КОМП'ЮТЕРНІ НАУКИ

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Intelligent System for Monitoring Compliance with Vehicle Parking Regulations

This study is dedicated to the development of an intelligent system for monitoring compliance with parking regulations using neural networks. The objective has been achieved through the synthesis of mathematical models of the technological process of intelligent parking monitoring, taking into account the technological aspects of vehicle detection with the YOLO model, as well as license plate localization and recognition. Based on this, a generalized model of the intelligent monitoring system and its architecture have been proposed. The results of experimental testing on real video recordings are presented, confirming the system's suitability for operation under varying lighting conditions, different viewing angles, and video quality. The chosen data collection strategy 'one frame per minute' ensures a balance between monitoring accuracy and computational efficiency, making the system scalable and effective for integration into intelligent parking management systems.
neural networks, YOLO model, EasyOCR framework, automated parking compliance control, intelligent monitoring, license plate recognition

Problem Statement. In most Ukrainian cities, automated video surveillance systems have been implemented; however, these systems generally lack built-in functions of intelligent analysis for monitoring compliance with parking regulations. Even those systems that are capable of license plate recognition or motion detection account for parking violations only in a limited way, particularly in the context of non-payment for the use of parking spaces or the legally regulated duration of vehicle presence within the control zone. This problem remains unresolved to date, which makes it reasonable and necessary to introduce an intelligent system for monitoring compliance with parking regulations.

To effectively address this problem, it is necessary to employ artificial intelligence methods, particularly deep neural networks. The use of neural networks enables high-accuracy object classification and provides solutions to computer vision tasks. The proposed approach makes it possible to implement automated monitoring of compliance with parking regulations, reducing time and financial costs while increasing the overall efficiency of parking zone management. This approach is highly promising within the framework of the Smart City concept.

Analysis of Recent Research and Publications. Previously, classical computer vision methods were widely used for license plate identification, in particular threshold segmentation and contour analysis. Threshold segmentation made it possible to extract license plates based on color contrast; however, it was overly sensitive to changes in lighting conditions [1]. Contour analysis detected rectangular objects but often mistakenly included extraneous elements [2]. The main drawbacks of such methods are their instability under variations in brightness, viewing angle, and image quality, which significantly reduces recognition accuracy. In addition, they require considerable hardware resources, since processing is performed across the entire frame. As noted in the work of Anagnostopoulos et al. [3], traditional methods yield acceptable results under laboratory conditions but lose effectiveness in real-world environments.

In this context, methods based on convolutional neural networks (CNNs) have gained popularity, demonstrating high accuracy and adaptability to complex imaging conditions [4]. In particular, the YOLO algorithm enables precise localization of license plates even under variations in lighting and viewing angles. A stepwise approach is considered optimal: first detecting the license plate region, followed by the application of an OCR algorithm for character recognition, which reduces computational costs. In Yakovlev's work, the YOLOv5 model was used for detection and EasyOCR for recognition, achieving an accuracy of 95.57% on a dataset of 20,000 images [1]. In the study by Podorozhniak et al., the use of Mask R-CNN was proposed, which transforms distorted regions into rectangular ones, thereby increasing recognition accuracy to 96% at camera angles up to 63° [5].

Other researchers have also made significant contributions to the development of license plate recognition systems. Vysotskyi and Yavorskyi adapted the YOLO model to Ukrainian license plates based on the AutoRia dataset, and applied EasyOCR for OCR, though they noted its instability under poor lighting conditions [6]. In the work of Vakalyuk et al., classical methods were compared, including the Viola–Jones algorithm for plate detection and SVM for character classification. The Viola–Jones method provides high processing speed, but its accuracy decreases when the plate tilt exceeds 30°, whereas SVM effectively separates character classes by maximizing the margin between them [7].

Scientific research works [8–11] have also reported theoretical and practical results concerning the digitalization of business processes across various industries. In particular, these studies examined and presented the results of applying artificial intelligence technologies for the digital transformation of different areas of human activity, demonstrating both the efficiency and feasibility of AI adoption. For instance, in [11] an adaptive model of investor surveys was developed, employing modern machine learning methods to form a detailed continuous risk profile. In this way, the authors ensured higher accuracy and personalization of risk profiling compared to traditional methods, while the integration of adaptive question selection with advanced machine learning techniques optimized the business process.

Therefore, modern neural network approaches demonstrate significantly higher accuracy, stability, and suitability for integration into intelligent systems for monitoring compliance with parking regulations.

Problem Definition. The purpose of this study is to develop an intelligent system for monitoring compliance with parking regulations using neural networks, based on video footage from surveillance cameras located near parking zones. To achieve this objective, the following tasks must be addressed:

1. Mathematical formalization of the technological process of intelligent monitoring of compliance with parking regulations, taking into account the following technological aspects: vehicle detection using the YOLO (You Only Look Once) model, enabling fast and accurate object identification within a frame; license plate localization and recognition, implemented through a combined approach involving YOLO for license plate region detection and EasyOCR for subsequent text recognition; verification of parking fee payment as a key system component, performed by querying the relevant database or API containing payment status information linked to the license plate.

2. Synthesis of a generalized model of the intelligent monitoring system in accordance with the proposed mathematical models of the technological process of intelligent parking regulation monitoring.

3. Development of the system architecture for the intelligent monitoring system, considering the technological aspects of real-world operating conditions.

4. Experimental evaluation of the intelligent system, representative of real-world conditions and typical parking scenarios, including partial object occlusion, variable lighting, and diverse license plate types.

Main Results. In the problem statement, it was defined that the process of intelligent monitoring of compliance with parking regulations must include the following components:

- vehicle detection performed using the YOLO model,
- license plate localization and recognition,
- verification of parking fee payment.

It is also established that the operating conditions of the intelligent system involve typical parking scenarios, including partial object occlusion, variable lighting, and diverse license plate types.

Mathematical formalization of the technological process. Let the set of cameras be denoted as $\mathrm{C} = \{1, \dots, \mathrm{C}\}$, with the time axis discretized by a step of $\Delta(\mathrm{c})$, $\Delta = 60$ c in the baseline configuration. For a camera $\mathrm{c} \in \mathrm{C}$ at time $t_k = t_0 + k\Delta$ a frame $x_{c,k} \in \chi \subset \mathbb{R}^{H \times W \times 3}$ is observed. This "1 frame per minute" policy is chosen to reduce computational load and data storage requirements, while still maintaining suitability for detecting changes in the parking lot.

Let $\mathcal{Z}$ denote the set of parking zone identifiers, and let $z(c) \in \mathcal{Z}$ represent the zone monitored by camera c.

For vehicle (V) detection, each frame is processed by an object detector:

$$f_{veh}: \chi \to \mathcal{B}_{veh},\ \mathcal{B}_{veh} = \{(b_i, s_i)\}_{i-1}^{N_{veh}},$$

where $b_i \in \mathbb{R}^4$ represents the bounding box and $s_i \in [0,1]$ denotes the confidence score. A YOLO family model with pre-trained weights is employed. Detections with $s_i \geq \tau_{veh}$ (typically $\tau_{veh} = 0.5$).

License plate detection of vehicles: for each detected vehicle, a subtask is defined as

$$f_{lp}: \chi \times \mathcal{B}_{veh} \to \mathcal{B}_{lp}, \mathcal{B}_{lp} = \{(\ell_i, r_j)\}_{j-1}^{N_{lp}} ,$$

where $\ell_i \subset b_i$ denotes the bounding box of the vehicle's license plate, and $r_i \in [0,1]$ represents the confidence score. Only $\ell_i \subseteq b_i$ that satisfy geometric constraints (aspect ratio, minimum area, orientation) are retained, while false positives are discarded.

The relationship "license plate belongs to vehicle" is formalized as an optimization problem of maximizing the overlap:

$$assig(\ell) = \arg\max_{b \in \mathcal{B}_{veh}} IoU(\ell, b) \quad \text{subject to } IoU(\ell, b) \geq \gamma,$$

where IoU denotes the intersection-over-union coefficient, with $\gamma \in (0,1)$.

OCR and license plate text normalization: for each license plate region, optical character recognition is applied:

$$f_{ocr}: \chi \times \mathcal{B}_{lp} \to (y, q),,$$

where $y = (y_1, \dots, y_m)$ is the sequence of recognized characters, and $q = (q_1, \dots, q_m)$ are the confidence scores of the characters.

After OCR, a normalizer $\pi(\cdot)$ is applied (regular expressions, alphabet constraints, country-specific templates), which returns the canonical license plate number $p \in \mathcal{P}$. The result is accepted if

$$\bar{q} = \frac{1}{m} \sum_{i-1}^{m} q_i \geq \tau_{ocr}.$$

Detection of "arrival" and "presence" of a vehicle: for a license plate p in zone z, we define the temporal set of occurrences

$$\mathcal{T}_{p,z} = \{t_k : \exists c : z(c) = z, p \text{ recognised on } x_{c,k}.$$

Estimation of the Vehicle Arrival Time at the Parking Lot

$$t_{p,z}^{in} = \min \mathcal{T}_{p,z},$$

and the moment of the last observation

$$t_{p,z}^{last} = \max \mathcal{T}_{p,z}.$$

Mathematical Model of Payment and Grace Period: let the payment database be defined as the set of intervals

$$\mathcal{R} = \{(p, z, [a,b], is_{paid})\}.$$

According to the policy, a grace period of $\delta = 15$ minutes is applied after arrival. A payment is considered valid if $\exists(p, z, [a,b], is_{paid} = true)$ such that the control time moment t is covered:

$$t \in [a,b] \quad \text{or} \quad [a,b] \cap [t_{p,z}^{in}, t_{p,z}^{in} + \delta] \neq \emptyset.$$

In the absence of coverage after the expiration of the grace period, a violation event is generated.

Decision rule and event generation: let us define the decision

$$d(p,z,t) = \begin{cases} OK, \exists \text{ payment that covers } t \\ VIOL, t \geq t_{p,z}^{in} + \delta \wedge \neg\exists \text{ payment that covers } t \end{cases}.$$

Violation event:

$$e = (p, z, t, c, URI(x_{c,k}), meta),$$

where $URI(x_{c,k})$ – a reference to the evidence frame, $meta$ – service attributes (bounding box coordinates, confidence scores, inspection module identifier).

System quality: for a violation that has occurred, the a priori estimate of full recall is:

$$R_{e2e} \approx R_{veh} \cdot R_{lp} \cdot R_{ocr} \cdot R_{sampl}(\Delta, \delta),$$

where R_{veh} is the recall of the vehicle detector at threshold τ_{veh}; R_{pl} is the recall of the license plate detector (conditional: given a detected vehicle); R_{ocr} is the probability of correct license plate recognition, given correct localization; $R_{sampl}(\Delta, \delta)$ is the probability that the system captures a frame after the expiration of the grace period (determined by the sampling policy and the distribution of parking duration).

Sampling model. Assume that the arrival moment is uniformly distributed with respect to the grid Δ: $U \sim Unif(0, \Delta)$. Let T_{dwell} - denote the random parking duration. Then

$$R_{sampl}(\Delta, \delta) = \mathbb{P}(T_{dwell} \geq \delta + U) = \frac{1}{\Delta}\int_0^{\Delta} \mathbb{P}(T_{dwell} \geq \delta + u)du/$$

If $\mathbb{P}(T_{dwell} \geq \delta + \Delta)$ is high, then R_{sampl} approaches 1. This formalizes the statement regarding the sufficiency of $\Delta = 60$ s for parking lots with slow dynamics.

Geometric and logical constraints. License plate geometry: for ℓ the following holds: $a_{min} \leq \frac{width(\ell)}{height(\ell)} \leq a_{max}$ та $area(\ell) \geq A_{min}$. Duplicates: for the set of license plates associated with a single b_i, we apply NMS in the space of texts/geometry; we select $\ell^* = \arg max_{\ell}(r_{\ell} \cdot \bar{q}_{\ell})$.

False license plate filtering: candidates with $IoU(\ell, b) < \gamma$ or those not matching the template $\pi(y)$ are discarded.

Integration model of payment access: payment verification is defined as a Boolean function

$$g(p,z,t) = 1(\exists(p, z, [a,b], true) s.t. t \in [a,b] \vee [a,b] \cap [t_{p,z}^{in}, t_{p,z}^{in} + \delta] \neq \emptyset),$$

is invoked at the decision-making stage $d(p, z, t)$. In the case of $g = 0$ для $t \geq t_{p,z}^{in} + \delta$, a penalty event is generated and sent to the inspection module.

Using the entire video stream in real-time mode is not advisable; capturing one frame per minute is sufficient. The proposed data collection strategy - one frame per minute - reduces the computational load and ensures scalability of the solution for large parking areas. This approach significantly decreases the volume of data to be stored compared to continuous video streaming, thereby reducing server load, simplifying database integration, and optimizing computational resources. Processing a single frame per minute is adequate for detecting and identifying vehicles, as well as recognizing their license plates in the context of parking lots, where changes occur relatively infrequently. This reduces computational overhead and makes it possible to employ more accurate algorithms, such as Faster R-CNN, without loss of performance.

Methodology of Generalized Model and System Architecture Synthesis. After receiving a frame, the system proceeds to the object detection stage, where all vehicles present in the image are identified. Preliminary image processing of vehicles is performed using the YOLO object detection algorithm. The model is loaded with pre-trained weights (on the COCO dataset), and for each image an analysis is performed to obtain the coordinates of the objects (bounding boxes) where the vehicles are located, as well as their confidence scores. Further filtering retains only those objects whose detection confidence exceeds the established threshold (≥ 0.5). Figures 2 and 3 illustrate the highlighted areas around each vehicle and its license plate.

The next step is the filtering of detected license plates, during which the system matches the identified regions with the positions of vehicles. This filtering eliminates false detections, such as text elements or other objects that may mistakenly be identified as license plates. The resulting image files (Figures 1 and 2) are stored in a local directory for subsequent processing.

The subsequent stage involves image preprocessing, aimed at preparing the data for effective recognition. Through color normalization procedures, images are converted into the appropriate color space - RGB, to preserve color information, or Grayscale, to simplify computations. Scaling to a standardized size (e.g., 640×480 pixels) reduces computational costs and ensures a unified input for the neural network.

To minimize noise and improve image quality, smoothing filters are applied, such as Gaussian Blur or Median Filter, which preserve object contours and enhance the accuracy of subsequent license plate detection.

The next step is the detection and localization of license plates. Within each vehicle bounding box, smaller candidate regions potentially containing license plates are searched using a specialized YOLO detection model. The results are further filtered to discard regions that do not correspond to the geometric characteristics of license plates.

After the license plates are localized on the extracted images, optical character recognition (OCR) is applied using the EasyOCR library. The results, subsequently stored in the database, enable automation of the parking payment control process.

Verification of parking payment is one of the key components of the system. According to the current regulations, the driver is granted a grace period of approximately 15 minutes to complete payment after arrival is recorded. If payment is not made within this period, the system automatically generates a violation event, which is sent to the inspection module. Such an event contains the vehicle's license plate number, a photographic record of the violation, and the detection timestamp, enabling inspectors to respond promptly to the situation.

As an illustrative example, consider the operation of the payment component of the intelligent parking monitoring system. The system sends a query containing verification parameters and invokes a system function (Figures 4 and 5) against the database to check the payment status of a specific vehicle. If the database contains a record showing that the vehicle with license plate VO9916ET has paid for parking at PARK123, and the violation time 15:30 falls within the interval 14:00–16:00, the function will return True. If the record is absent or is_paid = False, the system will call send_fine_event(...) and return False.

The generalized model diagram of the intelligent parking monitoring system is presented in Figure 1. Overall, this model encompasses data collection, processing, storage, transmission, and analysis.

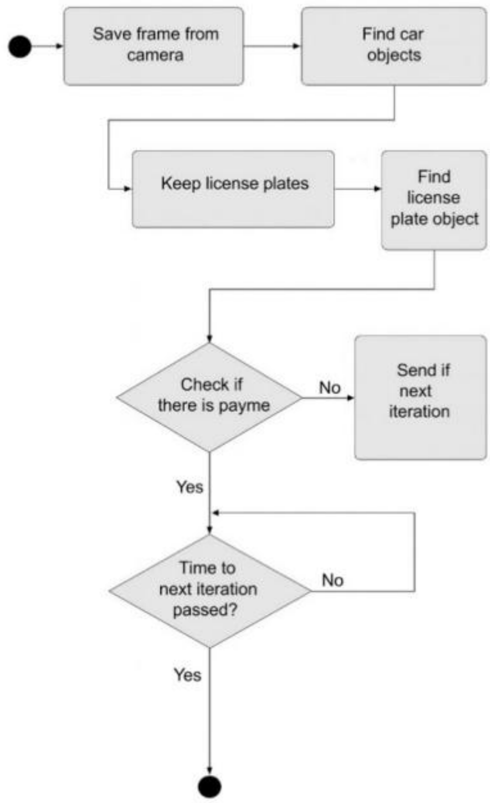

Figure 1 – Diagram of the generalized model of the intelligent system for monitoring compliance with parking regulations
Source: developed by the authors

Thus, the intelligent system consists of the following functional modules: Save frame from camera, Detect car objects, Detect license-plate objects, Keep plates that lie within car objects, Recognize plate number, Check if payment exists, Send violation event. The software component of the intelligent system was implemented using the Python programming language.

The approach chosen by the authors automates the control process, eliminating the need for manual inspection of parking areas. Inspectors receive targeted notifications only for cases requiring intervention, which significantly improves operational efficiency and allows optimizing control service resources.

Experimental results. For the experiment, frames were selected from surveillance cameras at a parking lot located at: 12 Taras Shevchenko Boulevard, Ternopil (Fig. 2), and 21 Ruska Street, Ternopil (Fig. 3). The selected images contain several vehicles positioned at different viewing angles and distances from the camera, enabling the evaluation of the recognition algorithms' robustness to perspective and scale variations.

Figure 2 – Frame from a surveillance camera installed at the parking lot, 12 Taras Shevchenko Boulevard, Ternopil

Source: developed by the authors

Figure 3 – Frame from a surveillance camera installed at the parking lot, 21 Ruska Street, Ternopil

Source: developed by the authors

Such an environment is representative of real operating conditions of the system, as it includes typical parking scenarios, in particular partial object occlusion, variable lighting, and diverse types of license plates. This ensures sufficient variability of data for testing the accuracy and reliability of the proposed methods.

Conclusions. As a result of the research, an intelligent system for monitoring compliance with parking regulations using neural networks based on video footage from surveillance cameras located near parking zones has been proposed. The main outcomes are as follows:

1. A mathematical formalization of the technological process of intelligent monitoring of compliance with parking regulations has been carried out, taking into account such technological aspects as vehicle detection using the YOLO model.

2. A generalized model of the intelligent system has been developed, which enables fast and accurate object detection within a frame, provides license plate localization and recognition (implemented through the combined use of YOLO for extracting the license plate region and EasyOCR for subsequent text recognition), and incorporates parking payment verification (payment status linked to the license plate).

3. The architecture of the intelligent system has been synthesized, considering the technological aspects of real-world operating conditions.

4. An experimental study of the developed intelligent system has been conducted, representative of real operating conditions, taking into account typical parking scenarios, including partial object occlusion, variable lighting, and diverse license plate types.

As a result of the conducted research, an intelligent system has been developed that allows effective control of parking payments. As demonstrated in the paper, the chosen data collection strategy of "one frame per minute" reduces the computational load and ensures scalability of the solution for large parking areas.

The system is based on modern computer vision algorithms - YOLO for object detection and EasyOCR for character recognition. This ensures high accuracy in image processing under real-world conditions. The developed system demonstrated robustness to variations in lighting, viewing angle, and video quality. The designed parking payment verification component automatically detects violations, ensures precise recording with frame preservation, and transmits the data to the inspection module for further action.

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Інтелектуальна система моніторингу дотримання правил паркування транспортних засобів

Праця присвячена створенню інтелектуальної системи моніторингу за дотриманням правил паркування з використанням нейронних мереж в умовах змінного освітлення, різних кутів огляду та якості відеопотоку. Ця мета досягнута шляхом математичної формалізації технологічного процесу інтелектуального моніторингу за дотриманням правил паркування з урахуванням таких технологічних аспектів, як детекція транспортного засобу із використанням моделі YOLO (You Only Look Once), локалізація і розпізнавання номерного знаку за допомогою комбінованого поєднання алгоритмів YOLO та EasyOCR (перший забезпечує виокремлення області номерного знака, другий – розпізнавання), перевірка факту оплати паркування з «прив'язкою» до номерного знака транспортного засобу.

На основі математичних моделей побудовано узагальнену модель інтелектуальної системи моніторингу за дотриманням правил паркування, запропоновано архітектуру інтелектуальної системи з урахуванням технологічних аспектів реальних умов функціонування системи та її програмну реалізацію.

Представлені результати експериментального тестування запропонованої інтелектуальної системи на реальних відеозаписах підтвердили її придатність до фукнціонування в умовах змінного освітлення, різних кутів огляду, якості відеозапису. Обрана стратегія збору даних – один кадр за хвилину – забезпечує баланс між точністю моніторингу та економією обчислювальних ресурсів, що робить і-систему масштабованою, ефективною для впровадження в інтелектуальні системи управління паркувальним простором.

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