software Co-Design

Introduction

The growing demand for intelligent autonomous systems has driven significant advancements in real-time perception technologies [1]. Autonomous vehicles, aerial drones, and mobile robots are now deployed in dynamic environments that require rapid interpretation of sensory data to make safe and accurate navigation decisions [2]. Among various sensory modalities, visual data offers rich contextual information, enabling systems to detect obstacles, recognize landmarks, and plan optimal trajectories, processing high-resolution image data in real-time presents computational challenges, especially when latency, power consumption, and hardware footprint

are critical constraints [3]. Conventional processing units, such as central processing units (CPUs) and graphics processing units (GPUs), while powerful, often fall short in meeting the stringent real-time and energy efficiency demands of embedded systems [4]. Consequently, reconfigurable hardware platforms like Field-Programmable Gate Arrays (FPGAs) have gained prominence as they offer hardware-level parallelism, low latency, and power-aware performance, all of which are essential for real-time image processing in autonomous navigation systems [5].

FPGAs are particularly suited for deterministic, high-throughput applications due to their reconfigurable logic fabric and support for custom data path design [6]. Unlike general-purpose processors, FPGAs can be tailored to meet the unique requirements of specific algorithms, enabling optimized computation and efficient memory access patterns [7]. In the context of image processing pipelines, this includes tasks such as edge detection, object recognition, semantic segmentation, and tracking, all of which can be efficiently mapped onto the parallel architecture of an FPGA [8]. Recent advancements in High-Level Synthesis (HLS) tools have further enabled rapid development and integration of complex algorithms onto FPGAs using high-level programming languages. This has accelerated the adoption of FPGAs across various sectors, particularly in autonomous systems where latency and energy efficiency cannot be compromised [9]. The ability to offload computationally intensive image processing tasks to dedicated hardware accelerators significantly enhances the real-time responsiveness and reliability of navigation systems operating in unpredictable and fast-changing environments [10].