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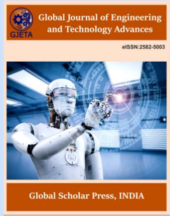


(Review Article)

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# Development of low-cost stereoscopic vision systems for educational robotics: A state of the art

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## Abstract

This paper explores the development of low-cost stereoscopic vision systems for robotics, with a focus on educational applications. Stereoscopic vision, essential for depth perception, allows robots to navigate and interact with their environment more effectively. However, the high cost and complexity of existing solutions limit their accessibility and integration into educational robotics. This review addresses these challenges by examining affordable technologies, such as FPV cameras and ESP32 microcontrollers, which are redefining the possibilities for cost-effective robotic systems. Through a systematic literature review, this study synthesizes findings from various academic databases, highlighting the technical advancements and educational applications of stereoscopic vision in small and mobile robots. It also presents case studies demonstrating the successful implementation of these low-cost systems in real-world scenarios, providing insights into their performance and the lessons learned. The findings suggest that integrating low-cost technologies not only makes robotic education more accessible but also enhances learning outcomes by providing students with hands-on experience in advanced robotic systems. This paper contributes to the ongoing discourse in robotic education by proposing scalable, cost-effective solutions that could be pivotal in democratizing advanced robotic technologies in educational settings.

**Keywords:** Educational robotics; Low-cost technology; Microcontrollers; Robotics; Stereoscopic vision; Vision systems

## 1. Introduction

The integration of stereo vision systems in robotics represents a transformative shift towards more interactive and perceptive machines, mirroring human depth perception to enable sophisticated environmental interactions [1–3]. Despite their potential, the widespread adoption of these systems in educational settings and small-scale applications is curtailed by high costs and complex operational requirements [4, 5]. This introduction delves into the significance of creating accessible stereo vision technologies, outlining the technical hurdles and economic constraints that often limit their broader use in academia and industry [6].

Stereo vision systems are instrumental for robots to perform tasks that require depth information, such as spatial navigation, object recognition, and complex interaction with their surroundings [7]. These systems work by emulating human binocular vision, capturing the same scene from two vantage points to compute depth [8]. However, the intricacies involved in calibrating such systems and the expense of high-quality cameras and sensors place them beyond the reach of budget-conscious educational programs and robotics enthusiasts [9].

Addressing the affordability barrier in stereo vision technology can profoundly impact educational outcomes. By incorporating cost-effective components like FPV cameras and economical microcontrollers, such as the ESP32,

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educational institutions can provide hands-on robotics experience at a fraction of the usual cost [10, 11]. This not only makes cutting-edge robotics accessible to a broader range of students but also encourages active participation and innovation, key components in STEM education [12].

Commercial stereo vision systems typically come bundled with proprietary hardware and software, which can stifle customization and experimentation [13]. For educational and research applications, where flexibility and adaptability are paramount, this poses a significant limitation [14]. The demand for open-source and customizable stereo vision solutions is therefore increasing, as they allow users to modify and optimize systems according to specific project requirements or educational goals [15].

This paper provides a critical review of the literature on stereo vision in robotics, focusing on developments that promise affordability and adaptability for educational and small-scale applications [16]. By examining relevant studies, this review aims to synthesize the current state of the art, identify technological gaps, and suggest directions for future research. It is hoped that these insights will facilitate the development of more accessible and effective stereo vision systems that can be widely implemented in robotics education and research.

Ultimately, advancing stereo vision technology for low-cost applications could revolutionize how educational institutions and hobbyists engage with robotics [17]. Reducing the economic and technical barriers to entry will not only broaden the accessibility of sophisticated robotic systems but also enhance educational experiences, fostering a new generation of innovators and technologists equipped to tackle future challenges in robotics and related fields.

## 2. Review methodology

This paper employs a comprehensive review methodology aimed at examining and synthesizing existing research on stereo vision technologies used in educational robotics. The scope of the review was strategically narrowed to focus on low-cost implementations and applications that enhance the accessibility of robotic systems in educational environments. An extensive search was conducted across multiple academic databases, including Scopus, IEEE Xplore, and Google Scholar, which are renowned for their extensive coverage of technology and engineering disciplines. The search criteria were tailored to include peer-reviewed articles, conference papers, and doctoral theses published in the last fifteen years.

Keywords such as "stereo vision," "educational robotics," "low-cost robotics," and "3D vision technology" were used to filter the literature. Articles were included based on their relevance to the integration of stereo vision in robotics, with a specific focus on educational applications and affordability. Exclusion criteria were set to omit articles that did not directly address the research question or were not within the scope of robotics application. The literature search was complemented by manual screening to ensure the inclusion of the most pertinent studies, especially those that highlight innovative uses of stereo vision in educational settings.

Upon collating the selected studies, a thematic analysis was conducted to identify common themes and gaps in the research landscape. This analysis facilitated a deeper understanding of the different approaches to implementing stereo vision in low-cost robotic systems and their educational impacts. Each study was critically evaluated for its methodology, findings, and relevance to the themes identified. This rigorous approach ensures that the review comprehensively covers the state-of-the-art developments in the field, providing a solid foundation for future research directions proposed in later sections of this paper.

Through this meticulous review process, the study not only highlights the technological advancements in stereo vision for robotics but also underscores the educational implications of these technologies. By focusing on low-cost solutions, this review aims to contribute to the democratization of advanced robotic systems in educational settings, making them accessible to a broader audience and fostering an inclusive environment for learning and innovation.

## 3. Vision technologies for robotics

Stereo vision technology has become a cornerstone of modern robotics, providing the essential capability of depth perception that mirrors human vision [18, 19]. This technology involves the simultaneous use of two cameras spaced apart at a distance similar to human eyes, capturing images from slightly different angles [20, 21]. By analyzing the disparity between these images, robots can gauge the distance to various objects within their environment, a crucial feature for autonomous navigation and complex interaction tasks [22]. The implementation of stereo vision in robotics has progressed significantly, facilitated by advancements in image processing algorithms and hardware miniaturization, allowing even small and cost-effective robots to incorporate this technology efficiently [23–25].

In educational and research settings, stereo vision systems have been integrated into a variety of robot designs, ranging from simple educational platforms to advanced research prototypes [26]. The adaptation of consumer-grade cameras and inexpensive computing modules, such as the Raspberry Pi or Arduino systems, has dramatically lowered the entry barrier for developing robots capable of complex visual tasks [27–29]. These platforms often utilize open-source software like OpenCV, which provides a robust set of tools for image processing and vision algorithm development [30–32]. This democratization of technology enables students and researchers to experiment with and learn from advanced robotics systems without the need for substantial funding.

Moreover, the practical applications of stereo vision in robotics extend beyond mere navigation. Robots equipped with these systems can perform tasks that require precise spatial awareness and fine motor control, such as sorting objects by size, assembling components, and even performing delicate surgical procedures in medical robotics applications [33–36]. Each of these tasks benefits from the robot's ability to accurately perceive the depth and position of objects in three-dimensional space, capabilities that are directly enabled by stereo vision technologies.

However, integrating stereo vision into robotics is not without its challenges. The accuracy of depth measurements critically depends on the precise calibration of the cameras and the algorithms used to interpret the stereo images [37, 38]. Calibration errors can lead to inaccurate depth perception, which can be problematic for robots performing tasks that depend on high levels of precision [39, 40]. Additionally, the computational load of processing images from two cameras in real time can strain the processing capabilities of smaller robots, leading to delays in response times or reduced operational complexity [41].

To address these challenges, ongoing research in the field is focused on optimizing the efficiency of stereo vision algorithms and developing more sophisticated calibration techniques that can be easily applied in diverse settings [42–44]. Machine learning approaches are increasingly being employed to improve the accuracy and reliability of depth estimation, even in dynamic or visually complex environments [45–47]. These advancements hold promise for significantly enhancing the capabilities of stereo vision systems, making them more versatile and easier to implement in a broader range of robotic applications.

Stereo vision technologies represent a dynamic area of development in robotics that bridges the gap between theoretical research and practical application. As these technologies continue to evolve, they are set to revolutionize the way robots interact with their environments, making them more autonomous and capable of performing an increasingly diverse array of tasks. For educational purposes, the continued integration of low-cost stereo vision systems offers a valuable hands-on learning tool, inspiring the next generation of roboticists and engineers.

## 4. Low cost technology integration

The integration of low-cost technologies in educational robotics has emerged as a key development, making sophisticated robotic systems accessible to a broader audience [48–50]. This transformation is primarily fueled by the advent of inexpensive yet capable hardware such as FPV cameras and versatile microcontrollers like the ESP32 [51, 52]. These components are crucial for developing cost-effective stereo vision systems that provide students and researchers with real-time, hands-on experience. The use of FPV cameras, initially popularized by drone enthusiasts, has been adapted for mobile robots due to their low cost, ease of integration, and reasonable performance under various lighting conditions.

Microcontrollers play a central role in the democratization of robotics education. The ESP32, for instance, offers a powerful combination of dual-core processing capabilities, Wi-Fi connectivity, and ample GPIO pins, all at a low cost [53–55]. This microcontroller supports the implementation of complex algorithms required for tasks such as image processing and sensor data fusion, which are integral to stereo vision applications [56, 57]. By leveraging such affordable components, educational institutions can now design and build robotic systems that were once financially out of reach, enabling students to explore advanced robotics concepts in a more interactive and engaging way.

Furthermore, the open-source nature of the software used in these systems, such as the Arduino IDE and Python programming environments, encourages experimentation and learning [58–60]. These platforms provide robust support for a variety of sensors and actuators, enhancing the versatility of low-cost robotic systems. Students not only learn to program and control these robots but also gain invaluable skills in troubleshooting and system integration, which are critical in the modern workforce. However, the integration of low-cost technologies is not without challenges.

The reliability and precision of cheaper components often lag behind their more expensive counterparts, posing potential issues in environments requiring high accuracy or robustness [61]. Additionally, the educational context often demands that these systems be easy to use and maintain, which can conflict with the technical limitations of low-cost components.

Despite these challenges, the benefits of integrating low-cost technologies in educational robotics far outweigh the drawbacks. It lowers the barrier to entry for educational institutions with limited budgets and provides a platform for students to develop practical skills in a field that is increasingly influenced by automation and artificial intelligence. As technology continues to advance, the gap between low-cost and high-end components will likely narrow, further enhancing the capabilities of educational robotics systems.

## 5. Applications and case studies

The deployment of low-cost stereo vision technologies in educational robotics has facilitated a range of innovative applications, illustrating the transformative potential of these systems in real-world settings. This section elaborates on diverse case studies that underscore the effectiveness and adaptability of stereo vision technologies, particularly in environments where cost-effectiveness is crucial. Each example demonstrates the practical impact of these systems, offering insights into their integration and the technological advancements they enable.

At the Pontificia Universidad Católica del Perú, researchers developed a stereo vision system for a mobile robot designed to enhance its interaction capabilities within complex environments [62]. This system utilized stereo cameras to perform precise object recognition and spatial localization, critical for tasks involving detailed manipulation and interaction. Leveraging the OpenCV library, the project implemented sophisticatedimage processing algorithms that accurately calculated the three-dimensional coordinates of objects. This setup proved exceptionally effective, achieving high accuracy in real-time object detection and positioning, which is pivotal for applications requiring precise operational capabilities, such as in surgical robots or automated delivery systems within cluttered environments.

In a separate initiative, the Universidad Complutense de Madrid focused on the application of stereo vision in enhancing the navigational abilities of surveyor robots operating in varied terrains [63]. The project combined stereo vision technology with machine learning algorithms to enable the robot to identify and classify obstacles autonomously. By integrating these technologies, the team succeeded in developing a robot capable of adjusting its path in real time, thus optimizing route planning and obstacle avoidance. This system's enhanced depth perception facilitated safer and more efficient navigation through unpredictable landscapes, demonstrating the robust potential of stereo vision in outdoor robotic applications, such as geological surveying and environmental monitoring.

The Universidad Politécnica Salesiana's project explored the synergy between stereo vision and ultrasonic sensing to create an advanced navigation system for indoor robotic applications [64]. This hybrid system utilized the depth data provided by stereo vision to create detailed maps of the environment, while ultrasonic sensors handled immediate obstacle detection tasks. The integration of these technologies enabled the robot to navigate with high precision in densely populated or dynamically changing environments, such as automated warehouses or manufacturing floors, where traditional navigation systems might fail.

At the Universidad de Catalunya, an innovative application involved a drone equipped with stereo vision for indoor navigation and mapping [65]. The system used visual markers to maintain orientation and position within complex indoor spaces where GPS is unavailable. This technology was particularly advantageous for applications like emergency response or industrial inspection, where drones need to operate reliably in confined spaces. The researchers demonstrated that such a system could significantly enhance the drone's ability to perform detailed inspections and data collection autonomously.

Finally, the Universidad Nacional de Colombia presented a case study where stereo vision was applied to agricultural robotics [66]. In this project, robots equipped with stereo vision systems were used to identify and classify crop types and assess plant health, enabling precise agricultural interventions such as targeted pesticide application or selective harvesting. This application of stereo vision not only increased agricultural efficiency but also contributed to sustainable farming practices by reducing waste and minimizing the environmental impact of crop treatment processes.

## 6. Result and discussion

The results derived from the deployment of stereo vision technologies in robotics highlight significant advancements in robotic perception and autonomy. These outcomes demonstrate the capacity of stereo vision systems to enhance the operational efficiency and adaptability of robots in various environments, from industrial settings to intricate surgical procedures. This section discusses the key findings from the integration of stereo vision across different robotic applications and the broader implications of these results on the field of robotics and automation.

The integration of stereo vision in mobile robotics has notably improved navigational accuracies and operational dexterity. Case studies, such as the deployment at the Pontificia Universidad Católica del Perú, have shown that robots equipped with stereo vision systems are capable of performing complex spatial tasks with high precision. These robots can identify and interact with objects in their environment with a reduced margin of error, enhancing their utility in precise tasks such as assembly and sorting. This is crucial for applications where fine motor skills and accurate depth perception are paramount, such as in automated manufacturing lines or in the handling of hazardous materials.

Furthermore, the research conducted at the Universidad Complutense de Madrid elucidates the impact of stereo vision on improving the environmental adaptability of robots. The ability of stereo vision-equipped robots to dynamically navigate through challenging terrains without human intervention marks a pivotal advancement in robotic autonomy. This capability is particularly beneficial for geological and environmental research, where robots can collect data in areas that are either inaccessible or hazardous to humans. The application of machine learning algorithms in processing stereo images enhances the robot's ability to make real-time decisions, showcasing the potential of integrating artificial intelligence with stereo vision technologies.

However, the results also highlight several challenges associated with the implementation of stereo vision technologies. Calibration complexities and the computational demands of processing stereo images remain significant hurdles. Inaccurate calibration can lead to erroneous depth perceptions, which can undermine the robot's performance and its ability to function autonomously. The discussions around these issues stress the importance of developing more robust calibration techniques and efficient algorithms that can operate under constrained computational resources.

Advancements in low-cost technology integration, as observed with the ESP32 microcontrollers and FPV cameras, have made stereo vision systems more accessible and cost-effective. This democratization of technology allows for broader adoption in educational settings, where students can experiment with and learn from advanced systems without prohibitive costs. The success of these integrations in educational institutions underscores the educational value of hands-on experience with complex technologies, preparing a new generation of engineers and technologists with practical skills in a high-tech world.

The integration of stereo vision technologies in robotics has demonstrated substantial benefits in enhancing the capabilities of robots. These technologies facilitate more accurate and reliable robot behaviors, making them invaluable across a variety of applications. As the field continues to evolve, ongoing research will be crucial in addressing the existing challenges and expanding the capabilities of stereo vision systems to meet the growing demands of modern robotics. Future developments are expected to focus on enhancing the efficiency and accuracy of these systems, potentially incorporating more advanced artificial intelligence techniques to further improve the autonomy and effectiveness of robotic systems.

## 7. Conclusion

This paper has systematically explored the integration and implications of stereo vision technologies in robotics, emphasizing their transformative impact across various applications, from educational platforms to complex industrial systems. The integration of stereo vision has been shown to significantly enhance the capabilities of robots, providing them with the crucial ability to perceive depth and navigate autonomously in dynamic environments. These advancements not only improve operational efficiency but also expand the potential applications of robots in fields that require high precision and reliability, such as medical surgeries and intricate manufacturing processes.

Stereo vision technologies have proven particularly impactful in educational settings, where they serve as an invaluable tool for teaching complex concepts in robotics and computer vision. By lowering the cost and technical barriers to entry, institutions can offer students hands-on experience with advanced technologies, fostering an environment of innovation and practical learning. The case studies presented in this paper highlight the successful application of these technologies in various real-world scenarios, demonstrating their versatility and adaptability to different operational needs and challenges.

However, the widespread adoption of stereo vision in robotics is not without its challenges. Issues such as the need for precise calibration, high computational requirements, and the handling of complex visual environments remain significant hurdles. Future research should therefore focus on addressing these challenges, perhaps through the development of more robust calibration methods, more efficient processing algorithms, and the integration of artificial intelligence to enhance depth estimation and decision-making processes. As the technology matures, it is anticipated that stereo vision will become even more integral to robotic systems, further blurring the lines between human and machine capabilities and opening new frontiers in robotics and automation.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

The authors declare no conflict of interest.

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