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Design and Review of Three-layer Crime Prevention through Environmental Design Framework Based on Multimodal Sensor Networks for Public Safety in Smart Cities

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As urbanization accelerates worldwide, public safety has become a critical indicator for sustainable urban development. Traditional crime prevention through environmental design (CPTED) primarily focuses on static physical changes, which often fail to respond flexibly to dynamic crime patterns in smart cities. We propose a new intelligent sensor-integrated CPTED framework to overcome these limitations. By analyzing global leading cases in Singapore, Barcelona, and South Korea, we establish a three-layer digital CPTED framework consisting of a physical layer, a sensing layer, and an integration layer. The physical layer emphasizes the material properties of sensor housings and enclosure design to ensure durability in harsh environments. The sensing layer focuses on multimodal data fusion and edge computing for real-time preprocessing. The integration layer enables immediate physical feedback to urban facilities through integrated platforms. Furthermore, the study provides technical guidelines, including a geometric analysis of the detection area and measures for securing hardware reliability. This multidisciplinary model, merging engineering sensor systems with urban design, contributes to establishing safety standards and efficient operation systems for future smart cities.

1. Introduction

1.1 Background and necessity of research

As urbanization accelerates worldwide, public safety is emerging as a critical indicator of sustainable urban development.(1,2) Consequently, crime prevention through environmental design (CPTED), which aims to fundamentally block the possibility of crime through the design of urban spaces, has been accepted as a standard design strategy by urban planners and public

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safety experts globally.(3) Traditional CPTED theory was focused on suppressing crime through static changes in the physical environment, such as improving lighting systems, managing landscaping to ensure visibility, and designing spatial structures that enable natural surveillance.(4) While this approach has contributed to lowering crime rates and increasing citizens' sense of psychological safety in numerous cities worldwide, it has shown technical limitations in failing to respond flexibly to rapid environmental changes and in having difficulty in fully controlling dynamic crime patterns occurring at specific times or in blind spots.(5) Unlike the second-generation CPTED, which emphasizes social and community-focused interventions, this third-generation paradigm is characterized by its digital and dynamic nature, driven by intelligent sensing networks.

The smart city paradigm, which is spreading along with the progress of the fourth industrial revolution, is providing a technical turning point to overcome the limitations of these traditional security systems.(6) In particular, the introduction of intelligent sensor networks based IoT technology is inducing the urban environment to evolve from a simple physical space into an active response system on the basis of data.(7) Precision image sensors mounted on intelligent closed-circuit television (CCTV), acoustic sensors that detect abnormal sounds, and thermal infrared sensors that capture activity in deserted spaces collect vast amounts of data throughout the city in real time to capture signs of crime in advance and enable immediate responses.(8) These technical changes suggest the need for digitized dynamic security design beyond the static CPTED of the past.

However, despite the rapid development of sensor technology, academic convergence between sensor engineering and urban design is still in its early stages. Most existing studies tend to focus only on improving the sensitivity of sensor hardware or optimizing data analysis algorithms, and discussions on design methodology regarding how these sensors should be organically integrated with the actual physical infrastructure and architectural environment of the city are lacking. In particular, considering the physical application aspect of sensor systems that this journal, Sensors and Materials, focuses on, precise guidelines are needed for installation geometry to maximize the detection performance of sensors, the characteristics of housing materials so that reliability can be maintained even under the harsh conditions of the outdoor urban environment, and aesthetic integration with urban furniture. Therefore, establishing a new design framework that integrates the technical characteristics of intelligent sensor networks with the design principles of CPTED is an urgent research task to secure public safety and efficient operation of global smart cities.

1.2 Purpose and methods of research

The primary purpose of this study is to theoretically establish and propose an intelligent sensor-integrated CPTED framework optimized for the global smart city environment. Through this, we intend to overcome the fragmented limitations of introducing technology-centered security systems and to build an academic foundation for a next-generation safe city model in which urban infrastructure and sensor networks are integrated. In this study, we aim to provide specific technical application guidelines for urban designers and to suggest hardware design directions reflecting the constraints of actual urban spaces for sensor system developers.

The specific methodology of this study to achieve these goals is as follows. First, through the latest academic literature and global standard guides, we clarify the conceptual definition of third-generation CPTED, in which traditional CPTED principles have evolved in combination with smart technology. In this process, we classify the functional characteristics of multimodal sensor technologies such as visual, auditory, and environmental sensors, and construct a functional matching matrix by linking them with the core principles of CPTED: surveillance, access control, and territorial reinforcement.

Second, we conduct a comparative analysis of security system cases in major cities that are leading the introduction of smart city technology worldwide. We derive empirical data such as sensor installation density, communication data linkage level, and physical housing installation methods for Singapore's Smart Nation infrastructure, Barcelona's Digital City project, and other large-scale smart city models in Asia, and use them as a basis for framework design.

Third, on the basis of the results of theoretical review and case analysis, we construct a three-layer intelligent CPTED framework consisting of a physical layer, a sensing layer, and an integration layer. Here, considering the readership of Sensors and Materials, we include detailed hardware design elements such as sensor installation height, overlap of detection ranges, network deployment considering energy efficiency, and measures to secure material durability in accordance with outdoor environmental conditions.

Finally, we review the practical applicability of the proposed framework and present policy implications and technical development directions for future smart city security standardization and ethical data management. This study will make an important contribution in presenting a new multidisciplinary research model for building a safe urban environment where technology and humans coexist by merging engineering sensor systems and humanistic social urban design.

2. Literature Review: Analysis of Cases of Global Smart City Security Sensor Introduction

2.1 Technical trends of global smart city security systems

Major metropolitan areas are actively introducing security infrastructure utilizing information and communication technology to respond to safety issues caused by rapid population growth and urbanization.(9,10) While early smart city security was limited to simple high-definition CCTV installation and centralized control, recent trends are evolving toward the intelligentization of sensor networks and the construction of data integration platforms.(11) In particular, with the development of edge computing technology, methods of processing data immediately at sensor terminals to minimize latency are spreading, and this has become a key technology for securing the golden hour in the event of crimes or accidents.(12) These technical trends are combined with CPTED principles, which are physical environment designs, to form a more sophisticated urban safety network.

2.2 Analysis of major leading cases: Smart cities in Singapore, Barcelona, and South Korea

2.2.1 Singapore: Smart Nation Sensor Platform (SNSP)

Singapore is operating the SNSP under the Smart Nation strategy to reconfigure the entire country as one smart city.(13) The technical core of the Singapore case is the use of streetlights as a core hub for data collection rather than just lighting fixtures.(14) Intelligent streetlights installed throughout Singapore integrate high-resolution visual sensors as well as environmental monitoring sensors.(15) In particular, it applies dynamic sampling technology that analyzes crowd density in real time and immediately shortens the data collection cycle of surrounding sensors when abnormal signs are detected.(16) This organic combination of multimodal sensors is evaluated as a case of maximizing natural surveillance, a core principle of CPTED, digitally, and shows a model in which urban physical environment and sensor hardware are perfectly integrated. Despite their success, these cities have faced challenges regarding data privacy and public perception of pervasive sensor monitoring, which necessitates transparent data management protocols.

2.2.2 Barcelona, Spain: Sentilo and superblock security model

Barcelona is intelligentizing urban infrastructure through Sentilo, an open source-based sensor management platform.(17) A unique aspect of Barcelona's security strategy is the combination of pedestrian-centered spatial design, called superblocks, with sensor networks.(18) Since citizens' activities are frequent in these areas where vehicle traffic is restricted, the exposure of sensors can cause psychological intimidation. To solve this, Barcelona adopted a method of precisely embedding sensors inside urban furniture such as benches, trash cans, and bicycle rental stations.(19) This is an important academic case showing how the physical packaging and housing design of sensors, which Sensors and Materials emphasizes, should harmonize with the urban landscape.

2.2.3 South Korea: Songdo International City and Seoul's S-DoT system

South Korea is a leading country that has systematically introduced smart cities from the urban development stage, presenting a standard model for smart city design worldwide.(20) Songdo International City in Incheon built an intelligent sensor network connected to an integrated control center in underground utility tunnels and ground facilities from the early stages of city construction.(21) In particular, it is operating an access control system that immediately blocks escape routes in the event of a crime by deploying passive infrared ray (PIR) sensors for floating population analysis and license plate recognition sensors at major intersections and park entrances.(22)

In addition, Seoul detects minute changes in the city through the smart city data of things (S-DoTs) system.(23) S-DoT is a standardized sensor package that simultaneously collects more than 10 types of data such as the amount of fine dust, noise, illuminance, and floating population.(24) In terms of security, S-DoT is a linkage technology that automatically moves the focus of nearby intelligent CCTVs to that point when the noise level in a specific area rises sharply or the illuminance falls below the threshold, considering them danger signals.(25) These cases in South Korea prove how much data fusion between sensors and stereoscopic deployment strategies can increase the effectiveness of CPTED rather than the performance of individual sensors.

2.2.4 London, UK and North American cities: Predictive security systems

London, UK, which operates one of the densest CCTV networks in the world, has been recently converting it from simple recording devices into AI-based intelligent visual sensors.(26) Sensors deployed in areas where crime is frequent analyze the behavior patterns of pedestrians to automatically detect crime precursors such as loitering or intrusion.(27) Major North American cities are also advancing multimodal security systems that supplement visual blind spots with acoustic data through ShotSpotter technology, a gunshot detection sensor.(28) These global cases confirm that sensor technology occupies an essential position as an invisible infrastructure for urban safety.

2.3 Limitations and implications of current systems

Despite the leading cases mentioned above, several common limitations have arisen in the actual operation process. First is the durability and maintenance issue of sensor hardware. The outdoor urban environment includes various factors that adversely affect sensor performance, such as temperature changes, humidity, and salt damage. In many cases, problems such as reduced precision or malfunction due to material defects in sensor protection housings have been reported. This suggests that research on the material properties that protect sensors is as essential as the technical specifications of the sensors themselves. Second is the problem of data fragmentation. Since sensors from different manufacturers are operated individually, linkage between data is not smooth, making it difficult to analyze complex risk situations, for example, a technical disconnection occurring where visual sensors cannot immediately track threat signals captured by acoustic sensors. Third is disharmony with urban design. Frequent cases show that emphasizing only security efficiency causes sensors and hardware to harm the urban landscape or give citizens a negative perception of being surveilled. Therefore, new design guidelines that can guarantee the detection efficiency of sensors while naturally blending in as part of spatial design are required. In conclusion, the implications derived through global case analysis are that a framework is needed in which physical deployment of sensors, material reliability, and data integration systems are organically combined beyond simple technology introduction. These analysis results serve as the logical basis for the three-layer digital CPTED framework proposed in this study.

3 Proposal of Intelligent Sensor-integrated CPTED Framework

3.1 Classification of intelligent sensor technologies and matching with CPTED elements

To effectively implement CPTED in a digital environment, a design strategy is required that organically links the physical characteristics of each sensor technology with the five core principles of CPTED. While traditional CPTED relies on static facilities such as lighting or landscaping to achieve surveillance effects, CPTED in smart cities adopts a method of dynamically changing the environment on the basis of data collected by intelligent sensors. Intelligent visual sensors are a core technology for digitizing natural surveillance principles, using AI algorithms to classify specific behavior patterns such as loitering or intrusion in real time. Additionally, nonvisual sensors such as acoustic sensors or PIR sensors provide complementary surveillance data in blind spots or night environments where visual sensors have difficulty capturing information, thereby increasing the reliability of the overall system. The following shows in detail how these sensor technologies functionally match each design principle of CPTED (Table 1).

3.2 Three-layer-based digital CPTED design framework

In this study, we propose a three-layer framework consisting of a physical layer, a sensing layer, and an integration layer to systematize the process of integrating sensors into urban spaces.

3.2.1 Physical layer

The physical layer includes the actual urban infrastructure and housing where sensor hardware is installed. This is the stage of determining how to integrate sensors into urban furniture such as streetlights, benches, and building exteriors. A particularly important element from the perspective of Sensors and Materials is the material properties of the sensor protection

Table 1
Functional matching and security effects of intelligent sensor technology and CPTED principles.

CPTED principle	Matching intelligent sensor technology	Technical function and security effect
Natural Surveillance	AI CCTV (image sensor), Acoustic sensor	Automatic control and lighting adjustment when abnormal behavior or sounds are detected
Natural Access Control	RFID, NFC, Ultra-wideband (UWB) sensors	Real-time alarm and physical blocking of linkage when unauthorized persons enter specific areas
Territorial Reinforcement	Virtual Fencing, LiDAR sensors	Establishing psychological boundaries through warning broadcasts and data recording when boundaries are crossed
Activity Support	Floating population analysis sensors, PIR sensors	Optimizing the placement of lighting and safety facilities through pedestrian traffic analysis
Maintenance	Self-diagnosis sensors, Environmental sensors	Ensuring constant operation by detecting damage or functional degradation of security facilities in real time

enclosure. Core design elements of this layer include polymer materials or special coating technologies that can protect the sensor from corrosion, temperature and humidity changes, and physical impacts while securing signal transparency.

3.2.2 Sensing layer

The sensing layer is the stage of collecting and preprocessing raw data through various sensor networks. This framework adopts a multimodal sensing method to overcome the limitations of a single sensor. For example, if a visual sensor cannot secure visibility owing to fog or a night environment, an acoustic sensor or thermal infrared sensor provides complementary data to increase detection reliability. In addition, edge computing technology is applied for real-time data processing, allowing immediate risk judgment at the local terminal.

3.2.3 Integration layer

The integration layer is the final stage of analyzing collected data on an integrated platform and controlling urban facilities in real time. When a risk signal is detected from a sensor, immediate physical feedback is provided, such as increasing the illuminance of smart streetlights in the area or broadcasting a warning through a speaker. This means the completion of real-time CPTED that actively changes the environment to suppress crime, rather than just recognizing the possibility of crime.

3.3 Optimal sensor installation guidelines and technical review

To ensure the practical applicability of the framework, precise standards for the physical installation method and material selection of sensors are required. When designing the installation of visual sensors, securing the detection area (A) in accordance with the installation height (h) and the field of view ($\varnothing$) is a key factor determining security efficiency. The detection area can be modeled using the following geometric formula, enabling a deployment that minimizes blind spots (Table 2).

$$A = \pi \times \left(h \times \tan\left(\varnothing / 2\right)\right)^2 \tag{1}$$

Table 2
Components and functions of the digital CPTED three-layer framework.

Layer	Key components	Core technology and design considerations
Physical Layer	Smart poles, Sensor housings, Enclosures	Securing material reliability, polymer protection materials, and special coating technologies
Sensing Layer	Multimodal sensor networks, Edge computing terminals	Data fusion algorithms, real-time preprocessing, and risk judgment
Integration Layer	Integrated platforms, Smart facility controllers	Adaptive lighting control, warning system linkage, and real-time response systems

Here, *h* denotes the installation height and ∅ represents the field of view of the sensor. Through such calculations, a deployment design must be carried out to secure maximum surveillance efficiency with a minimum number of sensors. Second, the material and durability of the sensor housing must be secured. Security sensors for smart cities should be designed with the goal of a durability of more than 10 years. Therefore, polycarbonate materials that can prevent yellowing due to UV ray exposure or aluminum alloy cases with excellent heat dissipation efficiency should be used to prevent the degradation of sensor elements. Thermal management using aluminum alloys is critical as extreme urban microclimates can lead to heat accumulation, significantly affecting sensor longevity and signal accuracy. In addition, material design must be carried out in parallel to satisfy dustproof and waterproof ratings of IP66 or higher to maintain precision even in harsh outdoor environments. Third is the standardization and security of data linkage. To ensure interoperability in an environment where sensors from various manufacturers are mixed, standard interface specifications [e.g., open network video interface forum (ONVIF), and message queuing telemetry transport (MQTT)] must be observed. Furthermore, the inclusion of hardware security modules (HSMs) to prevent leakage of collected video and personal data and data encryption transmission technology must be considered. Hardware-level encryption provided by HSM offers a more robust defense against physical tampering than standard software-based encryption, ensuring the integrity of the physical layer.

4 Conclusions

4.1 Summary of research results and academic significance

In line with the spread of the smart city paradigm, we proposed an intelligent sensor-integrated CPTED framework combining traditional CPTED with digital technology. While past CPTED relied on static changes in the physical environment to suppress crime, the framework established in this study focuses on building a system that monitors urban spaces in real time through multimodal sensor networks and responds dynamically to threat situations.

In particular, the three-layer structure comprising a physical layer, sensing layer, and integration layer proposed in this study has considerable significance in academically linking the technical specifications of sensor hardware with the spatial characteristics of urban design. By describing in detail technical guides such as the material durability of sensor housings,

Table 3
Technical specifications and material standards for securing the reliability of sensor systems.

Technical review item	Detailed design standards	Expected effect and purpose
Hardware durability	Dustproof and waterproof rating of IP66 or higher	Maintaining precision and preventing malfunction in harsh outdoor environments
Material characteristics	Anti-UV polycarbonate, Aluminum alloy	Preventing lens yellowing and extending lifespan by suppressing degradation
Data security	Inclusion of HSMs	Securing personal data leakage prevention and data encryption transmission
Interoperability	Compliance with ONVIF and MQTT standard specifications	Ensuring seamless integration and scalability across heterogeneous sensor systems

detection efficiency in accordance with installation geometry, and data processing methods using edge computing, which the readership of Sensors and Materials pays attention to, we specifically suggested how engineering solutions can be applied to actual urban safety policies (Table 3).

4.2 Expected effects and policy implications

We can expect the following positive effects by applying the proposed framework when constructing smart city security infrastructure in the future.

- Technical Aspect: Detection accuracy can be increased and blind spots can be considerably reduced through data fusion between visual, acoustic, and environmental sensors. In particular, hardware design guidelines that can maintain reliability even under harsh outdoor environmental conditions will contribute to reducing the life cycle cost of sensor systems.
- Urban Design Aspect: By providing installation standards that allow security facilities to maximize functions while harmonizing with the urban landscape, it will be possible to minimize citizens' resistance to surveillance and maximize their sense of psychological safety.
- Policy Aspect: By providing guidelines to manage fragmented security technologies as a single integrated system, the proposed framework can contribute to future smart city security standardization work and the activation of related industries.

4.3 Limitations and future tasks

Although this study was focused on proposing a theoretical framework and analyzing global cases, limitations in securing long-term empirical data in actual urban environments were revealed. To overcome such limitations, the following studies should be additionally conducted in the future.

First is research on the ethics and personal information protection of AI-based sensor systems. As detection efficiency increases, concerns about infringing on citizens' privacy may grow, so multidisciplinary discussions on anonymization technology in the data collection process and legal regulatory guidelines should be conducted in parallel.

Second is the construction of an energy-independent sensor network. To solve the power supply problem of numerous sensors deployed in large-scale urban spaces, research on material and structural optimization of low-power sensor systems using solar or piezoelectric energy harvesting technology is required.

Third is advanced linkage with digital twins, which must be expanded into an intelligent control system that predicts areas with a high possibility of crime and preemptively allocates safety resources by simulating sensor data in real time on a virtual model identical to the actual urban space.

In conclusion, in this study, we presented a blueprint for a future-oriented smart security city through the fusion of sensor systems for urban safety and CPTED theory. When technology and human-centered design are organically combined, a sustainable smart city where citizens can live with peace of mind will finally be completed.

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