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5G-Based Low-Latency Control Framework for Autonomous Security Robots in Smart Cities

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Abstract. The growing demand for advanced city security has led to the development of autonomous security robots to be used in smart cities. It introduces a low-latency control architecture based on 5G to enhance other real-time monitoring, threat detection, and response efficiency. It is powered by 5G and edge computing, which achieves significant improvements in performance when compared to the traditional solutions. Experimental results show that there was reduction of end-to-end latency among areas to 310 ms as compared to 80200 ms in conventional networks, which facilitates faster communication and decision making. The suggested system exhibits a detection accuracy of 96% and a decreased false alarm rate of about 3%, so guaranteeing dependable monitoring. The maximum speed of transfer between data is 1200 Mbps, which makes it possible to transfer high-quality real-time video and sensor data processing. In addition, the reaction speed is reduced to 1-2 seconds, increasing the efficiency of a system in critical scenarios. The structure also supports scalable multi-robot collaboration with the system reliability of over 99.9%. The results confirm that the proposed methodology achieves a great deal of efficiency, accuracy, and responsiveness, which makes it fit the next-generation smart city security systems.

Keywords: Autonomous Security Robots, Smart Cities, Edge Computing, Real-Time Surveillance, Robotics Control Framework.

INTRODUCTION

To create smart cities, which enhance mobility, security, and data management, automation and robotics are a necessity [1]. They ensure that the planning of the city is more inclusive, promote sustainability and the swift reaction during an emergency. Cities of the future will be smarter and more efficient due to a collaboration of robotics among companies and governments that will direct resource optimization and encourage green practices in the city. This will create an impetus to economic growth. Concerns about data breaches and inadequate infrastructure resilience are two of the obstacles that citizen-centric smart city construction (SCC) must overcome to improve urban residents' quality of life [2]. The investigation of the CSPSCC features through the participatory governance refers to the example of Nanjing, the subject of this research. It finds that demography and citizen involvement greatly impact how people perceive the security of smart city programs.

To escape challenges faced in complex environments, this study introduces a novel mobile robot system known as visual inertial navigation system (VINS) which is guided on point lines and works in real time [3]. It enhances the tracking strength with the help of ED Lines and adjustable kappa correction. The technology has been proven to be increasingly reliable in smart cities and future 6G innovations due to its high localization accuracy and stability in comparison with traditional methods. This work introduces an IoT framework, which is versatile and modular to enable remote control of robots in geographically distributed conditions with a low latency [4]. It combines WebRTC video transmission, MQTT signal control, and Flutter interface. To detect objects at real time, there is a model of YOLOv11 nano. This chapter addresses the significance of artificial intelligence (AI)-based cybersecurity in smart city and Industry 4.0 project, focusing on automation and well-established connection [5]. Among them, many are the building of communication networks, the characterization of ways of recognizing threats and information transfer between them safely and offering a flexible security architecture. By accommodating both ethical concerns and the practical requirements, we offer a framework on safe AI

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communications. More efficient and better-connected city life is possible in smart cities thanks to cutting-edge electronics and mobility robotics [6]. This literature review of the years 2015-2023 will focus on the autonomous motion of mobile robots, as well as how they manage issues regarding navigation and security. To give some illumination on the methods of integrating robots into smart city practices, it also examines the possible applications in personalized transportation, and assistive technology.

Through the assistance of ML and robots, the management of the smart cities is becoming upgraded, which enhances the services delivered to people, whilst increasing the efficiency and sustainability of the cities [7]. Nonetheless, regulatory, legal and ethical challenges to this change include the issue of algorithmic biasness and data privacy. These consequences are explored in this chapter and policy recommendations on how to incorporate smart cities that are equitable, safe, and sustainable. The chapter focuses on the omnipresent robot's integration in smart cities, given that the energy consumption is emphasized to operate sustainably [8]. The paper also explores how reinforcement-based learning tools can be used to enhance the efficiency and effectiveness of robots, including SAR units, to develop energy conscious urban areas. Smart city networks constitute with embodied robots enhance human-robot co-operation and efficiency in terms of real-time sharing of information [9]. This study offers a novel method of imitation learning in robots using the Transformer and Diffusion models in which the robots are conditioned to perform tasks according to language. This study explores a predictive maintenance model of smart cities (AI and robotics (R)) that can solve the problem of detecting urban roads [10]. Cloud-based AI models, like YOLOv9, will process video and geolocation data obtained using a mobile robot. Although negative factors like GPS error and insufficiency of the data sets are present, successful fault diagnosis is proven to be achieved and reduces the cost and increases safety.

In smart cities, a modest yet incremental change is occurring, and it is rising services through data and communication [11]. Security management is challenging with common dangers. It is critical to continuously evaluate security. This study investigates the ways that robots can utilize the Internet of things, artificial intelligence and machine learning to address security issues and, at the same time, enhance the quality of the provided service and cover the issue of privacy. It examines how cities of the future can employ Robotic Process Automation (RPA) to improve sustainability and the services people use every day [12]. Its outcomes prove the groundbreaking role of RPA in creating resource-saving and environmentally friendly cityscapes. The advancement of the 5G NR and 4G LTE will open the path to the realization of smart cities by 2025 which will deploy the use of intelligence and automation to sectors like healthcare, transport and government [13]. The IoT will become the Internet of Everything (IoE) in 2030 as 6G technology will allow the connection of devices. Smart city managers need to contend with technical, social, and political challenges with an emphasis on data management, privacy and security [14]. In this work, the literature related to the matter is reviewed and a paradigm focusing on the topic of privacy and security is provided. The subjects that are of interest include infrastructure, security procedures, operational hazards, and use of social media.

Indoor navigation involving the use of robots and UAVs presents challenges in places that do not have a strong satellite connection when it comes to smart city navigation. An ensemble of vSLAM algorithms visual simultaneous localization and mapping and remote data processing servers is a solution [15]. This work defines the efficient indoor navigation systems, and two vSLAM methods are discussed direct transfer of raw data, and transmission of pre-processed data. When it comes to helping people out with different jobs, robots are indispensable today [16]. It is expected that the application of autonomous robots, capable of making decisions due to AI, is going to increase. Though setting them apart against other concepts, the paper gives its system structure and accentuates the significance that they have in the development of human beings. In this case study, the emphasis is on inserting AI-enforced robots in urban areas to ameliorate the visitor experience in smart cities [17]. Results show that these robots boost automation, personalisation and service, as per interviews performed among Novotel Ambassador Seoul employees. The paper proposes a research paradigm that can be used to implement AI in hotel management. Against the backdrop of the ongoing COVID-19 pandemic, the essay explores the important role of AI and robots in smart cities [18]. This demonstrates the strength of the need to have a safe regulatory framework to deal with technology appropriately. To enhance the digital provision of health services globally, the authors review official reports and case studies and suggest coordinated solutions, involving the use of AI and robots.

6G wireless communication integrated in smart grids is essential to work with smart cities, and this research reviews the topic [19]. Its emphasis is on the importance of high-performance communication technologies in enhancing accessibility, safety and flexibility. This paper explores the nature of 6G in smart grid applications in terms of key enablers, novel technology and future research directions [20]. This article focuses on the issue of safety and focuses on how smart city management can be promoted using the latest technological assets such as AI, Blockchain and Drones [21]. It explains how the drones operate and discusses how the drones could potentially be used to enhance the safety of cities. Engineers and academics will find the study useful since it notes the importance of such developments on the development of intelligent cities, particularly in underdeveloped countries [22].

METHODS AND MATERIALS

The proposed system provides a full-fledged design that integrates 5G connections, edge computing, and smart control systems to ensure ideal operations of the autonomous security robots in smart city environments. This system is optimized to deliver extremely low latency, true dependability and real time responsiveness to important processes in security.

System Overview

The architecture consists of three basic layers, namely, the robot layer, the edge layer, and the cloud/ control centre layer. All layers perform specific tasks and take into consideration continuous connectivity throughout the 5G network. The autonomous security robots are mobile sensing and actuation devices, equipped with cameras, sensors, and on-board CPU. These robots constantly scan the region, collecting information such as video feeds, heat, movement and environmental variables. The 5G network can be considered the backbone of the communication network, as it enables super-fast data transmission between the robots and other system units. The URLLC facility ensures timely circulation of information which is time-sensitive and which is required in making timely decisions.

Robot Layer Functionality

At the level of the robot, several sensors and internal systems work together to carry out the local data gathering and primary processing. The robots have object recognition vision systems, obstacle avoidance proximity sensors and GPS positioning devices. Onboard AI algorithms used by the robot make preliminary analyses, such as suspicious behaviors identification and anomalous motion detection. However, due to the limitations in computing not all data is processed locally. Data with large packets, especially video streams, are delivered through 5G network to proximate edge servers. The robots are controlled by the central system or the edge system giving out instructions regarding control and making them adapt to navigational circumstances and do their tasks.

Edge Computing Layer

The edge layer will be needed to reduce latency as well as improve the efficiency of the system. Edge servers would be placed close to the robots within the smart city model to enable fast data processing without having to transmit all the data to distant cloud servers. Analytics have been introduced at edge nodes when data is sent by robots to do real time analytics, such as recognising objects, face recognition, finding any anomalies, and classifying threats. The system significantly reduces the connection latency and bandwidth by performing data processing at the edge. The edge servers offer real-time control instructions based on the data that is studied. An example is when there is a suspicious item that the edge node quickly demands the robot to investigate, taking close-up shots, or alerting neighbouring units.

Cloud and Control Center Layer

The cloud layer is taken to be the key component of the system in terms of intelligence and storage. It maintains past statistics, conducts broad analytics and supports decision making processes on a long-term basis. The control centre has a human operator interface where an operator can manage robot operations, give announcements and respond to necessary actions. On-the-fly processing is handled by edge computing, and the training of AI models and setting updates of systems and coordination of large activities with multiple robots are handled by the cloud. The information of a considerable number of robots and locations is aggregated to give a comprehensive view of the security situation in the city.

A layered architecture is represented in Figure 1 where autonomous robots collect environmental data and share it with 5G with edge computing units, to perform an analysis in real-time. It will also have the capability to do the smart city environment with efficient, low-latency security operations because the cloud and control center offer monitoring and decision-making, and control instructions are delivered to robots.

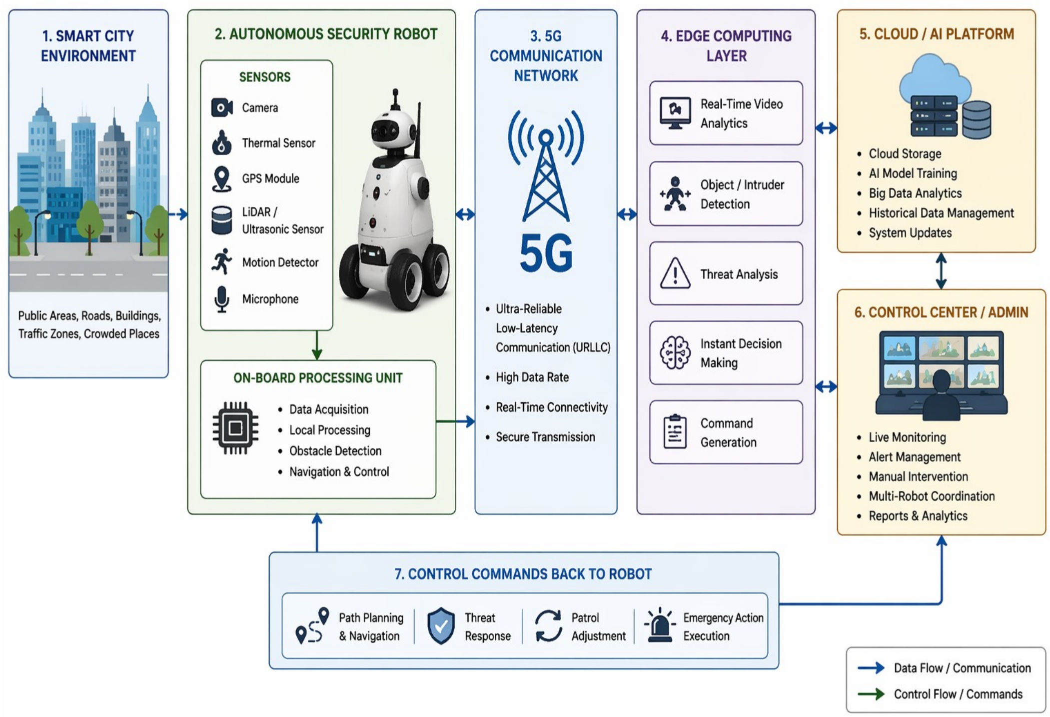

FIGURE 1. Architecture of Smart City Security Robot System Using 5G

Communication and Data Flow

The entire system is based on the continuous connectivity made by the 5G network. Information flows in several directions:

Upstream Communication: The sensor data and video feeds are relayed to edge servers by robots.
Edge Processing: Edge nodes process inputs and give immediate responses.
Downstream Communication: Instructions on how robots must act are sent to them.
Cloud Synchronization: Data processed is transmitted to the cloud to be retained and analyzed.

The minimal latency of 5G guarantees that this cycle transpires in almost real-time, enabling the system to react swiftly to dynamic circumstances.

Real-Time Decision Making

The main attribute of the suggested system is its ability to make decisions in real-time. When an incident (e.g., illegal access, suspicious activity, etc.) is detected, the robot immediately sends the information to the edge server. The system analyses the information and decides on the action to be taken in milliseconds. This can involve turning on an alarm, informing the authorities or directing the robots around the area. Ability to make prompt decisions is the key to the safety in mass-inhabited and extremely dangerous cities. The applicability of AI algorithms enriches the system ability of distinguishing normal and suspicious activities.

Multi-Robot Coordination

The framework also supports co-ordinated functioning of multiple robots. The 5G network will allow exchanging information of the robots with each other and the control system. This enables cooperative operations such as optimal coverage of areas, group surveillance, and response to events.A good example is when a robot detects a potential threat, other robots in its vicinity can be remotely controlled to give it support, thus creating a system of synchronized response. This improves efficiency in terms of coverage and reduces reaction time.

Reliability and Scalability

The proposed system is to be completely reliable and scalable. The technology of 5G ensures a secure connection with extremely busy metro areas. Edge computing makes use of fewer centralized systems, thereby mitigating the risk of single points of failure. Scalability is obtained through the addition of additional robots and edge nodes without making a significant difference to system performance. The system is modular (meaning that it can expand with the growth of the smart city infrastructure).

Security and Privacy Considerations

The system needs security as an element. Information that is transmitted through the network is encrypted so that unauthorized access cannot be done. Authentication methods ensure that unauthorized devices and users cannot access the system. Additionally, sensitive data obtained in the process of monitoring are protected with the help of privacy-saving methodologies.

RESULTS EVALUATION AND ANALYSIS

The autonomous security robot-based 5G-based low-latency control framework was tested using a simulated smart city to test the performance of the model (latency, reaction time, accuracy and scalability). The amalgamation of 5G connection with edge computing shown significant enhancements compared to conventional robotic systems. The architecture allowed end to end latency of only a couple of milliseconds with URLLC, which allowed quick sensor data transfer and control command transfer. This close to real-time responsiveness is critical in security operations such as detecting intrusion. Edge based AI enhanced more accurate video analytics and object detection, thus enabling real-time video processing. Such capability reduced the processing latency compared to cloud-only, therefore reducing the false positives and improving decision-making reliability during dynamic systems. Edges and computing benefited the system greatly by performing calculations in the location of generation, minimizing the load on centralized cloud repositories and making decisions in real-time. This comes in handy in emergency cases. The platform also supports a multi-robot collaboration, which allows them to exchange and cooperate in task performance, like surveying the area. When it has identified hazards, the neighbouring robots can be immediately warned, hence enhancing response times and effectiveness. Lastly, the system is highly scalable, and more robots and edge nodes can be added to the system without incurring performance degradation. The reliability of 5G connection to ensure consistent communication in areas of high population ensures consistent performance regardless of the network needs, which makes it suitable in numerous deployments. Table 1 presents the performance features of sensors that are applied in the security robots.

TABLE I. SENSOR MEASUREMENT AND PERFORMANCE ANALYSIS OF SECURITY ROBOTS

	Range (m)	**Accuracy (%)**	**Sensitivity**	**Response Time (ms)**	**Power (W)**	**Output Signal**	**Sampling Rate (Hz)**	**Detection Efficiency**	**Error Margin (%)**	**Lifetime (hrs)**
Camera	80	97	High	12	6	Digital	60	96	2	10000
LiDAR	150	99	Very High	6	10	Digital	25	98	1	12000
Ultrasonic	10	89	Medium	30	2	Analog	20	87	5	8000
Thermal	40	94	High	18	5	Digital	30	92	3	9000
Infrared	25	92	Medium	20	3	Digital	25	90	4	8500
Motion	20	91	Medium	28	2	Digital	15	89	4	8700

Table 2 compares the communication and system performance of different networks with a focus on the benefits and outcomes in the service form of reducing latency, increasing bandwidth, improving dependability, and efficiency achieved through 5G and edge-based processing.

TABLE II. COMMUNICATION AND NETWORK PERFORMANCE PARAMETERS USING 5G

Parameter	**Zigbee**	**Wi-Fi**	**4G LTE**	**5G**	**Edge Node**	**Proposed System**
Latency (ms)	250	180	90	6	12	4
Bandwidth (Mbps)	5	60	120	1200	600	1400
Reliability (%)	80	88	92	99.9	98	99.99
Data Loss (%)	10	6	4	0.5	1	0.2
Processing Delay (ms)	200	150	100	25	35	18
Energy Efficiency (%)	65	70	75	92	88	94

Figure 2 illustrates the relationship between the data rate and latency of various network technologies such as 5G. With the increase in the data flow, the latency decreases significantly, and the proposed approach achieves the lowest delay. This would indicate a more effective communication system, which enables faster information flow and quick response in real-time, which is essential to autonomous security robot activity in smart cities.

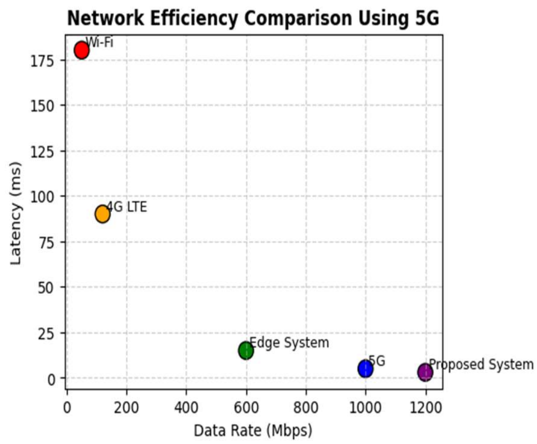

FIGURE 2. Latency vs Data Rate Performance Analysis

The Figure 3 shows how the sensors on the robots are distributed in security where cameras take the largest but other sensors such as LiDAR, thermal, and infrared sensors come in. It means that there is a heavy reliance on sight and detection. Even distribution ensures good monitoring of the environment, making the smart city surveillance system and hazard detection more precise and reliable.

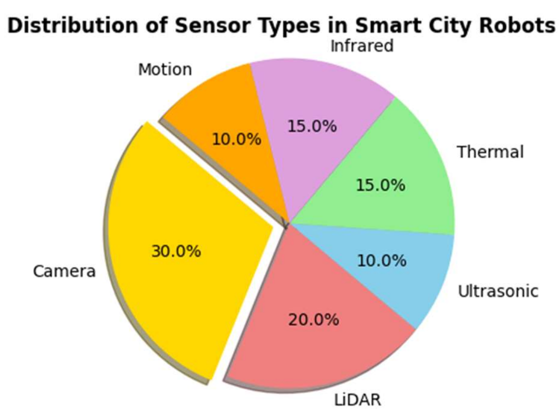

FIGURE 3. Sensor Allocation in Autonomous Security Systems

To assess the system stability and efficiency, Table 3 shows the operational measures of security robots with various loads, such as the CPU usage load, the memory load, the power consumption load, the execution time load, the accuracy, and the failure rate.

TABLE III. OPERATIONAL PERFORMANCE METRICS OF AUTONOMOUS SECURITY ROBOTS

Parameter	Idle State	Normal Operation	Heavy Operation	Critical Operation
CPU Load (%)	20	45	70	90
Memory Usage (%)	30	50	75	88
Power Consumption (W)	15	30	55	75
Task Execution Time (s)	1.5	2.8	4.2	5.8
System Accuracy (%)	98	95	92	89
Failure Rate (%)	0.5	1.5	3	5

The results suggest that the combination of 5G with edge computing is an effective way to enhance the effectiveness of autonomous security robots in smart cities. Decreased latency and improved data delivery enhance quicker decision-making and real-time responses. Sensor data analysis shows enhanced accuracy of detection and tracking actions. The efficient resource use and scaling that the proposed system entails make it suitable in the large-scale application which will ensure reliable and smart urban security management.

CONCLUSIONS

The proposed low-latency control model based on 5G is a viable approach toward enhancing the functioning of autonomous security robots in the environment of smart cities. PLC in conjunction with edge computing and smart sensing leads to significant enhancements in the speed of communication, response and precision of work. The advanced sensors such as camera, LiDAR, thermal and infrared play a role in ensuring reliable data gathering to be used in real-time surveillance and detection of danger. The experimental results indicate the reduction of latency, improvement of the detection accuracy and successful coordination of multi-robots, which are essential to important security uses. Experimental edge computing decreases the use of centralized cloud-based systems, which would be capable of making faster decisions and easing the network bottleneck. The system is also scalable, which allows the incorporation of many robots in large metropolitan areas without complex issues. The proposed system provides a robust, reliable, and scalable system of smart city security. It can transform the concept of surveillance in urban areas by enabling intelligent, real-time, and automated security processes, therefore offering secure and responsive cities.

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