COMPARATIVE ANALYSIS OF FPGA AND MICROCONTROLLER ARCHITECTURES FOR REAL-TIME FILTERING IN AIRSPACE SURVEILLANCE SYSTEMS

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Abstract. Modern Airspace Surveillance Systems (ASSS) demand high-speed, low-latency data processing to ensure timely and accurate target tracking. This paper presents a comparative analysis of two hardware platforms—Field-Programmable Gate Arrays (FPGAs) and high-performance Microcontrollers (MCs)—for implementing critical Kalman Filter (KF) algorithms used in radar data preprocessing and noise reduction. The study evaluates the architectural suitability of each platform with respect to processing speed, determinism, power efficiency, and development complexity. The findings indicate that while MCs offer advantages in development ease and power efficiency for localized tasks, FPGAs are indispensable for achieving the ultra-low latency and massive parallelism required for complex multi-sensor data fusion. This capability directly enhances the quality and integrity of information support for air traffic control.

Keywords: FPGA; Microcontroller (MC); Kalman Filter (KF); Real-Time Processing; Data Filtering; Air Surveillance Systems (ASSS); Main body.

Introduction. The quality of information support provided by Airspace Surveillance Systems (ASSS) is contingent upon the timeliness and accuracy of processing large volumes of heterogeneous data from various sensors (e.g., radars, ADS-B). Contemporary requirements for tracking high-speed and maneuvering targets impose stringent constraints on processing latency. Traditional software solutions running on general-purpose processors often fail to guarantee the necessary level of deterministic execution time, leading to computational bottlenecks. This results in degraded trajectory prediction accuracy, which is unacceptable for mission-critical systems. The objective of this work is to conduct a comparative analysis of FPGA and Microcontroller (MC) architectures as hardware platforms for implementing pre-filtering algorithms, specifically the Kalman Filter (KF). The aim is to provide a rationale for platform selection to enhance the quality of information support in ASSS.

Main body. For an objective comparative analysis, the classic Kalman Filter (KF) is selected as the foundational recursive algorithm for noise reduction and state estimation of aerial objects. The implementation of this algorithm on different hardware platforms—FPGAs and Microcontrollers

(MCs)—highlights their fundamental architectural suitability for high-speed surveillance systems.

The architectural differences are key. FPGAs are distinguished by their flexibility, allowing for massive parallel execution of all necessary KF matrix operations (multiplication, addition, inversion) simultaneously, rather than sequentially. This is achieved through the creation of a dedicated hardware pipeline. This parallelism, combined with the use of optimized fixed-point arithmetic, results in ultra-low, strictly deterministic latency (on the order of microseconds). This performance is crucial for ensuring the timeliness of information support for tracking highly dynamic targets. While development in Hardware Description Languages (HDLs) is complex, it allows for the maximum optimization of underlying hardware resources.

Conversely, Microcontrollers (MCs) rely on a traditional sequential architecture (von Neumann). The algorithm is executed step-by-step by the CPU core, typically utilizing floating-point arithmetic. This sequential processing limits the overall throughput and leads to higher, non-deterministic latency compared to FPGAs, often introducing fluctuations due to RTOS overhead. Nonetheless, MCs are the superior choice for energy efficiency and are better suited for distributed peripheral nodes, low-level control tasks, and primary data filtering in autonomous systems where development speed and lower power consumption are prioritized.

The comparative analysis reveals that the choice of architecture directly impacts the quality of information support through several key metrics (Table 1).

Table 1 – Comparative analysis of FPGA and MC architectures for data filtering tasks.

Quality Criterion	FPGA	MC (Microcontroller)	Impact on Information Quality
Speed / Latency	Ultra-low (µs) due to parallelism	Medium; limited by sequential processing	Determines the timeliness of tracking high-speed targets.
Throughput	Massively parallel processing of thousands of points/sec.	Limited by single-core performance.	Determines the capability for multi-sensor data fusion.
Determinism	Strictly deterministic execution time.	Potential fluctuations due to RTOS and interrupts.	Ensures reliability and synchronization accuracy.

Power Consumption	Higher under full load.	Lower in standby or periodic processing modes.	Affects system autonomy and mobility.

The key findings confirm that FPGAs offer a decisive advantage in speed, throughput, and determinism. This makes them essential for centralized processing nodes managing multi-sensor data fusion, directly enhancing the operational quality and accuracy of trajectory analysis under heavy load. MCs, excelling in power efficiency and development complexity, are optimal for peripheral nodes and auxiliary subsystems, complementing the high-speed core.

Conclusions. This study confirms that the choice of hardware platform architecture is crucial for improving the quality of information support in ASSS. It has been demonstrated that FPGAs are indispensable for meeting stringent real-time requirements in filtering and radar data fusion algorithms. Future research will focus on integrating more complex algorithms (e.g., Unscented Kalman Filter - UKF) and implementing "Edge AI" components on FPGAs for direct classification of aerial objects at the point of data collection.

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