Revolutionizing Surveillance: A Brief Survey of Edge AI Terminals in Road Infrastructure

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***Abstract*—The evolution of Closed-Circuit Television (CCTV) systems, initially designed for security, has transcended into diverse domains, impacting public spaces, transportation hubs, and commercial districts. While serving traditional roles in crime prevention, these systems now play vital roles in correctional institutions, education, and various industries. The proliferation of CCTV cameras, though providing extensive surveillance, presents challenges of network congestion and resource-intensive processing. This prompts the need for innovative solutions. Edge AI Terminals—a transformative approach that strategically places advanced computing capabilities closer to data sources, reducing reliance on centralized servers. Additionally, it can employ cutting-edge AI algorithms, enabling heightened efficiency and responsiveness. In this paper, we discuss the evolution of CVTV usage and the revolution of surveillance by integrating edge AI technology. We further discuss how edge AI terminals can play a key role in future road infrastructure. Finally, some major challenges and their potential solutions are highlighted.**

***Index Terms*—Edge AI, Surveillance, CCTV.**

I. Introduction

The widespread implementation of Closed-Circuit Television (CCTV) systems has evolved beyond their original applications in security, extending their influence across various domains such as public spaces, transportation hubs, and commercial districts. Initially designed for crime prevention and enhancing public safety, these systems now serve essential functions in correctional institutions, educational facilities, residential areas, and commercial spaces [1]. The impact of CCTV has expanded further into many sectors, such as e-commerce, healthcare, benefit payments, voter verification, and banking, where CCTV technology reinforces security measures, verifies identities, and optimizes urban operations.

Despite the extensive surveillance coverage facilitated by the proliferation of CCTV cameras, challenges have arisen, particularly concerning network congestion and resource-intensive data processing. The increasing volume of data generated by the growing number of cameras strains network resources, resulting in congestion, compromised real-time data transfer, and diminished overall system responsiveness. These challenges, stemming from the expansion of CCTV networks, call for innovative solutions to uphold and enhance the efficiency of surveillance systems.

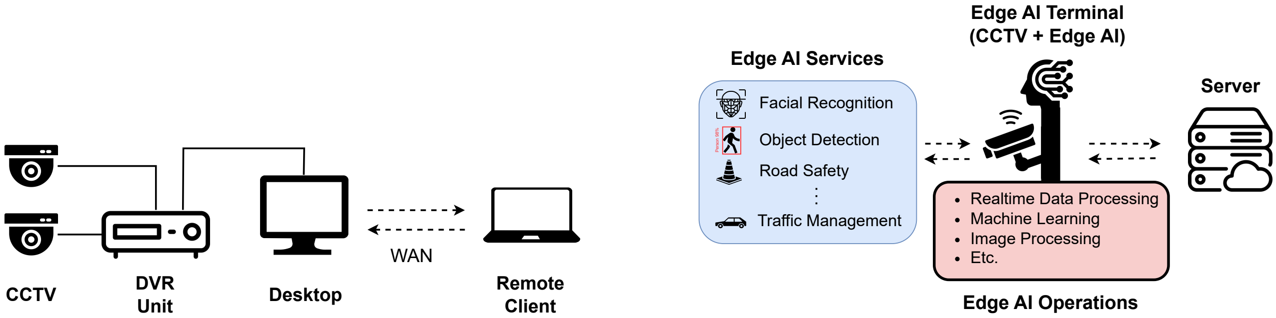
In response to these challenges, the concept of Edge AI Terminals emerges as a transformative remedy. Edge AI Terminals signify a paradigm shift in surveillance technology, strategically placing advanced computing capabilities closer to the data source, thereby diminishing reliance on centralized servers [2]. This decentralized approach empowers immediate and thorough data analysis using state-of-the-art Artificial Intelligence (AI) algorithms, facilitating quicker response times and heightened operational efficiency [3]. As we delve into subsequent sections, we explore how Edge AI Terminals provide solutions to tackle the dynamic challenges posed by the increasing scale and complexity of modern surveillance systems. By integrating Edge AI technology, we envisage a future in which surveillance systems not only capture video data but also actively contribute to proactive and intelligent urban management.

The rest of the manuscript is organized as follows. Section II describes the evolution of CCTV usage. Section III details some edge AI technologies and discusses the integration of edge AI into CCTV systems. Section IV describes the role of edge AI in road infrastructure. Section V highlights some open challenges in edge AI and proposes potential solutions. Finally, in section VI, conclusions and future work are presented.

II. Evolution of CCTV Usage

The deployment of CCTV cameras in urban environments has evolved beyond traditional security measures, offering a broad spectrum of applications that significantly contribute to the effective management of urban spaces. While initially serving the primary purpose of crime prevention and enhancing public safety in public spaces, transport hubs, and commercial districts worldwide, these systems have extended their utility across various urban domains [1]. In correctional institutions, educational facilities, residential areas, and commercial spaces, CCTV's pivotal role in verifying identities, ensuring child safety, and fortifying residential security is indispensable [4].

Moreover, their impact extends to diverse sectors like e-commerce, healthcare, benefit payments, voter verification, and banking, playing a pivotal role in fraud mitigation through stringent identity verification measures, fortifying security, and optimizing urban operations.



(a) Traditional CCTV System

(b) Edge AI Integrated CCTV System

Fig. 1. Traditional vs Edge AI Integrated Surveillance.

A. Role in Crime Prevention and Investigations

Statistical findings reveal the dual role of CCTV in preventing crime and aiding investigations. For instance, a study analyzing 251,195 crimes recorded by the British Transport Police on the British railway network between 2011 and 2015 highlighted the instrumental role of CCTV in investigations. The study found that CCTV was available to investigators in 45% of cases, proving useful in 29% of cases (65% of those cases where it was available) [5]. This statistical evidence showcases the significant impact of CCTV as an investigative tool, notably improving crime resolution rates across various crime types except for drugs/weapons possession and fraud.

B. Transforming Urban Traffic Dynamics

CCTV-enabled systems have also revolutionized traffic management, improving road safety and optimizing traffic flow [6]. These systems monitor multiple internal cameras and analyze captured images to extract essential traffic insights, including speed, vehicle composition, shapes, types, identification numbers, and instances of violations or accidents [7], [8]. CCTV integration facilitates improved traffic dynamics, swift accident detection, reduced journey times, lower fuel consumption, minimized emissions, and heightened traveler satisfaction.

C. CCTV Network Expansion: Navigating Operational Challenges

The growth of CCTV networks, while offering numerous benefits, also presents substantial challenges [9]. The exponential increase in cameras strains network resources, causing congestion and heightened data processing demands. This surge in data overwhelms network bandwidth, causing transmission bottlenecks that hinder real-time data transfer, affecting video streaming and storage efficiency. Consequently, network reliability and responsiveness suffer, compromising overall surveillance system effectiveness. The significant data surge from these cameras necessitates robust storage, potent computing resources, and streamlined data processing, intensifying resource requirements. Managing this massive data flow also demands stringent measures for data security, integrity, and accessibility, adding complexity and costs to operational management.

D. Addressing Challenges through Edge AI

To combat these challenges, innovative strategies and technological advancements are sought to address these issues. Current research emphasizes intelligent video analytics, machine learning algorithms, and edge computing to streamline data processing, automated video analysis, and minimize human intervention [10], [11]. These technologies aim to enhance surveillance system efficiency, scalability, and accuracy, striving for more reliable and responsive CCTV systems amid their expanding scale and complexity.

III. Emergence of Edge AI Terminals

Edge AI technologies, exemplified by powerful devices like Nvidia's Jetson AGX Orin and Jetson Orin Nano that let you run multiple neural networks in parallel, have emerged as game-changers, especially in the surveillance landscape [12]. These AI-driven terminals embody the fusion of high-performance computing and energy-efficient design [2]. Their capacity for on-site data acquisition, complex analysis, and rapid decision-making introduces a transformative dimension in surveillance by reducing reliance on remote servers. Figure 1 provides a comparison between traditional surveillance systems and advanced edge AI terminal integrated surveillance systems.

A. Impact on Traffic Management

Integration of Edge AI into CCTV systems represents a considerable leap in traffic management along with other technologies. This integration enables swift identification of congestion areas and dynamic optimization of traffic signals through AI-driven video analysis. Real-time analysis by Edge AI expedites incident detection and significantly enhances accident prevention, thereby improving road safety standards.

B. Case Studies and Practical Implementations

In a recent project in Liverpool, a smart visual sensor leveraging edge computing, computer vision, and deep neural networks monitored real-time multi-modal transportation, ensuring citizen privacy was implemented [13]. This sensor effectively tracked transportation activities within urban centers showcasing the potential of edge AI within the CCTV realm. AI cameras, serving as edge devices are another technological advancement that uses lightweight deep learning models to detect traffic flow and incidents from roadside images [14]. They transmit essential information to conserve network bandwidth and server resources. However, optimizing these devices and configuring environment-related parameters before deployment is crucial [15].

C. Technological Advancements and Challenges

The emergence of Edge AI terminals signifies a fundamental shift in surveillance technology. These terminals enable onsite data processing within CCTV networks, reducing reliance on centralized servers. This decentralized approach empowers immediate and comprehensive data analysis using advanced AI algorithms and high-speed processing, greatly enhancing operational efficiency and response times in surveillance.

Integration of Edge AI technology into existing CCTV infrastructure marks a significant advancement in surveillance capabilities. It refers to AI computations performed within real-world devices, closer to end-users rather than in centralized data centers. These terminals facilitate advanced analytics directly from video feeds, including traffic behavior analysis, facial recognition, and swift incident identification. This transformative integration propels CCTV systems beyond mere video capture devices, making them proactive and intelligent surveillance solutions.

This pivotal moment in surveillance technology brings promises of enhanced operational efficiencies and heralds a new era of decentralized and intelligent surveillance infrastructure. Edge AI's applications span various sectors, offering tailored AI capabilities optimized for resource-constrained environments. It enables real-time decision-making closer to data generation points, ensuring quicker responses and reduced latency. Exploring machine learning algorithms optimized for resource limitations is a significant aspect of this evolving field, presenting both challenges and promising research directions, driving innovation in Edge AI.

IV. Key Role in Future Road Infrastructure

The integration of Edge AI Terminals into future road infrastructure stands as a pivotal advancement with far-reaching implications for transportation systems. These sophisticated devices play a multifaceted role in shaping the future of road networks and vehicular operations. Edge AI terminals are recognized for their decentralized computing capabilities. These capabilities empower them to process data locally, addressing the dynamic challenges of modern road networks. The decentralized approach of edge terminals is instrumental in optimizing traffic flow and mitigating congestion, ultimately enhancing overall road efficiency. In addition, these terminals can help perform better traffic management, facilitate cooperative and autonomous vehicles on the road, and enhance road safety [16]. Figure 2 represents potential services that can be supported with edge AI terminals. Numerous studies have been performed to illuminate the potential of edge AI in road infrastructure. Some of these studies are discussed in this section.

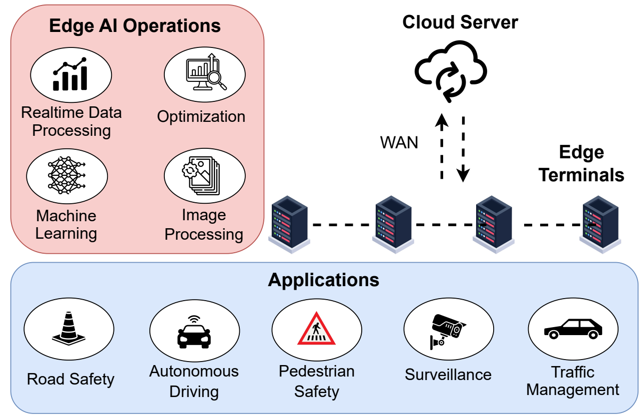


Fig. 2. Potential Edge AI Services.

A. Potential of Edge AI Terminals in Road Traffic Management

Edge AI terminals emerge as a cornerstone in the evolution of intelligent transportation systems, offering unparalleled potential. Their decentralized computing capabilities, coupled with real-time data processing, position them as key enablers for addressing the dynamic challenges of modern road networks. The research underscores the critical role of edge AI in optimizing traffic flow and mitigating congestion, thereby enhancing overall road efficiency.

Edge AI plays a critical role in optimizing traffic flow by leveraging machine learning algorithms and processing data at the edge. These terminals contribute to more efficient traffic management, reducing congestion, and enhancing the overall functioning of road networks [17]. In this regard, [18] proposes a new edge traffic flow detection scheme based on deep learning. A vehicle detection algorithm based on the YOLOv3 model is trained with a great volume of traffic data. The paper proposed a real-time vehicle tracking counter for vehicles that combines vehicle detection and vehicle tracking algorithms to realize the detection of traffic flow.

B. Enabling Autonomous and Cooperative Driving

A fundamental aspect of Edge AI terminals lies in their ability to facilitate autonomous and cooperative driving scenarios. By harnessing the power of machine learning algorithms, these terminals swiftly and accurately collect and analyze real-time road conditions [19]. This capability is integral to the success of autonomous vehicles, ensuring they can make informed decisions based on the immediate environment. Research showcases advancements in edge-based perception systems, enhancing the safety and reliability of autonomous driving.

The authors in [20] highlight the role of edge AI in autonomous driving. In addition to real-time object detection for enhancing safety by swiftly identifying and analyzing objects in a vehicle's surroundings, it also optimizes traffic flow prediction by leveraging advanced edge computing. It further enables intelligent decision-making for vehicles through the near-real-time deployment of deep learning models at the edge, improving responsiveness and reliability in dynamic driving scenarios. Considering the potential of edge AI in autonomous and cooperative driving, the authors in [21] introduce the Intelligence-Net framework for Connected and Autonomous Vehicles (CAVs) using Multi-Access Edge Computing (MEC) and blockchain technology. Their framework enables CAVs to share driving intelligence in near real-time. The process involves dividing roads into segments, detecting environmental changes, updating local driving models, aggregating models through MECNs, achieving consensus through blockchain, and downloading the latest models for adaptive driving.

C. Enhancing Road Safety and Reducing Social Costs

The provision of timely warning and avoidance information represents a pivotal contribution of Edge AI Terminals towards road safety. By actively monitoring roadside stops, accidents, and pedestrian activities, these terminals offer actionable insights to both vehicles and pedestrians [22].

The proposed mechanism in [23] leverages Edge AI and VANET, enabling autonomous vehicles to detect anomalies, share road information, and contribute to enhanced road safety. Employing the Residual Convolutional Neural Network (ResNet-18) and Visual Geometry Group (VGG-11), the study demonstrates effective automatic detection and classification of road anomalies, including potholes, bumps, cracks, and defect-free segments. The integration of AI edge computing in the proposed solution by [24] enables the recognition of zebra crossings in real-time, contributing to the overall safety of visually impaired pedestrians navigating complex outdoor environments. Their research focuses on delivering real-time messages about the crossing's current situation and the traffic light signal to visually impaired pedestrians.

V. Challenges and Potential Solutions

This section entails some major challenges associated with edge AI in the context of road infrastructure and related services. Moreover, potential solutions to these challenges are also highlighted.

A. Expediting AI Processes with Edge AI

AI model training poses computational challenges due to prolonged construction times for efficient models. Currently, the dynamic and adaptive partitioning of AI tasks, utilizing edge services, has emerged as a key consideration for efficient task completion. Edge AI offers a robust computing architecture for demanding AI applications, addressing computational complexities effectively. The implementation of distributed learning, such as federated learning, facilitates training with constrained resources while preserving data privacy. This approach involves uploading only local model parameters to edge terminals, allowing the exploration of distributed learning models to accelerate the learning process in resource-limited edge environments.

B. Enhancing Security and Privacy Safeguards

Information gathering in vehicles relies heavily on communications between vehicles and between vehicles and roadside infrastructure. The high mobility of vehicles often results in interruptions and frequent failures of communication links. Additionally, malicious attacks by hackers on sensors and communication channels pose significant privacy threats. Potential remedies involve implementing server access control, communication authentication, and the adoption of distributed learning models.

C. Addressing High Mobility Challenges

The escalating density of road traffic introduces dynamic changes in network topology due to frequent and high-speed vehicle movements. The substantial mobility of intelligent vehicles, a key characteristic in vehicular networks, not only hinders stable wireless communication but also complicates the collaborative optimization of allocating computing and cache resources. Investigating data routing distribution protocols and predicting vehicle movements could offer potential enhancements in this scenario.

VI. Conclusions and Future Work

In conclusion, the evolution of Closed-Circuit Television (CCTV) systems from their initial security applications to broader urban domains has brought forth challenges, notably network congestion and resource-intensive processing. Addressing these issues, Edge AI Terminals offer a transformative solution by decentralizing computing capabilities, enhancing real-time data analysis, and fostering operational efficiency. As we navigate the evolving landscape of modern surveillance systems, the integration of Edge AI technology promises a future where surveillance not only captures video data but actively contributes to proactive and intelligent urban management. Future work involves refining Edge AI applications, tackling open challenges, and further study on optimizing the synergy between advanced computing and surveillance for enhanced urban resilience and security.

VII. Acknowledgement

This work was supported by the Commercialization Promotion Agency for R&D Outcomes(COMPA) grant funded by the Korean Government(Ministry of Science and ICT). (RS-2023-00304695).

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