Hybrid Approaches to Building Intelligent Robotic Systems on FPGAs and MCUs for Industry 5.0 Tasks

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***Abstract* — The paper considers hybrid approaches to the development of intelligent robotic systems using microcontrollers (MCU) and programmable logic integrated circuits (FPGAs) in the context of Industry 5.0 tasks. The advantages and limitations of existing technical solutions in the construction of cognitive and collaborative robots are analyzed. The feasibility of combining MCU and FPGAs within the framework of decentralized control systems capable of adaptation, interaction and learning in real time is substantiated. The proposed approaches demonstrate the potential for increasing the efficiency of distributed robot systems in human-centric technologies.**

Keywords — Industry 5.0, Microcontroller, FPGA, Robotics, Collaborative Robots, Hybrid Architecture, Cognitive Systems.

I. INTRODUCTION

The current stage of robotics development in the context of the transition to Industry 5.0 is accompanied by an active search for solutions that combine a high level of flexibility, adaptability and intelligent interaction between man and machine [1,2]. One of the challenges of this direction is the creation of effective hardware and software platforms for controlling robots, capable of real self-learning, real-time processing of sensor data and distributed information processing [3,4]. In this context, hybrid approaches that combine the capabilities of microcontrollers and FPGAs for building controlled and autonomous systems focused on cognitive and collaborative behavior [5,6] are gaining particular relevance.

II. FUNCTIONAL ASPECTS OF THE MCU–FPGA HYBRID ARCHITECTURE IN COLLABORATIVE ROBOTICS

The use of microcontrollers such as ESP32, STM32 or ESP8266MOD(12F) provides an affordable and energy-efficient solution for local control of actuators, data collection from sensors, implementation of basic control algorithms, network interaction between nodes [7-9]. At the same time, these devices have limited computing resources, in particular when performing parallel tasks, intensive data processing or implementing complex neural networks. FPGAs, in turn, allow the creation of specialized parallel hardware modules for processing video streams, implementing high-speed interaction, autonomous action planning and reactive response to external influences. This approach allows you to build intelligence into the system without significantly increasing delays or power consumption, which is critically important for mobile robots.

The advantage of the hybrid architecture is the ability to divide the functional load: the MCU is responsible for communications, basic logic, and data reading, while the FPGA performs tasks that require high performance — processing sensory information, making decisions at the level of local agents, calculating optimal trajectories, etc. [10]. In addition, the FPGA allows the implementation of hardware modules of neural networks or fuzzy logic, which allows significantly improving the cognitive properties of the system [11,12]. However, these solutions require more complex design, knowledge of digital logic, and an appropriate development environment, which increases the threshold of entry and the cost of implementation.

Existing studies demonstrate the successful combination of MCU and FPGA in platforms for autonomous mobile robots, robot assistants, and collaborative systems. For example, the MCU implements wireless communication protocols (Wi-Fi, ZigBee), local planning, and the FPGA provides parallel processing of data from cameras, IMU, LIDAR, as well as the calculation of neural network representations for behavioral strategies [13,14]. An important advantage of such systems is the ability to scale and reconfigure to the specifics of the environment or task without the need to completely replace the hardware. In the context of collaborative robotics, especially in small-sized multi-component systems (e.g., swarms of humanoid robots), a hybrid architecture allows achieving a balance between the autonomy of individual agents and their coordination in the team [15,16]. Due to local processing and response to sensory stimuli, robots can effectively interact with the environment and other agents, reducing the load on the central server or global network. Also important is a distributed decision-making system, where each agent has basic intellectual ability, but in cooperation complex behavior is achieved - for example, joint manipulation, obstacle avoidance or learning through interaction..

III. Overview of hybrid system architectures for collaborative robots adaptive control

In modern practice of building intelligent robotic systems, hybrid approaches that combine microcontrollers (MCU) and programmable logic integrated circuits (FPGAs) are increasingly used [17,18]. One of the most common is the MCU-centric approach, in which the microcontroller performs basic calculations, decision logic, drive control and communication, while the FPGA is used as an auxiliary unit for hardware implementation of individual functions, such as signal filtering, PWM generation or signal processing from sensors. This approach is easy to implement and especially convenient for educational or consumer applications, as it requires minimal knowledge of digital logic and does not require complex development tools. Its advantages include the availability of components, energy efficiency and rapid prototyping. However, this approach limits the use of FPGA capabilities and does not provide an adequate level of parallel processing or implementation of complex artificial intelligence algorithms.

The opposite approach in terms of structure is the approach in which the FPGA is the main computing platform, and the microcontroller performs auxiliary functions, in particular, interface management, data transfer or user communication support. This approach allows you to use all the advantages of FPGA hardware parallelism - high performance, determinism in execution time, efficient data processing in real time. FPGA can simultaneously process information from several sensors, control actuators, implement hardware modules of neural networks or fuzzy logic. This is critically important in autonomous systems, drones, robots operating in a complex or dynamic environment. However, such an architecture requires a deep understanding of circuit design, learning hardware description languages, and significantly more time and resources for design.

One of the most balanced is the co-process or cognitive-sensory model, in which the microcontroller and FPGA operate as independent but synchronized modules. In this architecture, the MCU implements behavioral logic, communication, and the FPGA is responsible for high-speed processing of sensor data, decision-making in critical situations, execution of learning algorithms or neural network evaluation. Such interaction allows you to build flexible and adaptive systems in which autonomous agents are capable of self-learning, adaptation to environmental changes and distributed interaction. Despite this, the implementation requires complex synchronization between components, as well as effective organization of data exchange between the MCU and the FPGA, which requires a well-thought-out software architecture.

Integrated systems on a chip, such as FPGA-based SoC (such as Zynq) [19], combine the ARM core and FPGA logic on a single hardware platform. This design allows you to implement a full-fledged operating system based on the ARM processor and at the same time use programmable logic for fast data processing or performance of specific hardware functions. These solutions allow for the creation of compact and high-performance systems capable of processing video streams, implementing SLAM algorithms or machine vision in real time. The advantages include high integration, reduced communication delays between processor and logic modules, and ease of deployment of complex software. However, such an architecture has a high cost, relatively limited flexibility in scaling, and requires more expensive development tools.

The last of the approaches considered is a modular multi-level architecture, in which one or more microcontrollers coordinate the operation of a set of modules on the FPGA, each of which performs a specific computational or sensor task. Such a structure allows for easy scaling of the system, distributing the computational load between subsystems, and provides flexibility in configuration for specific tasks. Such an architecture is especially effective in collaborative robotics, where many agents or subsystems must act autonomously but in a coordinated manner. However, the disadvantage is the difficulty of synchronizing a large number of modules, delays in data exchange between system levels, and high complexity of design and debugging.

All these approaches have their strengths, and the choice of a specific architecture depends on the requirements for speed, energy efficiency, scalability, and intellectual complexity of the task. Hybrid systems that effectively combine the advantages of MCU and FPGA have great potential for implementing decentralized, autonomous, and adaptive robots, which meets the requirements of human-centric and flexible automation characteristic of Industry 5.0 [20]. Table 1 compares existing hybrid approaches to building intelligent robotic systems using microcontrollers (MCUs) and programmable logic integrated circuits (FPGAs) [21-23].

TABLE I. Comparison of existing hybrid approaches to the construction of intelligent robotic systems

Approach	Architecture	Functional distribution	Application examples
MCU-centric with FPGA support	MCU as the main controller, FPGA as the peripheral logic	MCU- planning, communication, drive control FPGA- sensor data filtering, PWM, encoders	Household robots, STEM robotics
FPGA-centric with MCU support	FPGA as the main computer, MCU as the auxiliary controller	FPGA- motion control, data processing, neural networks MCU- user interfaces, communication	Robots for industrial control, autonomous drones
Co-process (cognitive-sensory) model	MCU and FPGA work in parallel as equal modules	MCU- control and logic FPGA- sensorics, adaptive learning, machine vision	Swarms of mobile agents, humanoids, autonomous navigation systems
FPGA-based SoC with integrated MCU (Zynq type)	MCU (ARM) + FPGA on a single chip	ARM- OS, logic, exchange FPGA: peripherals, video processing, high-speed logic	Service and medical robots, embedded computer vision
Modular multi-level system (MCU + multiple FPGAs)	The MCU coordinates a group of FPGA modules	MCU- dispatching, collecting results FPGA- local processing in subsystems	Collaborative robots, complex robotic environments

Based on the analysis of Table 1 of hybrid approaches to building intelligent robotic systems based on microcontrollers and FPGAs, we can make a generalized conclusion that none of the approaches is universal, but each has its own niche of application depending on the specific requirements for functionality, performance, flexibility and level of autonomy of the system. MCU-centric models demonstrate high availability and simplicity, but have limited scalability and low computing power. FPGA-oriented architectures, on the contrary, are capable of high-speed data processing and implementation of complex intelligent algorithms, but their complexity, cost and requirements for specialized knowledge make them less suitable for rapid deployment in wide engineering environments. Co-process approaches seem to be the most balanced, where each component performs a clearly defined role, which allows building adaptive and modular systems that are able to respond in real time and effectively interact with other agents. In the context of developing control systems for collaborative robots, especially in multi-component network environments, it is advisable to use a hybrid co-processing model or architecture based on integrated SoCs, since they provide a balance between computing power, response time, autonomy and the possibility of cognitive interaction. This is especially important for scenarios where a group of robots must jointly solve problems in a dynamic environment, respond to new input signals, share information, and form a coordinated behavior without wasting time on centralized coordination. In the future, it is recommended to focus on the development of modular hybrid platforms with flexible configuration, open interaction protocols between MCU and FPGA, as well as software expansion for the rapid implementation of intelligent functions without the need for deep system reflashing. This approach will allow creating efficient, reliable and scalable control systems for new generation collaborative robots, fully consistent with the principles of Industry 5.0 [24-30].

CONCLUSION

Thus, hybrid approaches based on MCU and FPGA are a promising direction for the development of modern robotic systems within the framework of the Industry 5.0 paradigm. They allow creating smart, flexible and scalable platforms with high adaptability, which are able not only to perform complex tasks in real time, but also to integrate into a human-centric environment, interacting with users, other machines and information systems. Further research should be aimed at optimizing architectures, reducing power consumption, unifying MCU/FPGA interfaces, as well as developing libraries for the rapid implementation of intelligent agents in decentralized robot networks.

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