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FPGA IMPLEMENTATION IN MOBILE ROBOT APPLICATIONS: STATE OF THE ART REVIEW

Hussam M. Rostum
Institute of Automation and Info-Communication, University of Miskolc, Hungary
3515 Miskolc-Egyetemváros, e-mail: hussam.rostum@uni-miskolc.hu

Noha Hammami
Institute of Information Technology, University of Miskolc, Hungary
3515 Miskolc-Egyetemváros, e-mail: noha.hammami@student.uni-miskolc.hu

Omar M. Salih
Institute of Automation and Info-Communication, University of Miskolc, Hungary
Technical College of Kirkuk, Northern Technical University, Iraq
3515 Miskolc-Egyetemváros, e-mail: omar.salih@uni-miskolc.hu

Abstract

Field-programmable gate arrays (FPGAs) have emerged as a valuable technology in mobile robotics due to their unique ability to be reconfigured to perform specific tasks efficiently. This article presents a comprehensive state-of-the-art review of the implementations of FPGAs in mobile robots. The article explores the various applications where FPGAs have been successfully integrated and discuss their advantages and limitations. The review covers vital areas such as perception, control, navigation, and communication, highlighting each domain's innovative approaches and advancements. Additionally, the study examines FPGAs' impact on mobile robot performance, including improvements in real-time processing, energy efficiency, and adaptability to changing environments. Furthermore, challenges and current efforts in leveraging FPGAs for mobile robotics are discussed, paving the way for exciting developments and possibilities in this rapidly evolving field. This review is a valuable resource for researchers, engineers, and enthusiasts interested in understanding the state of the art and potential of FPGA implementations in mobile robots.

Keywords: *FPGA, Robot Navigation, Robot Control, Robot Vision, Mobile Robots*

1. Introduction

Mobile robotics is one of the most rapidly developing fields of study. Due to their sophisticated capabilities, they can replace humans in various areas. These robots' advantages over human labor include increased efficiency, accuracy, safety, adaptability, and reduced overhead costs. Among the many uses for mobile robots are monitoring, patrolling, rescue tasks, factory automation, guides, individual assistance, transportation, healthcare, and so on. A mobile robot can travel within its environments autonomously (for example, in a factory, lab, or on another planet) (Rubio et al., 2019). For this reason, it can be defined as an autonomous agent, which can monitor the environment state and analyze the features of the extracted data from sensors to move safely while performing its required function. A fundamental requirement of the mobile robot is to locate its location within the environment and find the right trajectory when it needs to move. This process involves using many algorithms to avoid obstacles and collisions and get insight. If the environment is known, trajectory planning algorithms are required in order to plan the movement. In contrast, if the environment is obscure, the mobile robot should interact with what is detected by the sensed information. Moreover, it also requires a control framework or cognition module to coordinate all of the subsystems that comprise the robot as a whole (Sanchez et al., 2021; Rubio et al., 2019).

Field programmable gate arrays (FPGAs) are reconfigurable devices consisting of an array of programmable logic blocks, and reconfigurable interconnecting to allow the logic blocks to be routed and interconnected. Despite the intense competition in Central Processing Units (CPUs) and Graphics Processing Units (GPUs), they are still represented as high-performance implementation platforms. The key advantage of using FPGA is the convenience of integrating most circuit types due to their ease of interfacing. Additionally, they can fully support real-time computing, and inherent parallelism architecture, and reconfigurable and reprogrammable according to the user's requirements. In comparison to their competitors CPUs and GPUs, FPGAs are low-power-consuming devices (Boutros et al., 2021). Thus, FPGA technology is versatile and can be applied to various domains and industries due to its many uses and benefits. In this context, mobile robots can employ the capabilities of this technology to overcome challenges and achieve optimally functioning robotic applications. In the case of FPGAs, it is possible to achieve superior energy efficiency and real-time performance. Furthermore, it demonstrates unprecedented design flexibility.

This study provides a state-of-the-art review of using FPGA technology for the development of mobile robotic systems through the last three years between 2020–2022 and the current year up to this paper's date. The paper focuses on the main applications of mobile robots, including the basics: navigation mechanisms, Control methods, and vision-based systems. The paper is arranged as follows: section two explains the mobile robot navigation applications and the advantages of using FPGA for these types of applications. Section three touches the FPGA-based controllers, which is the essential unit in the mobile robot to control and run the applications. The vision applications are explored in section four, while section five discusses these applications in general and shows the influence of deploying FPGA in mobile robots, and concludes the sections by giving some comparisons.

2. Advantages of Using the FPGA in Mobile Robot Navigation Systems

In the realm of navigation and localization, where precision and real-time processing are paramount, technology has continuously evolved to meet the growing demands of various applications. One such groundbreaking technology that has revolutionized these domains are FPGAs. FPGA, a highly versatile and programmable integrated circuit, has emerged as a game-changer, providing unparalleled performance, flexibility, and efficiency. Navigation and localization systems are vital in diverse industries, such as robotics, autonomous vehicles, aerospace, and even smartphone-based applications. Traditional approaches often relied on software algorithms running on general-purpose processors. Still, the need for faster, more reliable, and more power-efficient solutions has driven the adoption of FPGA technology. FPGAs excel in navigation and localization applications because they can handle massive parallel processing, low latency requirements, and customizable hardware acceleration. These programmable devices can be tailored to specific tasks, enabling developers to implement complex algorithms directly into the hardware, resulting in remarkable performance gains. One of the key advantages of FPGA in navigation and localization lies in its ability to handle sensor fusion. Sensor fusion involves integrating data from multiple sensors such as cameras, LiDAR, GPS, inertial measurement units (IMUs), and radar to comprehensively understand the environment. FPGAs can process and fuse these sensor inputs in real-time, allowing for precise positioning, mapping, and obstacle detection with minimal delay.

Due to the computational requirements of mobile robot activities, which depend on multiple parameters associated with the behavior of robotic applications and the dynamic environment in which the robot operates, designing a comprehensive robot navigation system poses significant challenges.

To address this, reconfigurable architectures, known for their flexibility, are suitable for developing such dynamic systems. The navigation steps of mobile robots, including perception, localization, obstacle avoidance, and path planning, are highly intricate and cannot be easily embedded within a single navigation controller. Ghorbel et al. (Ghorbel et al., 2020) present a versatile and adaptable platform based on technology for studying and prototyping complete and unified robot navigation systems. Their approach utilizes the dynamic reconfiguration mechanism provided by FPGA technology, allowing modifications to the navigation controller based on the specific requirements of different navigation algorithms. The authors specifically demonstrate the effectiveness of their platform in the localization step. Their system employs dynamic reconfiguration, enabling seamless switching between three distinct localization techniques. This flexibility allows them to address considerations such as energy/surface ratio and efficiently utilize available resources to implement additional robot tasks.

Another problem is the computational complexity imposed by implementing particle filters, specifically in real-time applications. Particle filtering is a powerful Bayesian estimation technique used for tracking and localization purposes, but its non-analytical and non-parametric nature can lead to high computational demands. Traditional CPU or DSP (Digital Signal Processing) based implementation schemes struggle to handle the computational load, making real-time implementation challenging. Krishna et al. (Krishna et al., 2020) address this problem by utilizing an FPGA-based hardware architecture. The FPGA provides a dedicated and high-speed platform that allows for efficient execution of the particle filter algorithm. The architecture incorporates techniques like pipelining and parallelization, which can significantly reduce the execution time of the algorithm- approximately 5.62 microseconds for processing 1,024 particles. These techniques enable the particle filter to be implemented in real-time applications, such as source localization using an Unmanned Ground Vehicle (UGV) with a photodiode sensor.

Furthermore, FPGAs offer a flexible and programmable hardware platform that efficiently integrates different components and interfaces. Romanov et al. (Romanov et al., 2019) used the FPGA to facilitate the integration of the Marvelmind beacon and Ethernet POWERLINK, enabling seamless communication between the navigation and control systems. By employing FPGA technology, they overcomed the challenge of integrating these components into the hardware of the indoor mobile robot. The FPGA provides a versatile and adaptable platform that enables quick and efficient integration, enabling the navigation system to implement using low-cost microchips. This solution allows for the rapid integration of the navigation system into the robot hardware, addressing the challenge of hardware compatibility and enabling the robot to navigate effectively in an indoor environment. *Figure 1* shows the structure of the proposed mobile robot navigation system implementation in (Romanov et al., 2019). The SPI interface was chosen as the communication interface between FPGA and the Marvelmind beacon since it is the fastest available interface. The data received via SPI pass the integrity check at the hardware level, and are sent to the Ethernet POWERLINK interface block implemented based on a TinyCN core created at the Russian Technological University. The navigation system obtained can be quickly integrated into indoor intelligent mobile robots, and the low area size of the FPGA cores used means that it can be implemented with low cost microchips.

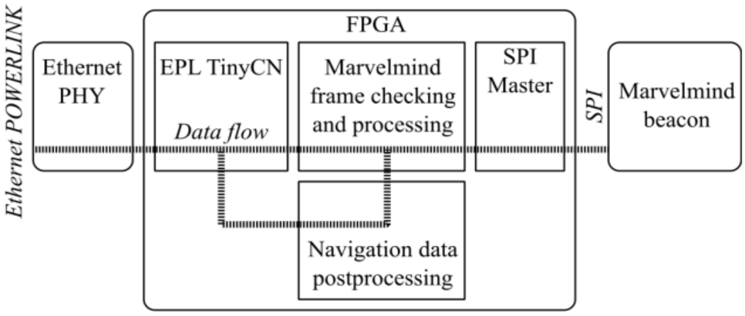

Figure 1. *Structure of the proposed implementation of the mobile robot navigation system*

Also, the FPGA plays a crucial role in implementing configurable on-chip systems based on the FPGA + ARM core architecture. It enables the efficient processing and handling of sonar signals, which is essential for successfully detecting underwater objects in motion. By utilizing the FPGA's configurability and processing capabilities, Burdinsky et al. (Burdinsky et al., 2022) overcome the challenge of developing a robust and effective sonar navigation system for underwater robotic systems. The FPGA acts as a critical technology solution in addressing the complexities of sonar signal processing and enhances the capabilities of the robotics system in navigating underwater environments. The authors leverage the FPGA + ARM core architecture to efficiently handle sonar signals, utilizing its configurability and processing capabilities. The developed algorithms enable accurate detection of underwater objects in motion, further enhancing the navigation capabilities of the robotic system in aquatic environments.

In addition, Basha et al. (Basha et al., 2022) address the crucial need to design a method that enables the navigation system to dynamically adapt to different navigation algorithms for accomplishing specific tasks. Their proposed method leverages dynamic reconfiguration and efficient allocation of hardware and software resources to enhance mobile robots' performance and fault tolerance. Allowing system modifications during runtime facilitates effective collaboration between robots, thereby improving their ability to assist humans in various service-based applications. This research work (Basha et al., 2022) offers a valuable solution for achieving adaptive and efficient hardware reconfiguration in mobile robotic systems. In addition, the authors present the hardware implementation of navigation algorithms on the Zynq SoC XC7Z020CLG484-1, using Xilinx Vivado 2017.3 for simulation and synthesis. Verilog, a real-time hardware description language, is employed to deploy multiple robots, while the Software Development Kit (SDK) aids in generating integrated software applications for Xilinx embedded processors. Notably, the study highlights the adoption of FPGA-based robots in service-based applications and provides significant assisting humans in their daily lives.

FPGA-based solutions can tackle the computational demands of advanced algorithms used in Simultaneous Localization and Mapping (SLAM) techniques. SLAM algorithms enable autonomous systems to construct maps of unknown environments while simultaneously localizing themselves within those maps. By offloading these intensive computations to FPGA hardware, real-time SLAM implementations become feasible, enhancing the capabilities of navigation systems. As known, the computational intensity of LiDAR SLAM systems, particularly when implemented on mobile robots with limited processing capabilities, concedes a big challenge. SLAM involves constructing an accurate model of the environment and estimating the robot's position based on LiDAR scans. However, performing these tasks in real-time poses significant challenges due to the computational complexity involved. Traditional software-based implementations may struggle to achieve the desired performance and efficiency. To overcome this problem, Sugiura et al. (Sugiura et al., 2022) propose a universal, low-power, and resource-efficient accelerator design for 2D LiDAR SLAM. The goal is to leverage the capabilities of FPGAs (Pynq-Z2) to accelerate key tasks, such as scan matching and loop-closure detection, while maintaining accuracy and real-time performance. By offloading these computationally intensive operations to dedicated scan-matching cores on the programmable logic part, the proposed design improved the overall performance and efficiency of LiDAR SLAM systems on resource-limited platforms. As a result of this study, the Correlative Scan Matching (CSM) core speeds up scan matching by up to 14.09×, 14.84×, and 7.88×, and loop-closure detection in graph-based SLAM by up to 18.92×, while consuming only 2.4 W. This reduces the wall-clock execution time by up to 4.67×, 4.00×, and 4.06×, enabling real-time performance in typical indoor scenarios. The error of trajectory estimate is less than 10 cm and 0.05 rad (2.8°) in most cases.

Humanoid robots encounter challenges in maintaining stable gait patterns, which can lead to the failure of vSLAM tracking systems, such as KinectFusion. This failure disrupts the robot's ability to estimate its pose accurately and hampers its navigation and interaction capabilities. Gkeka et al. (Gkeka et al., 2023) propose a pose graph optimization module that utilizes RGB (ORB) features to address this issue. This module extends the functionality of the KinectFusion pipeline, allowing for the recovery of the robot's stance during unstable gait patterns. Through developing and testing embedded MPSoC FPGA designs and exploring architectural improvements, the researchers strive to achieve real-time vSLAM performance in humanoid robots while maintaining accuracy and energy efficiency. The FPGA design yielded a frame rate of 37.8 frames per second (31 fps for the design with no untracked frames), showcasing a significant performance improvement compared to the fastest hardware-based implementation with precise calculations (1.87 fps) and the software-only precise implementation on the ARM CPU (1.59 fps). This underscores the notable advancements achieved through the FPGA design.

Another compelling aspect of FPGA technology is its adaptability. As new navigation and localization algorithms are developed and refined, FPGA designs can be updated and reconfigured accordingly, offering a future-proof solution (Gkeka et al., 2023). This flexibility allows for rapid prototyping and iterative improvements, ensuring that FPGA-based systems remain at the forefront of innovation in this fast-paced field. *Figure 2* shows the proposed vSLAM pipeline, blue blocks indicate the original KinectFusion pipeline, whereas green blocks indicate the additional pose graph pipeline proposed.

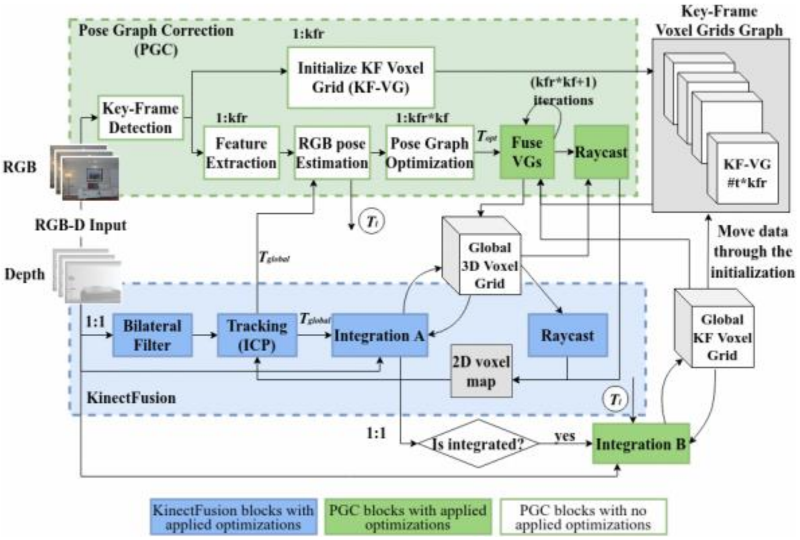

Figure 2. *The system architecture*

3. Harnessing FPGA capacities for mobile robotic control systems

Since mobile robots are so widely used in the mechanical, electrical, and customer service industries, their control systems have attracted much attention. As a result, researchers in the area of mobile robotics have found themselves increasingly drawn to the prospect of developing a highly efficient controller. A reconfigurable control system implies that the calculations can be modified to adjust to the needs of a specific program (Jahn et al., 2020). Rapid response, adaptability, reliability, and being capable of reprogramming are just some of the many advantages of FPGA technology that allow for the realization of advanced adaptive control systems that seek to achieve, in real-time, dynamic control of systems through modification and learning. So automated systems of motors and robots employ FPGA-based technology as a controller platform to benefit from its strengths (Wan et al., 2021). *Figure 3* shows a general block diagram of a control robotic system where several control algorithms can be integrated with the FPGA chip. The literature is rich with previously implemented examples of control systems and mobile robotic technologies.

Figure 3. *General block diagram of FPGA-based control robotic system*

In recent years, machine learning has made significant strides in control systems and other applications. The use of neural networks is widespread in scientific literature and engineering practice. Abbas Issa et al. (Issa et al., 2021) presented a reconfigurable insightful controller for mobile robots. Programming known as reconfigurable control framework, was used to modify the structure of the control system, and the FPGA chip was used in the planning and implementation of the controller. The proposed control system has been developed based on a neural network and then built on an Xilinx FPGA Spartan 3A chip. The designed robot's task is to navigate a predetermined distance in an unfamiliar environment, discovering and avoiding obstacles along the way. The position and speed are dynamically controlled. The response appears identical to the MATLAB simulation response prior to execution, so the findings of the software-designed regulator can be trusted. The results demonstrated that the proposed intelligent controller provides outstanding and effective performance and that the proposed approach is appropriate for systems that need controllers with a high level of efficiency. Sandipan Pine and B. Choudhury proposed a modified particle swarm optimization method (MPSO) as an automated control technique for a mobile robot, to implement the presented algorithm in real-time while following a moving car, by employing an FPGA. The simulation is run in MATLAB and Xilinx FPGA. They compared the proposed algorithm with the existing PSO algorithm. MPSO embedded with FPGA was found to be superior to PSO-FPGA in terms of number of lookup tables, timer frequency, and execution time (Pine et al., 2020).

There are many applications for the Q-Learning technique, including effective navigation and track planning. Q-Learning's results cannot be employed to immediately regulate the robot to perform a particular task in the lab. A controller is required to coordinate the efforts of the various sensors, actuators, and primary accelerators to translate Q-Learning commands into low-level transmissions. Infall Syafalni et al. introduced the accelerator utilizing an FPGA for Q-learning employed in the mobile robot's control framework. The sensors, motors, and accelerators are all linked to the control system.

The mobile robot's controller has been successfully integrated with the FPGA chip. Additionally, the simulation outcome for the actuator's regulation also demonstrates stability. This control system is helpful in the development of applications like intelligent navigation and the Internet of Things (IoT) (Syafalni et al., 2022). Mobile robots frequently employ grid maps, which are simplified representations of actual maps, because they facilitate efficient processes for navigation and perception. Path-planning strategies on a grid map are essential in robotics and other fields. The path-planning process must be real-time in some applications. For example, mobile robotics can work in a dynamic environment where obstacles and routes change suddenly. In order to implement path planning as a real-time strategy, Yuzhi Zhou et al. developed A* accelerator and executed it on the Xilinx Kintex-7 FPGA platform. Experiments demonstrate that the proposed hardware accelerator improves efficiency by 37–75 times compared to a software implementation. It is appropriate for applications involving real-time route planning (Zhou et al., 2020).

Developing autonomous mobile robots (AMR) with low power consumption is crucial, particularly for time-sensitive tasks. Due to their reliance on batteries for movement, AMRs typically have limited operational runtime. Traditional power optimization methods frequently limit robot mobility and restrict the ability to navigate freely. To achieve the best possible balance between power efficiency and performance regarding navigational calculations, Senthurbavan Kirubaharan et al. presented a hardware accelerator built using field-programmable gate arrays (FPGAs). Experimental and simulation outcomes demonstrate that the presented hardware accelerator reduces power consumption by a factor of 4.12 and enhances Power-Delay-Product (PDP) by a factor of 12.35 compared to the cutting-edge implementation (Kirubaharan et al., 2020). In this context, Jyoti Bali et al. discussed the importance of energy-efficient facilities for I4.0's vision of the smart manufacturing ecosystem. The importance of creating FPGA-based systems for sensing, decision-making process, and actuation is emphasized. Hence, this article primarily addresses the FPGA-based environmentally friendly energy models implemented for the sensor fusion approach employed by mobile robots (Bali et al., 2021). While the study by Aws Saber presented the design and implementation of a mobile robot regulator using a Spartan-3 FPGA platform. Because of the low cost of implementing counters within an FPGA, Each component is designed separately and assembled using counters. The performance of the regulator was satisfactory. It has been discovered that the counter-based robot motion and environmental perception regulator design is the most cost-effective over FPGA (Saber et al., 2023).

On the other hand, because of the complex nature of the system, describing it with computational models is challenging. A solution can be adapted to control these systems in a way that does not necessitate precise information about the model. In these situations, neural networks are typically used exactly as mentioned earlier. According to Roland Bartók and József Vásárhelyi (Bartók et al., 2022), it is possible to create a complex control mechanism with a detailed description of the system's rule-driven behavior. Fuzzy logic is considered a powerful tool for characterizing the system's behavior. With a fuzzy interpolation technique such as the Fuzzy Interpolation in a Vague Environment (FIVE) approach, it's possible to avoid the drawbacks of traditional fuzzy logic applications. In the proposed system, they presented the FIVE technique's adaptable parameterizable hardware-accelerator execution using an FPGA. They later used this methodology to model an autonomous robot's behaviors. The FIVE approach was implemented on an FPGA with the help of a framework written in Verilog. As a result, the computation process has been accelerated.

The flexibility in electronic circuit design and the ability to execute commands in parallel are just two of many benefits of implementing a servomotor regulator in an FPGA rather than a traditional microcontroller. To enhance productivity and achieve superior performance, Lejla Mehmedovic et al.

implemented an FPGA for hexapod mobile robot navigation based on a tripod gate. The proposed controller is programmed in Hardware Description Language (HDL) Verilog and executed on the Cyclone IV FPGA platform, so that the steering wheel's location and direction are always synchronized perfectly (Crockett et al., 2019). On the other hand, The System on Chip (SoC) is popular due to its strong capabilities. It's an integrated circuit that combines programmable logic (PL) with a processing system (PS), is the PL's functional equivalent. By leveraging the FPGA fabric, hardware acceleration and real-time processing can be implemented, and the PL provides high-level programming and processing capabilities (Barrios et al., 2020). Overall, the SoC enables the development of notable robotic systems. Thus, the study (Fu, 2021) shows the use of SoCs in the field of mobile robotics. Specifically, this paper details the development and construction of a real-time platform for robot navigation that combines, in a single Xilinx Zynq R onboard the Chip, neural network methods, image processing algorithms, path planning, and movement tracking for a mobile robot, a BlueBotics Shrimp. They provided an effective solution to enable a shrimp robot's autonomous exploration of challenging environments. While, The master's thesis by Yuhong Fu aimed to improve the performance of a LiDAR technology-based SLAM framework in indoor scenes, lower the resource requirements of the SLAM strategy, and lower the cost of the entire platform. In the study, two SLAM systems—one utilizing a Corner Feature Extraction (CFE) and the other employing a genetic algorithm—were developed and implemented with a concentration on energy-efficient and fast architectural design. Finally, they implemented and tested a SLAM system that utilizes FPGA-based hardware acceleration; they used the Xilinx PYNQ Z2 board, and the results were compared to those of a software-only approach. The system was operated on a prototype of a mobile robot in real-world environments (Bouzid et al., 2020). Ahmed et al. (Reda et al., 2020) introduced a hybrid reconfigurable data acquisition and preprocessing system. The system includes a hardware calibrator and two different filters developed and tested with noisy analog inertial sensors. Additionally, an MRVA (multi-range voltage adjuster) has been successfully implemented to maintain voltages within the permissible range defined by XADC. Analysis of the experimental results indicates the presence of significant noise in the second channel of the MRVA. The implemented data acquisition part of the system demonstrates a measurement precision of 99.92% for the first channel (X-axis accelerometer), while the second (Y-axis accelerometer) and third (gyroscope) channels achieve accuracies of 99.72% and 99.97%, respectively.

Comparing the performance of SMAF (Simple Moving Average Filter) and WMAF (Weighted Moving Average Filter), SMAF exhibits superior results with better standard deviation, probability density, and lower hardware resource utilization and power consumption. However, it should be noted that SMAF utilizes a considerable portion of the FPAA's (Field Programmable Analog Array) hardware resources, employing 100% of the inputs/outputs, and 37% of the OPAMPs and capacitors. Noise analysis reveals that the SMAF-based digital conditioner reduces the standard deviation by 70.99% in the second channel, following a Burr distribution. The experimental findings suggest that the filters used in this study are not well-suited for positioning, and alternative filtering methods should be considered. Furthermore, the proposed system is not limited to IMUs (Inertial Measurement Units) but has broader applications for various analog sensors.

Another research (Wang et al., 2019) discussed the implementations of Model Predictive Control (MPC) and adaptive MPC controllers to control an autonomous vehicle steering system. The deployments were performed for both constant and changing dynamics systems. The models were implemented on FPGA using MATLAB HDL coder, and different strategies were adopted to optimize resource utilization. The results showed that the MPC controller provides satisfactory control for a constant dynamics system. Still, it couldn't handle changing operating conditions, while adaptive MPC offers good control for changing dynamics systems. In addition to analyzing the performance of the controllers, the implementations were discussed in terms of resource utilization and power consumption using different strategies. The results showed a very slight improvement regarding the total power consumption.

4. Exploiting of FPGA Capabilities in Mobile Robots based Vision Applications

Mobile robots-based vision applications are becoming increasingly diffused in various fields, ranging from industrial automation to healthcare and logistics. These robots are designed for performing complex tasks in dynamic and unstructured environments, requiring robust perception and vision capabilities. Mobile robots are connected to sensors that collect information about the external environment. Different sensors can be used in vision applications, for instance, (laser, ultrasonic, or infrared sensors and cameras). Basically, Vision applications that incorporate camera systems and image processing algorithms play an essential role in robot perception and interaction within the environment. In contrast, the intensive computational requirements of real-time vision applications are challenging and an open research issue for efficient and powerful solutions. *Figure 4* illustrates the basic block diagram of the mobile robot's vision system. The processing of real-time huge-sized visual information obtained from sensors and cameras can represent the key challenge in mobile robot implementation. The computational demands of these tasks require significant computational resources and complex algorithms to fulfill environment perception. In the same context, latency is another important factor to consider when implementing these algorithms. Delays in real-time visual information processing can hinder the robot's ability to respond to dynamic environment conditions. High latencies can lead to missed functional concerns and safety requirements; therefore, real-time decision-making can be affected (Bali et al., 2021; Millet et al., 2021; Liu et al., 2018).

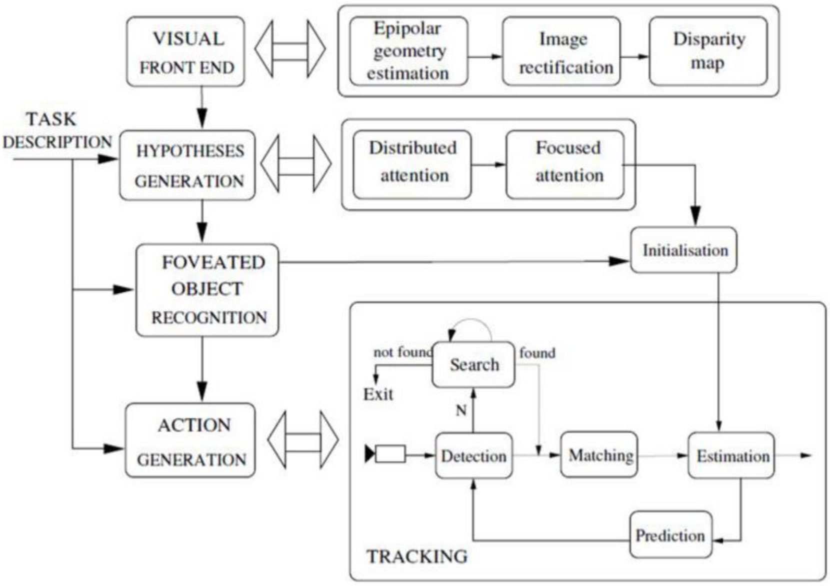

Figure 4. *Basic block diagram of the mobile robot vision system*

FPGAs have addressed a promising innovation for tending to the computational necessities of versatile robot vision applications. FPGAs, in contrast to CPUs and GPUs, provide reconfigurable hardware that can be sufficient to satisfy specific application requirements, facilitating effective parallelism and speeding up computation. FPGAs' inherent parallelism and reconfigurability make them capable of deploying real-time image processing tasks, providing an ideal platform for deploying mobile robot vision. Moreover, robot vision application may rely on multiple sensors and cameras to capture visual and depth information, which add additional complexity for integrating and synchronizing their outputs. FPGAs can assist in integrating advanced vision algorithms directly onto mobile robot platforms, eliminating the need for external computing resources. This benefit reduces latency and enhances the robot's connectivity and self-sufficiency, allowing it to operate in real-world environments without depending on other components. Addressing these challenges requires sophisticated algorithms, efficient hardware architectures, and optimized software implementations. Technological advances like FPGA-based acceleration, parallel processing, and sensor fusion techniques are instrumental in overcoming these obstacles and enabling real-time visual information processing in robotics (Swirski et al., 2021; Nayak et al., 2019).

Due to its inherent complexity, the application of DSP algorithms for a mobile robot demands high-speed data processing on the speed of performance. In (Pine et al., 2020; Tan et al., 2022), an auto-mobile robot control movement strategy is proposed based on image processing techniques and a modified particle swarm optimization algorithm (MPSO). The image processing techniques involve preprocessing operations: image resizing and converting from RGB to grayscale, Soble edge detection, and then feature extraction. The extracted features perform some instructions (i.e. start, stop, right, stop) and estimate the mobile robot's direction with the aid of the proposed MPSO algorithm to find the best location. The proposed systems showed noticeable excellence in performance and resource utilization.

The Visual Inertial Odometer (VIO) is a rapidly developed SLAM application in Autonomous Mobile Robots (AMRs). It recognizes the positioning function by combining a camera and Inertial Measurement Unit (IMU). The main restriction factors among these applications are algorithm complexity, the accelerator's long development cycle, and ARM's power supply limitations. Tan et al. (Naji et al., 2022) design and implement an accelerated reconfigurable real-time core that supports multiple VIO algorithms regarding low energy consumption, high precision, low area usage, low memory utilization, and high-speed characteristics. The designed system has been implemented using Xilinx XCVU 440 FPGA and proved its efficiency compared with the state-of-the-art models. The key features of the proposed design are adapting different VIO-based Kalman filters, fixed and floating points, and reusing memory techniques. A novel Autonomous and Versatile Parking System (AVPS) algorithm is proposed for autonomous vehicles without driver intrusion (Bo-Jun et al., 2020). The algorithm can determine the optimal parking mode based on the collected data from five infrared sensors among four available parking modes. These modes are parallel, perpendicular, head-out-angled, and head-in-angled parking modes. The proposed system is implemented in an FPGA Cyclone III board and a mobile robot and simulated using the ModelSim simulation tool.

Image identification is essential in robotic vision tasks, including automatic industry and Automated Guided Vehicles (AVGs). Ghorbel et al. (Ghorbel et al., 2020) proposed an image recognition-based mobile robot, including positioning, motion control, and image recognition systems. The system has been implemented using myRIO-1900 by National Instruments (NI), adopting ARM Cortex-A9 and Xilinx Z-7010 to help mobile robots accomplish specified actions. A generic unified mobile robot navigation platform has been studied and prototyped using FPGA (Benotsmane et al., 2022). The platform is flexible and dynamic reconfigurable; it switches between three different localization modes.

The energy and utilization area are the main considered parameters among these modes to fulfill energy requirements and exploit the device resources for other robotic applications (Jiang et al., 2022). In single- and multi-robot applications, vision-based robot monitoring is often utilized for observation, debugging, and tracking. Most recent multi-robot tracking research incorporating vision algorithms is deployed on general-purpose computers. These technologies are not applicable to embedded applications that need high robustness, low resources, and low power requirements. Due to their enormous inherent parallelism, hardware accelerators based on FPGAs are well suited to handle computationally demanding applications like vision processing. The authors in (Benotsmane et al., 2022) suggest employing GigE Vision cameras as part of an FPGA-based system for multi-robot tracking. A comprehensive system includes an IP core for image preprocessing, an edge filter, and a multi-camera frame grabber. These implemented systems are used for detecting the locations of several mobile robots according to some markers on the robot's surface.

Mobile robots are used significantly in various fields of agricultural production applications. For instance, crop picking is a time-consuming and workers-intensive process. The authors in (Chen et al., 2020) presented a crop identification and localization approach to collect information for picking mobile robots. The designed system used binocular vision and deep learning and was deployed using FPGA hardware. The binocular cameras capture the information and identify and locate crops using deep learning techniques. Accelerating intelligent vision for crop detection mobile robots using FPGA in the agricultural field is also studied by (Chan et al., 2020). The implemented robot adapts machine learning based on YOLOv3 for broccoli and cauliflower detection. Compared to GPU-based implementation, the FPGA-based mobile robot has achieved a power efficiency of up to 4.12 times and a throughput speed of up to 6.85 times. Moreover, it can operate in harsh farm conditions where drastic conditions like temperature and humidity can change.

Stereo vision is a crucial technique in autonomous mobile robots to estimate the surrounding environment's depth and 3-dimensional information. This technique uses pair of cameras positioned correctly to capture two different views of a common scene. The estimation can be accomplished by analyzing the differences in the visual data and perceiving the 3D structure of the environment. A novel hardware-based FPGA accelerator implementation has been introduced by (Bobyr et al., 2021) named StereoEngine, which is standalone, fully pipelined, and can estimate dense depth accurately and in an efficient energy method using a binary neural network (BNN). Speed and power efficiency have been improved by up to 50× and 211×, respectively, compared to traditional approaches. Likewise, a fuzzy model can calculate the depth map of stereo vision obtained from the mobile robot path. The soft arithmetic-based fuzzy inference has been constructed using the SAD (sum of absolute difference) method (Chan et al., 2020). The depth map is estimated by using RMSE (root mean square error), and the best soft operator can be selected according to the minimum RMSE. This algorithm showed an enhancement in the accuracy of estimation by about 20% when the soft operators' method is used, yielding increasing the efficiency of mobile robot control in stereo vision systems.

5. Conclusion

This review paper investigates the state-of-the-art FPGA technology deployment for mobile robot applications, exploring existing writings and examination studies, progressions, difficulties, and capability of utilizing FPGA innovation to mobile robots. The significant impact of FPGA technology on vision, navigation, and control in mobile robot applications has been highlighted. The integration of FPGA technology in navigation and localization has ushered in a new era of precision, efficiency, and real-time capabilities. With their inherent parallel processing capabilities, low latency, and hardware customization, FPGAs empower navigation systems to handle complex tasks like sensor fusion, SLAM, and more. As technology evolves, FPGA-based solutions are poised to play a pivotal role in unlocking the full potential of navigation and localization across various industries.

On the other hand, incorporating FPGA technology into mobile robotic systems' controllers was a notable and effective solution. It provides a noticeable boost in control mechanism performance as a hardware accelerator. Implementing computationally intensive control algorithms for FPGAs, real-time feedback control, and high-bandwidth communication can enable precise motion control, stability, and reliable robotic systems. In addition, since a single FPGA can support multiple robotic workloads, the control system's total cost and power consumption can be reduced, with the possibility of implementing various of real-time applications. Furthermore, FPGA-based implementations have proved their potential to meet the computational needs of real-time systems, empowering fast and more effective solutions for applications such as image processing, feature extraction, object recognition, and tracking. High-performance, low-latency visual perception in mobile robots has been made possible by FPGAs' reconfigurable parallel processing capabilities.

Table 1 briefly summary the literature reviews cited in this article. Despite these advancements, challenges remain in FPGA implementation for mobile robot applications. These include the complexity of FPGA design, resource constraints, power consumption optimization, and algorithm mapping. Addressing these challenges will require further research and development in hardware architectures, optimization techniques, and algorithmic design methodologies specific to mobile robot applications. Looking ahead, there are exciting opportunities for future advancements in FPGA-based mobile robot applications. Integrating FPGA technology with emerging fields such as artificial intelligence, deep learning, and edge computing holds great promise for enabling more intelligent, adaptive, and context-aware mobile robot behaviors. Additionally, exploring the potential of FPGA clusters and distributed processing architectures can further enhance the scalability and performance of mobile robot systems.

Table 1. *Summary of the literature reviews cited in this article*

Study	The Application	Implementation platform	The proposed method
(Ghorbel et al., 2020)	Computational requirements of mobile robot activities.	generic and a flexible platform based on FPGA technology	versatile and adaptable platform based on FPGA
(Krishna et al., 2020)	Computational complexity associated with implementing particle filters.	Artix-7	a dedicated and high-speed platform that allows for efficient execution of the particle filter algorithm
(Romanov et al., 2019)	The challenge of integrating components into the hardware of the indoor mobile robot.	Marvelmind hardware with UART and SPI interfaces as the basis for implementation on FPGA	versatile and adaptable platform based on FPGA that enables quick and efficient integration

Study	The Application	Implementation platform	The proposed method
(Burdinsky et al., 2022)	The challenge of developing a robust and effective sonar navigation system.	Zynq-7000	FPGA + ARM core architecture to efficiently handle sonar signals
(Basha et al., 2022)	The crucial need to design a method that enables the navigation system to adapt to different navigation algorithms dynamically.	Zynq-7000	hardware implementation of navigation algorithms on the Zynq SoC
(Sugiura et al., 2022)	The computational intensity of LiDAR SLAM.	Pynq-Z2	universal, low-power, and resource-efficient accelerator design for 2D LiDAR SLAM
(Gkeka et al., 2023)	Humanoid robots encounter challenges.	Zynq 7020, Virtex5	pose graph optimization module that utilizes RGB (ORB) features
(Issa et al., 2021)	A mobile robotic system requires reconfigurable adaptive controller.	MATLAB Simulion+ Spartan 3A/AN FPGA hardware +	An FPGA-based adaptive NN controller for robotic navigation
(Pine et al., 2020)	A real-time controller is needed for a mobile robot while following a moving car.	MATLAB simulation and Xilinx environment	FPGA- based swarm optimization method as an automated control technique for a mobile robot
(Syafalni et al., 2022)	A controller is necessary to coordinate the efforts of the various sensors, actuators, and primary accelerators to translate Q-Learning commands into low-level transmissions.	Xilinx Pynq Z1	Q-learning accelerator using an FPGA in the mobile robot's control framework
(Zhou et al., 2020)	A mobile robotic system requires real-time controller for path planning on a grid map.	Xilinx Kintex-7 FPGA	FPGA-based A* accelerator
(Kirubaharan et al., 2020)	To achieve the best possible balance between power efficiency and performance regarding navigational calculations for autonomous mobile robot.	Zynq-7000 SoC	A low-energy hardware accelerator built using FPGAs

Study	The Application	Implementation platform	The proposed method
(Saber et al., 2023)	A mobile robot with a regulator is needed at the lowest cost.	Spartan-3 FPGA	Low-cost counter-based robot motion and environmental perception regulator
(Crockett et al., 2019)	The complex nature of a robot control system, describing it with computational models is challenging.	Verilog framework	FIVE technique’s adaptable hardware-accelerator execution using FPGA for modeling robot behavior
(Bartók et al., 2022)	To take advantage of a servo motor regulator in an FPGA rather than a traditional microcontroller.	Cyclone IV FPGA	FPGA-based controller for hexapod mobile robot navigation
(Bouzid et al., 2020)	To lower the resource requirements of the SLAM strategy and reduce the cost of the entire system.	Xilinx PYNQ Z2	A SLAM system that utilizes FPGA-based hardware acceleration
(Fu, 2020)	An autonomous robot controller to explore challenging environments.	Xilinx Zynq R onboard	A real-time Soc platform using AI methods for shrimp robot navigation
(Pine et al., 2020; Tan et al., 2022)	Vision for mobile robot control [auto, left, right, stop].	Vivado simulation	modified particle swarm optimization algorithm
(Naji et al., 2022)	Visual Inertial Odometer (VIO) system for the four-wheeled robot.	Xilinx XCVU 440 FPGA evaluation board	Simultaneous localization and mapping (SLAM)
(Bo-Jun et al., 2022)	Autonomous and Versatile Mode Parking System (AVPS).	Altera Cyclone III board	Free space recognition
(Ghorbel et al., 2020)	Image identification-based mobile robot control.	RIO-1900	trapezoidal acceleration and deceleration and PID to control
(Benotsmane et al., 2022)	Navigation system for mobile robot.	Virtex-5 xc5vfx70t	relative, absolute, and hybrid localization systems
(Jiang et al., 2022)	Agricultural picking robots.	Zynq-7020	Stereo matching method
(Chen et al., 2020)	Mobile robot vision.	Altera Stratix V FPGA	StereoEngine: stereo vision accelerator using Binary Nural Networks (BNN)
(Bobyr et al., 2020)	Mobile robot stereo vision.	Simulation (MS) Visual Studio 2013 on the C#	programming language & SAD (sum of absolute

Study	The Application	Implementation platform	The proposed method
			difference) algorithm composition and fuzzy inference
(Chan et al., 2020)	Intelligent vision-guided crop detection.	Xilinx ZCU102	OLOv3 object detection neural network

References

[1] Rubio, F., Valero, F., & Llopis-Albert, C. (2019). A review of mobile robots: Concepts, methods, theoretical framework, and applications. *International Journal of Advanced Robotic Systems*, 16 (2). **https://doi.org/10.1177/1729881419839596**

[2] Sanchez-Ibanez, J. R., Perez-del-Pulgar, C. J., & García-Cerezo, A. (2021). Path planning for autonomous mobile robots: A review. *Sensors*, 21 (23), p. 7898. **https://doi.org/10.3390/s21237898**

[3] Boutros, A., & Betz, V. (2021). FPGA architecture: Principles and progression. *IEEE Circuits and Systems Magazine*, 21 (2), pp. 4–29. **https://doi.org/10.1109/MCAS.2021.3071607**

[4] Ghorbel, A., Ben Amor, N., & Jallouli, M. (2020). Design of a flexible reconfigurable mobile robot localization system using FPGA technology. *SN Applied Sciences*, 2, pp. 1–14. **https://doi.org/10.1007/s42452-020-2960-4**

[5] Krishna, A., van Schaik, A., & Thakur, C. S. (2020). Source localization using particle filtering on FPGA for robotic navigation with imprecise binary measurement. *arXiv preprint arXiv:2010.11911*. **https://doi.org/10.48550/arXiv.2010.11911**

[6] Romanov, A. M., Romanov, M. P., Morozov, A. A., & Slepynina, E. A. (2019). A navigation system for intelligent mobile robots. *IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, IEEE, pp. 652–656. **https://doi.org/10.1109/EIConRus.2019.8657234**

[7] Burdinsky, I. N., & Mironov, A. S. (2022, May). Using configurable on-chip systems in a sonar navigation system receiver for mobile autonomous robotic complexes. *Saint Petersburg International Conference on Integrated Navigation Systems (ICINS)*, IEEE, pp. 1–4. **https://doi.org/10.23919/ICINS51784.2022.9815409**

[8] Basha, M., Kumar, M. S., & Chinnaiah, M. C. (2022). Implementation of robotic navigation algorithms using partial reconfiguration on Zynq SoC. *ECS Transactions*, 107 (1), p. 13887. **https://doi.org/10.1149/10701.13887ecst**

[9] Sugiura, K., & Matsutani, H. (2022). A universal LiDAR SLAM accelerator system on low-cost FPGA. *IEEE Access*, 10, pp. 26931–26947. **https://doi.org/10.1109/ACCESS.2022.3157822**

[10] Gkeka, M. R., Patras, A., Tavoularis, N., Piperakis, S., Hourdakis, E., Trahanias, P., ... & Bellas, N. (2023). Reconfigurable system-on-chip architectures for robust visual SLAM on humanoid robots. *ACM Transactions on Embedded Computing Systems*, 22 (2), pp. 1–29. **https://doi.org/10.1145/3570210**

[11] Jahn, U., Heß, D., Stampa, M., Sutorma, A., Röhrig, C., Schulz, P., & Wolff, C. (2020). A taxonomy for mobile robots: Types, applications, capabilities, implementations, requirements, and challenges. *Robotics*, 9 (4), p. 109. **https://doi.org/10.3390/robotics9040109**

[12] Wan, Z., Yu, B., Li, T. Y., Tang, J., Zhu, Y., Wang, Y., ... & Liu, S. (2021). A survey of fpga-based robotic computing. *IEEE Circuits and Systems Magazine*, 21 (2), pp. 48–74. **https://doi.org/10.1109/MCAS.2021.3071609**

[13] Issa, A. H., Humod, A. T., & Gitaffa, S. A. (2021). FPGA implementation of reconfigurable intelligent controller for mobile robot. *Journal of Mechanical Engineering Research and Developments*, 44 (1), pp. 254–264.

[14] Pine, S., & Choudhury, B. B. (2020). FPGA implementation of modified swarm optimization based control strategy for a mobile robot. In: *Applications of Robotics in Industry Using Advanced Mechanisms: Proceedings of International Conference on Robotics and Its Industrial Applications 2019*. 1 Springer International Publishing, 280–290. **https://doi.org/10.1007/978-3-030-30271-9_26**

[15] Syafalni, I., Firdaus, M. I., Sutisna, N., Hadi, Y. W., & Adiono, T. (2022). Control system for mobile robot using FPGA-based Q-learning accelerator. *8th International Conference on Wireless and Telematics (ICWT)*, IEEE, pp. 1–6. **https://doi.org/10.1109/ICWT55831.2022.9935386**

[16] Zhou, Y., Jin, X., & Wang, T. (2020). FPGA Implementation of A* Algorithm for Real-Time Path Planning. *International Journal of Reconfigurable Computing*, 2020, 1–11. **https://doi.org/10.1155/2020/8896386**

[17] Kirubaharan, S., Jayasekara, P., & Weerakkody, D.: Low power FPGA-based hardware accelerator for autonomous navigation of mobile robots. **https://www.researchgate.net/publication/347438538_Low_Power_FPGA-based_Hardware_Accelerator_for_Autonomous_Navigation_of_Mobile_Robots**

[18] Bali, J., Arpitha, H., Anushree, N., & Giriyapur, A. (2021, September). Power-efficient strategies for sensing in autonomous mobile robots, a critical requirement of I4. 0 standard. In: *IOP Conference Series: Materials Science and Engineering*, Vol. 1187, No. 1, 012007, IOP Publishing. **https://doi.org/10.1088/1757-899X/1187/1/012007**

[19] Saber, A. H., Abdulla, A. A., Alwan, G., & Alsaigh, R. A. (2023). Low-cost embedded intelligent system design for smart mobile robot controller. *Przeglad Elektrotechniczny*, 99 (3). **https://doi.org/10.15199/48.2023.03.42**

[20] Bartók, R., & Vásárhelyi, J. (2022). Design of a FPGA accelerator for the FIVE fuzzy interpolation method. *International Journal of Computer Applications in Technology*, 68 (4), pp. 321–331. **https://doi.org/10.1504/IJCAT.2022.125185**

[21] Crockett, L., Northcote, D., Ramsay, C., Robinson, F., & Stewart, R. (2019). Exploring Zynq MPSoC: With PYNQ and machine learning applications. **https://pureportal.strath.ac.uk/en/publications/exploring-zynq-mpsoc-with-pynq-and-machine-learning-applications**

[22] Barrios-dV, S., Lopez-Franco, M., Rios, J. D., Arana-Daniel, N., Lopez-Franco, C., & Alanis, A. Y. (2020). An autonomous path controller in a system on chip for Shrimp robot. *Electronics*, 9 (3), p. 441. **https://doi.org/10.3390/electronics9030441**

[23] Fu, Y. (2021). *Design and development of an FPGA-based hardware accelerator for corner feature extraction and genetic algorithm-based SLAM system.* Doctoral dissertation, University of Turku.

[24] Bouzid, A., & Vásárhelyi, J. (2020). Implementation and experimentation of an embedded Data acquisition/preprocessing system based on a hybrid reconfigurable hardware accelerator for inertial measurements. *IEEE Transactions on Industry Applications*, 56 (2), pp. 2012–2019. **https://doi.org/10.1109/TIA.2020.2965888**

[25] Reda, A., Bouzid, A., & Vásárhelyi, J. (2020). Model predictive control for automated vehicle steering. *Acta Polytechnica Hungarica*, 17 (7), pp. 163–182. **https://doi.org/10.12700/APH.17.7.2020.7.9**

[26] Wang, Z., Wu, Y., & Niu, Q. (2019). Multi-sensor fusion in automated driving: A survey. *IEEE Access*, 8, pp. 2847–2868. **https://doi.org/10.1109/ACCESS.2019.2962554**

[27] Bali, J., Arpitha, H., Anushree, N., & Giriyapur, A. (2021, September). Power-efficient strategies for sensing in autonomous mobile robots, a critical requirement of I4. 0 standard. In: *IOP Conference Series: Materials Science and Engineering*, Vol. 1187, No. 1, 012007, IOP Publishing. **https://doi.org/10.1088/1757-899X/1187/1/012007**

[28] Millet, P., Grinberg, M., & Jahre, M. (2021). Challenges in the realm of embedded real-time image processing. *Towards Ubiquitous Low-power Image Processing Platforms*, pp. 3–13. **https://doi.org/10.1007/978-3-030-53532-2_1**

[29] Liu, L., Liu, S., Zhang, Z., Yu, B., Tang, J., & Xie, Y. (2018). Pirt: A runtime framework to enable energy-efficient real-time robotic applications on heterogeneous architectures. *arXiv preprint arXiv:1802.08359*. **https://doi.org/10.1109/MC.2020.3015950**

[30] Swirski, A. (2021). TULIPP and ClickCV: How the future demands of computer vision can be met using FPGAs. *Towards Ubiquitous Low-power Image Processing Platforms*, pp. 235–259. **https://doi.org/10.1007/978-3-030-53532-2_14**

[31] Nayak, J., Balas, V. E., Favorskaya, M. N., Choudhury, B. B., Rao, S. K. M., & Naik, B. (eds.). (2019). *Applications of robotics in industry using advanced mechanisms: Proceedings of International Conference on Robotics and Its Industrial Applications 2019.* Vol. 5, Springer Nature. **https://doi.org/10.1007/978-3-030-30271-9_26**

[32] Pine, S., & Choudhury, B. B. (2020). Path planning of a mobile robot through image processing on a FPGA board. *Indian Journal of Natural Sciences*, 60, pp. 20162–20169.

[33] Tan, Y., Sun, M., Deng, H., Wu, H., Zhou, M., Chen, Y., ... & An, F. (2022). A reconfigurable visual–inertial odometry accelerated core with high area and energy efficiency for autonomous mobile robots. *Sensors*, 22 (19), p. 7669. **https://doi.org/10.3390/s22197669**

[34] Naji, B., Abdelmoula, C., & Masmoudi, M. (2022). A real time algorithm for versatile mode parking system and its implementation on FPGA board. *Applied Sciences*, 12 (2), p. 655. **https://doi.org/10.3390/app12020655**

[35] Bo-Jun, Y., Kuo-Lan, S., Arkadevich, M. E., & Kuo-Hsien, H. (2020). Application of the MyRIO based mobile robot using vision system. Proceedings of the 2020 International Conference on Artificial Life and Robotics (ICAROB2020), Jan. 13-16, B-Con Plaza, Beppu, Oita, Japan

[36] Ghorbel, A., Ben Amor, N., & Jallouli, M. (2020). Design of a flexible reconfigurable mobile robot localization system using FPGA technology. *SN Applied Sciences*, 2, pp. 1–14. **https://doi.org/10.1007/s42452-020-2960-4**

[37] Benotsmane, R., & Vásárhelyi, J. (2022). Towards optimization of energy consumption of tello quad-rotor with mpc model implementation. *Energies*, 15 (23), p. 9207. **https://doi.org/10.3390/en15239207**

[38] Jiang, P., Luo, L., & Zhang, B. (2022, June). Research on target localization and recognition based on binocular vision and deep learning with FPGA. *Journal of Physics: Conference Series*, Vol. 2284, No. 1, 012009, IOP Publishing. **https://doi.org/10.1088/1742-6596/2284/1/012009**

[39] Chen, G., Ling, Y., He, T., Meng, H., He, S., Zhang, Y., & Huang, K. (2020). StereoEngine: An FPGA-based accelerator for real-time high-quality stereo estimation with binary neural network. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 39 (11), pp. 4179–4190. **https://doi.org/10.1109/TCAD.2020.3012864**

[40] Bobyr, M. V., Milostnaya, N. A., Gorbachev, S. V., Bhattacharyya, S., & Cao, J. (2021). The method of depth map calculating based on soft operators in multi-agent robotic stereo vision systems. *Research Transcripts in Computer, Electrical and Electronics Engineering*, 2, pp. 83–98. **https://doi.org/10.14357/08696527190207**

[41] Chan, C. W. H., Leong, P. H., & So, H. K. H. (2020). Vision guided crop detection in field robots using FPGA-based reconfigurable computers. *IEEE International Symposium on Circuits and Systems (ISCAS)*, IEEE, pp. 1–5. **https://doi.org/10.1109/ISCAS45731.2020.9181302**