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Article

Comparative Analysis of Technologies for Autonomous Aquatic Vehicle Surveillance Systems: Applicability in the Colombian Context

Análisis Comparativo de Tecnologías para Sistemas de Vigilancia Autónoma de Vehículos Acuáticos: Aplicabilidad en el Contexto Colombiano

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Abstract: The monitoring and surveillance of aquatic vehicles has become increasingly important globally for ensuring national security, controlling maritime and fluvial traffic, preventing illicit activities, and protecting sensitive ecosystems. This study presents a comprehensive benchmarking analysis of key technologies for autonomous surveillance systems (ASS) specifically adapted to Colombian environmental conditions. Through systematic literature review and comparative analysis, we evaluate optical sensors (RGB and thermal cameras), radar systems, acoustic sensors, and processing architectures (edge vs. cloud computing) under the challenging operational scenarios typical of Colombia's diverse aquatic environments. The research methodology encompasses four critical technological domains: detection sensors, processing architectures, power systems, and communication technologies. Results indicate that edge computing architectures combined with hybrid sensor configurations (optical + thermal for general surveillance, radar + PTZ camera for high-security applications) provide optimal performance for Colombian conditions. The study concludes with specific recommendations for large-scale deployment considering the unique geographical, climatic, and infrastructure constraints of the Colombian territory.

Keywords: Maritime surveillanc; Vessel detection; Edge computing; Thermal imaging; Radar systems; Colombian waterways; Autonomous surveillance systems

Resumen: La monitorización y vigilancia de vehículos acuáticos ha adquirido creciente importancia a nivel global para garantizar la seguridad nacional, controlar el tráfico marítimo y fluvial, prevenir actividades ilícitas y proteger ecosistemas sensibles. Este estudio presenta un análisis comparativo integral de las tecnologías clave para sistemas de vigilancia autónoma (SVA) específicamente adaptadas a las condiciones ambientales colombianas. Mediante revisión sistemática de literatura y análisis comparativo, evaluamos sensores ópticos (cámaras RGB y térmicas), sistemas radar, sensores acústicos y arquitecturas de procesamiento (edge vs. cloud computing) bajo los escenarios operativos desafiantes típicos de los diversos entornos acuáticos de Colombia. Los resultados indican que las arquitecturas de edge computing combinadas con configuraciones híbridas de sensores proporcionan el rendimiento óptimo para las condiciones colombianas. El estudio concluye con recomendaciones específicas para despliegue a gran escala considerando las restricciones geográficas, climáticas y de infraestructura únicas del territorio colombiano.

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Palabras clave: Vigilancia marítima; Detección de embarcaciones; Edge computing; Imagen térmica; Sistemas radar; Vías navegables colombianas; Sistemas de vigilancia autónoma

1. Introdution

The surveillance of aquatic vehicles represents one of the most complex challenges in the field of contemporary national security and environmental protection. Autonomous Surveillance Systems (ASS) have emerged as a fundamental technological solution to address the growing demand for continuous monitoring across extensive maritime and fluvial areas [5]. These systems integrate multiple sensing technologies, advanced image processing algorithms, and communication architectures to provide real-time vessel detection, tracking, and classification capabilities [17].

The development of computer vision algorithms based on deep learning has revolutionized automatic maritime object detection capabilities. Convolutional Neural Networks (CNNs) and specialized architectures such as YOLO (You Only Look Once) have demonstrated superior performance in vessel detection within complex maritime environments [11]. At the same time, advances in edge computing technologies have enabled local data processing, reducing latency and dependence on network connectivity in remote locations [13].

Colombia, due to its privileged geostrategic position, has approximately 3,208 km of coastline distributed between the Atlantic and Pacific Oceans, in addition to an extensive hydrographic network that includes navigable rivers such as the Magdalena, Atrato, Orinoco, and Amazon. This hydrological wealth constitutes both an economic advantage and a security challenge, particularly considering illicit activities such as drug trafficking, smuggling, and illegal fishing, which use these waterways as transportation corridors.

The environmental conditions of the Colombian territory present unique challenges for the implementation of technological surveillance systems. Climatic variability, including seasons of intense rainfall, high relative humidity (>80%), marine salinity, intense equatorial UV radiation, and complex acoustic biodiversity, imposes specific design requirements that are not adequately addressed by generic commercial solutions [6].

The main objective of this research is to conduct a systematic comparative analysis of the available technologies for autonomous aquatic vehicle surveillance systems, specifically evaluating their applicability, technical feasibility, and economic viability within the Colombian operational context. This study aims to provide a well-founded technical guide for the selection and implementation of surveillance technologies adapted to the country's geographic, climatic, and infrastructural particularities.

2. Methodology

The present study is conducted under a methodological design aimed at ensuring rigor, reproducibility, and relevance in the analysis of the technologies under consideration. To this end, a systematic approach is adopted that combines an exhaustive review of the scientific literature with a comparative analysis of both quantitative and qualitative nature. The methodological framework is structured into sequential phases, ranging from the definition of the scope and evaluation criteria to the assessment of the applicability of technological solutions within the Colombian context. This approach enables not only the identification of the state of the art but also the establishment of clear and objective comparison parameters that facilitate well-founded decision-making.

2.1. Methodological Approach

The methodology employed is based on a systematic review approach combined with quantitative and qualitative comparative analysis. The methodological process is structured into four main phases: (1) definition of the scope and evaluation criteria, (2) systematic review of the scientific literature, (3) comparative analysis of technologies, and (4) evaluation of their specific applicability to Colombia.

2.2. Selection and Evaluation Criteria

The comparative analysis encompasses four critical technological domains: detection sensors, processing architectures, power supply systems, and communication technologies. For each domain, specific evaluation metrics were established, including detection efficiency, total cost of ownership (TCO), operational robustness, and applicability under Colombian conditions.

Detection sensors were evaluated considering detection range, spatial resolution, immunity to adverse atmospheric conditions, nighttime operation capability, and energy consumption. For processing architectures, edge computing and cloud computing approaches were compared based on inference latency, bandwidth requirements, and infrastructure complexity [19].

2.3. Information Sources

Data collection was carried out through a systematic search of academic databases, including IEEE Xplore, ScienceDirect, Scopus, and Google Scholar. Search strings employed key terms such as "maritime surveillance," "vessel detection," "edge computing for computer vision," and "remote sensing systems." In addition, technical specifications from manufacturers and reports of implementations in geographically similar contexts were analyzed.

3. Sensing and Detection Technologies

The development of advanced maritime surveillance and monitoring systems relies heavily on the integration of multiple sensing and detection technologies, each with specific strengths and limitations under operational conditions. These systems range from optical and thermal cameras for visual characterization of vessels to radar, LiDAR, and acoustic sensors capable of operating in scenarios where direct vision is limited. The appropriate selection and combination of these technologies is critical to ensuring robust performance in complex environments such as Colombia's fluvial and maritime ecosystems, where atmospheric, topographic, and biological factors impose particular constraints on sensor effectiveness.

3.1. Optical Imaging Systems

Optical sensors constitute the fundamental basis of computer vision systems for maritime surveillance. RGB cameras operate in the visible spectrum (400–700 nm), using CMOS sensors to capture color and reflectance information with high spatial resolution. These data are directly processable by convolutional neural networks for tasks such as morphological and chromatic vessel classification [18].

Thermal cameras represent a crucial complementary technology, operating in the long-wave infrared (LWIR, 8–14 m) to detect radiant energy emitted by objects based on their temperature. This capability enables the identification of characteristic thermal gradients, such as heat generated by vessel engines contrasting with the surrounding water temperature, facilitating effective detection independent of ambient lighting conditions [9].

The primary vulnerability of all optical systems lies in their susceptibility to adverse atmospheric conditions. Phenomena such as Mie scattering, caused by suspended water particles during precipitation events or fog formation, significantly attenuate electromagnetic radiation in both the visible and infrared spectra, thereby reducing contrast and the effective detection range [2].

3.2. Radar and LiDAR Systems

Active radar systems provide robust detection capabilities through the emission of microwave pulses (typically in the X-band, 8–12 GHz) and the analysis of backscattered signals. This technology offers significant advantages in terms of detection range (up to several kilometers), continuous 24/7 operation, and resilience to adverse weather conditions due to the microwave wavelength being considerably larger than atmospheric water particles [10].

However, the implementation of radar systems in Colombian ecosystems faces specific challenges. In narrow rivers with dense vegetation, radio wave propagation may be affected by multipath phenomena, generating false echoes and increasing background noise. In maritime environments, sea clutter caused by wave reflections can mask small-sized vessels [20].

3.3. Underwater Acoustic Sensors

Acoustic detection systems operate through the propagation of sound waves in aquatic media, where acoustic waves are transmitted more efficiently than electromagnetic waves. Passive sensors (hydrophones) detect characteristic acoustic signatures generated by propeller cavitation, machinery vibrations, and hydrodynamic flow around the vessel hull [22].

The main challenge for implementation in Colombia lies in the complex bioacoustic noise spectrum present in high-biodiversity ecosystems. Sound emissions from marine fauna (e.g., cetaceans and crustaceans) may overlap with acoustic signatures of interest, reducing the signal-to-noise ratio and requiring adaptive filtering and classification algorithms [7].

4. Processing and Analysis Architectures

The processing and analysis of information captured by sensing systems constitute the functional core of maritime surveillance platforms, as these processes determine the ability to transform raw data into actionable information. Processing architectures range from classical computer vision techniques to deep learning algorithms that enable more accurate vessel detection and classification in complex scenarios. Complementarily, the definition of the computational infrastructure, whether based on edge computing or cloud computing, establishes the balance between response speed, resource availability, and scalability of the implemented solutions. Together, these elements form the analytical ecosystem required to ensure robust monitoring systems adapted to Colombia's operational conditions.

4.1. Computer Vision Techniques

Classical computer vision algorithms, including background subtraction and frame differencing, provide computationally efficient methods for motion detection. For object tracking, Kalman filters have demonstrated effectiveness as recursive estimators that predict future states of dynamic systems from noisy measurements, maintaining coherent trajectories even in the presence of temporary detection failures [16].

4.2. Deep Learning Algorithms

Convolutional neural network architectures have transformed the state of the art in maritime object detection. Detection models are generally classified into two main categories: two-stage architectures such as Faster R-CNN, which employ region proposal networks (RPNs) followed by classification, and one-stage architectures such as YOLO and SSD, which treat detection as a regression problem by processing entire images in a single pass [8].

Recent studies have shown that optimized versions of YOLO, specifically YOLOv3-Tiny, can achieve real-time vessel detection with accuracy exceeding 87% under variable maritime conditions, making them particularly suitable for deployment on edge computing hardware with limited resources [13].

4.3. Edge Computing vs. Cloud Computing

The choice of processing architecture critically determines the latency between data acquisition and alert generation. Edge computing enables local processing with millisecond-level latencies, making it essential for applications that require immediate response and autonomous operation in locations with limited connectivity [13].

In contrast, cloud computing offers virtually unlimited processing capacity for complex algorithms, making it more suitable for forensic analysis, model training, and large-scale analytics. The optimal selection depends on specific requirements related to latency, connectivity availability, and the computational resources needed [12].

5. Infrastructure and Support Systems

The effectiveness of maritime surveillance systems depends not only on sensing and processing technologies but also on the infrastructure and support systems that ensure sustained operation in demanding environments. These components include autonomous energy solutions capable of maintaining continuous operation in remote locations, environmental protection mechanisms that safeguard equipment against severe conditions of humidity, salinity, and biofouling, and communication platforms that ensure reliable data transmission in areas with limited connectivity. The integration of these elements is fundamental to achieving robust and resilient systems adapted to Colombia's geographic and climatic conditions.

5.1. Power Supply Systems

Autonomous operation in remote locations without access to conventional power grids requires on-site energy generation and storage solutions. Photovoltaic systems represent the most mature technology, combining solar panels, charge controllers, and battery banks to ensure continuous operation [3].

In coastal regions with wind potential, hybrid microgrids that combine solar and wind energy can significantly increase supply reliability. Battery bank sizing must consider not only nighttime operation but also extended periods of low solar irradiance during rainy seasons characteristic of Colombia's tropical climate [14].

5.2. Environmental Protection of Equipment

Electronic components require robust protection against severe environmental conditions, including humidity, salinity, and accelerated corrosion. IP66 and IP67 protection standards represent the minimum requirements for operation in maritime environments. The selection of corrosion-resistant materials, such as 316L stainless steel or aluminum with marine-grade coatings, is critical to ensuring operational durability [1].

Additional considerations include protection against biofouling (the growth of marine organisms), which can obstruct optical sensors and ventilation systems, requiring specific design strategies and preventive maintenance protocols [4].

5.3. Communication Technologies

Data transmission from remote locations presents significant challenges due to infrastructure limitations. Cellular networks (4G/5G) offer high bandwidth but limited coverage in rural and maritime areas. Satellite communication provides global coverage but entails high operational costs and increased latency [21].

LoRaWAN technologies represent a promising alternative for low-bandwidth data transmission (e.g., alerts and metadata), offering extended range and low energy consumption, particularly when integrated with Low Earth Orbit (LEO) satellite constellations for areas without terrestrial coverage [15].

6. Comparative Analysis of Technologies

The comparative analysis of technologies constitutes a key stage in identifying strengths, limitations, and potential synergies among different solutions applicable to maritime and fluvial surveillance. Based on technical and operational criteria, detection sensors, processing architectures, and support systems are evaluated in order to determine which combinations are most viable within the Colombian context. This approach enables not only the characterization of the individual performance of each technology but also the recognition of the need for multimodal integration and complementary infrastructures to ensure continuous, accurate, and efficient operation under the country's specific environmental, geographic, and logistical conditions.

6.1. Comparison of Detection Sensors

As presented in Table 1, the comparison of sensors demonstrates that no single technology is capable of comprehensively meeting the requirements of maritime and fluvial surveillance in Colombia. RGB cameras provide high visual resolution under favorable lighting conditions but are ineffective in darkness or fog, highlighting the complementary role of thermal cameras in nighttime operations. Radar systems, in turn, ensure long-range detection under all weather conditions, although they face limitations in scenarios with intense wave activity, while acoustic sensors are effective in discrete underwater environments, with the challenge of mitigating interference from bioacoustic noise. Overall, the findings summarized in Table 1 lead to the conclusion that multimodal integration of these technologies represents the most suitable strategy to address the diversity of environmental and operational conditions present in the country's maritime and fluvial ecosystems.

Table 1. Comparison of Detection Technologies Applicable to Maritime and Fluvial Surveillance in Colombia

Technology	Operating Principle	Main Advantage	Critical Limitation	Applicability in Colombia
RGB Camera	Capture of reflected light in the visible spectrum (400–700 nm)	High spatial resolution for detailed visual identification	Inoperative in darkness; severe degradation under rain or fog	Optimal for ports and marinas with adequate lighting conditions
Thermal Camera	Detection of infrared radiation emitted by objects (8–14 μm)	24/7 operation independent of ambient lighting	Limited resolution; susceptible to heavy rainfall	Excellent for nighttime surveillance in rivers and coastal areas
Radar	Emission and reception of microwave signals (8–12 GHz)	Long-range detection under all weather conditions	Lack of visual identification; sea clutter due to waves	Ideal for traffic control in main maritime and fluvial channels
Acoustic Sensor	Detection of sound waves propagating underwater	Discreet underwater detection without line of sight	Interference from marine fauna bioacoustic noise	Effective in narrow channels with low biodiversity levels

6.2. Evaluation of Processing Architectures

As shown in Table 2, each processing and analysis architecture presents advantages and limitations that condition its applicability in maritime and fluvial surveillance environments. Classical computer vision offers low-cost solutions with low computational complexity, although it is restricted to controlled scenarios. In contrast, deep learning models provide high accuracy and strong generalization capabilities, at the expense of requiring large volumes of labeled data and greater computational resources. Regarding infrastructure, edge computing stands out for its low latency and operational autonomy under limited connectivity conditions, making it ideal for real-time alert generation, while cloud computing offers virtually unlimited processing capacity and is more suitable for forensic analysis and complex model training. Collectively, Table 2 shows that the strategic integration of these architectures is essential to balance accuracy, response speed, and scalability in monitoring systems tailored to Colombian needs.

Table 2. Comparison of Processing and Analysis Architectures for Maritime and Fluvial Surveillance Applications in Colombia

Architecture	Methodology	Main Requirement	Operational Advantage	Recommended Application
Classical Vision	Explicit algorithms (background subtraction, Kalman filtering)	Controlled scenes with static backgrounds	Low computational cost; no training required	Basic motion detection
CNN / Deep Learning	Data-driven models (YOLO, Faster R-CNN)	Large datasets of labeled images	High accuracy and strong generalization capability	Accurate classification of vessel types
Edge Computing	Local processing on embedded devices	Hardware with inference capability (GPU/TPU)	Minimal latency; autonomous operation	Real-time alerts with minimal bandwidth usage
Cloud Computing	Remote processing on centralized servers	Reliable high-bandwidth connectivity	Virtually unlimited computational capacity	Forensic analysis and model training

6.2.1. Analysis of Support Systems

As summarized in Table 3, power supply and communication systems represent critical components for ensuring the sustained operation of surveillance platforms in maritime and fluvial environments. Photovoltaic solutions stand out due to their technological maturity and decreasing costs, although they face limitations during rainy seasons. Wind and micro-hydropower can complement energy generation, with constraints related to local resource availability and maintenance requirements. Regarding communications, cellular networks offer high speed and low latency but limited coverage in remote areas, while satellite systems ensure global reach at significantly higher costs. Overall, Table 3 shows that the optimal selection of support infrastructure requires a balance among reliability, cost, and adaptability to Colombia's specific geographic and climatic conditions.

Table 3. Comparison of Power Supply and Communication Technologies for Maritime and Fluvial Surveillance Systems in Colombia

Component	Technology	Main Advantage	Design Consideration	Challenge in Colombia
Power Supply	Solar Photovoltaic	Technological maturity and decreasing costs	Battery sizing to ensure system autonomy	Low solar irradiance during rainy seasons
	Wind (Micro)	Complementary 24/7 power generation	Assessment of local wind resources	Limited applicability to coastal regions
	Micro-hydropower	Stable generation in rivers with constant flow	Minimum flow rate and head requirements	Complex maintenance and potential ecological impact
Communication	Cellular (4G/5G)	High bandwidth and low latency	On-site verification of network coverage	Limited coverage in remote areas
	Satellite (LEO/GEO)	Global coverage	Cost–latency trade-off depending on application	High cost per transmitted gigabyte

7. Results

The definition of optimal technological configurations is essential for adapting maritime and fluvial surveillance systems to Colombia's particular conditions. Based on the results of the comparative analysis, integrated schemes are proposed that seek to balance performance, cost, and resilience against the country's environmental, geographic, and operational challenges. These configurations consider not only the selection of appropriate sensors and processing architectures but also energy infrastructure requirements, environmental protection, and communication systems, in order to ensure sustainable and effective solutions across different application scenarios.

7.1. Optimal Configurations for Colombia

Based on the comparative analysis, two optimal technological configurations are identified for different operational scenarios in Colombia:

Standard Configuration: For general surveillance and traffic control on major rivers, the combination of an RGB camera + thermal camera + edge computing processing provides the best cost–benefit balance. This configuration ensures 24/7 detection with visual classification capabilities, operating autonomously with minimal latency and moderate bandwidth requirements.

High-Security Configuration: For border surveillance and critical infrastructure protection, the integration of radar + PTZ camera + hybrid edge computing offers superior capabilities. Radar provides reliable detection under adverse weather conditions, while the PTZ camera enables precise identification of detected targets.

8. Conclusions

This study has demonstrated that there is no universally optimal technological solution for aquatic vehicle surveillance; appropriate selection requires a careful balance among detection performance, environmental robustness, and total cost of ownership. In the Colombian context, edge computing architectures combined with hybrid sensor configurations (optical–thermal or radar–optical) provide the most robust overall performance.

The main challenges identified include energy management during extended rainy periods, protection against accelerated corrosion in saline environments, and mitigation of bioacoustic interference in high-biodiversity ecosystems. These challenges require tailored engineering solutions that account for the specific characteristics of the national territory.

Future work should focus on the development of adaptive sensor fusion algorithms capable of automatically optimizing the contribution of each detection modality based on real-time environmental conditions. Additionally, further research is needed on acoustic classification algorithms specifically designed to distinguish between vessels of interest and marine fauna in tropical ecosystems.

The large-scale deployment of surveillance networks will require the development of optimized communication protocols for efficient transmission of critical data under bandwidth constraints, as well as predictive maintenance strategies based on data analytics from integrated environmental sensors.

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Authors' Biography

Iván Leiton Electronics engineer, graduated from the University of Ibagué, with experience in mechatronics, machine vision, artificial intelligence, and control engineering, areas in which he has developed highly demanding technical projects. He completed a Master's degree in Renewable Energies at the Universidad Internacional de La Rioja (UNIR). His first professional experience was in a multinational company within the energy sector, while simultaneously participating in the design of printed circuit boards for research projects at the Universidad Cooperativa de Colombia, focused on Internet of Things (IoT) solutions for agriculture. During this period, he strengthened his programming skills and advanced artificial intelligence techniques. On July 8, 2024, he entered the Escuela Naval de Cadetes "Almirante Padilla" with the firm purpose of putting his knowledge at the service of the Colombian Navy. After being commissioned as an officer in December 2024, he was assigned to the Centro de Desarrollo Tecnológico Naval, where he actively participates in research, innovation, and technological development projects aimed at strengthening the institution's strategic capabilities.