UDC 004.932:621.397.424:311.21](045)
DOI https://doi.org/10.32689/maup.it.2025.1.34

Maksym TISHKOV
Postgraduate Student at the Department of Mathematical Methods of System Analysis, Educational and Scientific Institute of Applied System Analysis, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»maksym.tishkov@gmail.com
ORCID: *0009-0006-1741-9977*

Oksana TYMOSHCHUK
Candidate of Technical Sciences, Associate Professor,Head of the Department of Mathematical Methods of System Analysis, Educational and Scientific Institute of Applied System Analysis, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute» tymoshchuk.oksana@lll.kpi.ua
ORCID: *0000-0003-1863-3095*

PEDESTRIAN SPEED ESTIMATION METHOD APPLICATION FOR STATISTICAL ANALYSIS OF CROWD DYNAMICS

Abstract. *This paper addresses the problem of pedestrian detection, tracking, and gait speed estimation based on video footage from a surveillance camera positioned above the walking area. Such a configuration is typical for surveillance systems in public spaces. The method proposed by the authors does not require any specialized equipment, making it suitable for a wide range of real-world scenarios.*

The aim *of this study is to evaluate the previously developed method for pedestrian speed estimation in a real-life case – video surveillance in a school corridor. The research seeks to assess the effectiveness and reliability of the algorithm under conditions that differ from a controlled laboratory environment.*

Research methodology. *To test the method, a video recording was conducted in a school corridor, where a surveillance camera captured pedestrian flows over a period of 6.5 hours. Using computer vision algorithms, pedestrians were detected, their trajectories tracked, and walking speeds estimated. In total, 1,841 trajectories were extracted, with an average walking speed of 1.15 m/s. The collected data enabled a statistical analysis that revealed patterns of pedestrian traffic under both normal and emergency conditions.*

Scientific novelty. *The study presents the first real-world validation of the previously proposed method, implemented without any prior environmental preparation or the use of additional sensors. A distinguishing feature of the experiment is the consideration of external factors, particularly regular air raid alerts occurring during wartime in Ukraine. Their impact on pedestrian behavior was identified and reflected in the analytical results. This approach contributes to a deeper understanding of human adaptive behavior in stressful situations.*

Conclusions. *The conducted study confirmed the effectiveness of the previously developed method for pedestrian detection, tracking, and speed estimation in real-world conditions. The obtained results can be used to further improve decision support systems in the fields of safety, evacuation planning, and crowd behavior analysis. The use of real data and the inclusion of a crisis context significantly enhance the practical value of the proposed methodology.*

Key words: *computer vision, object tracking, gait speed estimation, video surveillance, deep learning, crowd monitoring.*

Максим ТІШКОВ, Оксана ТИМОЩУК. ЗАСТОСУВАННЯ МЕТОДУ ОЦІНКИ ШВИДКОСТІ ПІШОХОДІВ ДЛЯ СТАТИСТИЧНОГО АНАЛІЗУ ДИНАМІКИ НАТОВПУ

Анотація. *У статті розглянуто задачу виявлення, відстеження та оцінки швидкості руху пішоходів на основі відеозаписів із камери спостереження, встановленої над зоною пересування. Така конфігурація є типовою для систем відеоспостереження в публічних просторах. Запропонований авторами метод не потребує жодного спеціалізованого обладнання, що дозволяє використовувати його в широкому спектрі реальних сценаріїв.*

Метою роботи *є апробація створеного раніше методу оцінки швидкості руху пішоходів на практичному прикладі з реального життя – відеоспостереження у шкільному коридорі. Дослідження має на меті перевірити ефективність і надійність алгоритму в умовах, які відрізняються від лабораторного середовища.*

Методологія дослідження. *Для випробування методу була організована зйомка в коридорі навчального закладу, де камера фіксувала пішохідні потоки протягом 6,5 годин. За допомогою алгоритмів комп'ютерного зору здійснювалося виявлення пішоходів, відстеження траєкторій та оцінка швидкості руху. Усього було отримано 1841 траєкторію, а середня швидкість руху склала 1,15 м/с. На основі зібраних даних проведено статистичний аналіз, що дозволив оцінити динаміку пішохідного трафіку у звичайних та екстрених умовах.*

Наукова новизна. *У роботі вперше апробовано раніше запропонований метод у реальних умовах, без попередньої підготовки середовища чи залучення додаткових сенсорів. Особливістю дослідження є врахування зовнішніх чинників, зокрема регулярних повітряних тривог, що відбуваються під час війни в Україні. Їхній вплив на поведінку пішоходів був ідентифікований та відображений у результатах аналізу. Такий підхід дозволяє глибше зрозуміти адаптивну поведінку людей у стресових ситуаціях.*

Висновки. *Проведене дослідження підтвердило ефективність розробленого раніше методу виявлення, відстеження та оцінки швидкості пішоходів у реальних умовах. Отримані результати можуть бути використані для подальшого вдосконалення систем підтримки прийняття рішень у сфері безпеки, планування евакуацій та* *аналізу поведінки натовпу. Залучення реальних даних та врахування кризового контексту підвищує прикладну цінність методики для практичного використання.*

Ключові слова: *комп'ютерний зір, трекінг об'єктів, оцінка швидкості ходьби, відеоспостереження, глибоке навчання, моніторинг натовпу.*

Introduction. In the modern world, there are a lot of places of crowd congregations, especially in big cities. Understanding crown movements may help to improve environments and make them more ergonomic and efficient for usage in daily life, and, what's more important, during emergencies.

To be able to analyze crowd movements, we need to formalize them and store data in some way. Crowd monitoring and tracking techniques, which require advanced methods of computer vision are used for such tasks.

This paper focuses on the data collection and processing of pedestrians' movement based on video from the camera located above the walking area. Collected data is being processed for gait speed estimation and performing analysis of the retrieved information about pedestrians's movement dynamic, which can be used, for example, for crowd modeling in regular and emergency situations. Ukrainian State building regulations [4] define requirements for buildings, including evacuation policies. This research might be beneficial for understanding pedestrians' movements and developing software for crowd modeling.

Problem statement. The paper proposes a process for data collection about crowd dynamics and aims to process and analyze collected data.

To achieve the goal, several key steps must be undertaken. First, a thorough review of existing literature on crowd dynamics analysis will provide a foundation for understanding current methodologies and identifying gaps. Based on this review, an appropriate method and software will be selected for detecting, tracking, and estimating the speed of pedestrians. Following this, relevant data will be collected in the form of video recordings from real-world scenarios, which will then undergo processing to extract numerical information necessary for analysis.

The processed data will be analyzed to derive meaningful insights into pedestrian movement. This analysis will include determining the number of pedestrians at each moment in time and examining how their average speed changes over time. Additionally, speed-time graphs will be generated to compare the behavior of pedestrians moving in groups with those moving individually. The analysis will also focus on understanding the distribution of speeds and identifying the minimum, maximum, and average speeds observed throughout the dataset.

Related papers. Computer vision techniques are the subject of multiple research papers and already became a part of commonly used software products that help in daily tasks. Advanced techniques like neural network models are utilized to implement intelligent systems that perform complex operations.

Kannadasan and Yogeswari [2] consider the problem of estimating the volume of vehicles on the road in real time. Authors utilize the YOLO-v5 model to detect and categorize detected objects. Authors improved the model to increase the performance of the object counting task to make it possible to perform operation in real time. It is beneficial for understanding flow density and density dynamics. However, we're interested also in the pedestrians' speed estimation which is not covered in this paper.

Shrivastav et al. [11] are solving a similar problem to Kannadasan and Yogeswari. They are counting pedestrians using the YOLO-v4 model. Authors also proposed a direction estimate method based on the pedestrians' trajectories, which provides information for understanding crowd dynamics.

M. W. Park et al. [9] performed an experiment in which 24 volunteers performed a video-recorded 10-m gait test. Authors estimated the gait speed using their method based on pose estimation. The author's aim is to determine the minimum distance between a pedestrian and smartphone camera. However, the actual speed estimation in the experiment is performed partially manually since the distance is calculated based on the markers on the video.

S. Mirzaei [12] addresses the challenge of monitoring intersections using a dual-camera system for enhanced detection, tracking, and predictive safety alerts for road users. The authors employ deep learning-based object detection and multi-object tracking to analyze vehicle and pedestrian movement. Their approach integrates predictive modeling to issue real-time safety alerts, improving intersection safety. Their system relies on a dual-camera setup and converts data from video sources to the GPS coordinates, which allows them to calculate the speed. However, their system relies on a dual-camera setup, while our study focuses on single-camera pedestrian speed estimation, which presents unique challenges in distance and motion analysis.

Recent advancements in pedestrian speed estimation have explored diverse sensing technologies, including Radar, LiDAR, and magnetometers. A. Boroomand et al. [1] leverages Frequency-Modulated Continuous Wave (FMCW) Radar to autonomously estimate gait speed by analyzing Doppler shifts in reflected signals, demonstrating its effectiveness in non-contact motion tracking. X. Peng and J. Shan [13] utilize Doppler LiDAR to accurately detect and track pedestrian motion, using laser-based velocity estimation to enhance tracking precision in urban environments. Meanwhile, Y. Liu [14] introduces a novel approach for indoor pedestrian speed estimation, combining magnetometer-based motion detection with odometry techniques to improve accuracy in GPS-denied environments. These studies highlight the growing use of multi-sensor technologies for precise and adaptable pedestrian speed estimation, with applications ranging from urban mobility and surveillance to healthcare and indoor navigation. However, these researches propose approaches that require more specific equipment for their implementation, which makes them less usable.

There are studies that use a similar approach as we do – videographic technique to estimate gait speed. Ali et al. [6] are estimating pedestrians' speed using recordings from a camera. They are using a software for detecting and storing coordinates of pedestrians, as we do. However, the camera is placed vertically at the ceiling of the shopping mall atrium, which is not a usual position of the camera. It also limits usage of the approach to a very specific use case. The camera position allows us to perform trivial calculations knowing pedestrians' coordinates on the image.

Ghomashchi et al. [5] used YOLO-v4 model for pedestrians detection and tracking from the bird's-eye-view video images. For speed estimation, a manual, to a great extent, method was used, based on a ray casting technique. Authors manually defined a polygon, which represented a crosswalk and calculated the time the pedestrian spent inside the defined polygon. Knowing the real length for the crosswalk and time, the speed was calculated. Authors utilize a similar technique for pedestrians' detection and tracking, but the method for speed estimation is more primitive and not usable in a random use case since it requires manual operations to be done.

The reviewed studies do not provide data on pedestrian movement dynamics in real-world scenarios with extended observation periods. Our research aims to address this gap.

Pedestrian speed estimation method. This section covers the steps of retrieving data for analyzing crowd dynamics, technical details of the proposed implementation, and briefly describes the method of pedestrian speed estimation along with the necessary prerequisites for its correct execution.

Our objective is to extract data enabling the construction of speed-time graphs, the derivation of speed distributions, and the identification of pedestrians moving individually or within groups. The methodology employed in this study was comprehensively detailed in our previous work [10]. Here, we provide a concise overview of the key concepts and introduce extensions to the approach.

The initial step of the proposed method involves the identification and tracking of pedestrians, achieved through the utilization of the YOLOv7 object detection model by Wang et al. [3]. The result of the object detection and tracking is the data about the coordinates of every detected object on every frame, stored in the relational database.

The next step is the speed estimation based on the stored data. Fig. 1 displays central projection from the camera point of the image plane on the real-world plane. Here:

$A_0B_0C_0D_0$ – image plane of the camera;

$\overrightarrow{BD}$ – movement vector. We can calculate the size of this vector in pixels;

$A_{0p}B_{0p}C_{0p}D_{0p}$ – area on the real-world plane visible on the image from the camera;

$\overrightarrow{B_pD_p}$ – vector on the real-world plane we are aiming to estimate.

The method presented in [10] enables the calculation of $\overrightarrow{B_pD_p}$, which is a diagonal of the trapeze $A_pB_pC_pD_p$.

$$B_pD_p = \sqrt{h^2 + \left(A_pB_p + h \cdot ctg\left(\angle A_pD_pC_p\right)\right)^2}, \tag{1}$$

where h – the height of the trapeze.

The equations required for calculating all parameters in (1) are provided in [10]. They are not reproduced here to avoid redundancy and maintain focus on the primary objectives of this study.

The required parameters for calculation are:

– Height of the camera position;
– The tilt angle of the camera;
– The focal length of the camera in millimeters;
– Camera resolution;
– Sensor size;
– Vertical viewing angle of the camera.

Additionally, a post-processing step is applied to the data to identify pedestrians within groups. The pedestrian is marked as one moving within a group if he intersects another pedestrian in 50% of all frames where he was detected.

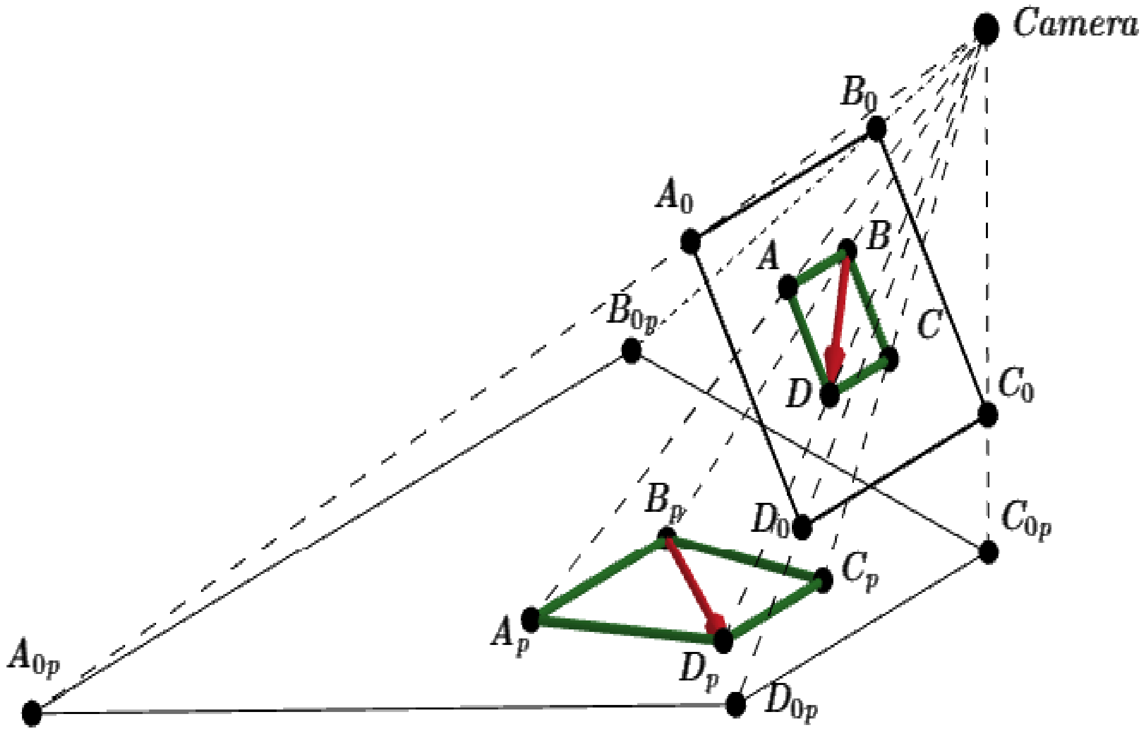

Fig. 1. Projection from image plane to a real-world plane

Data processing and analysis. As the video for processing a video from the camera positioned in the school hole was selected. The video was recorded during a working day in the Ukrainian school. The total duration of the video is 6,5 hours, starting at 8:12 AM till 2:43 PM. It is worth mentioning that the recording was made in November 2024, during the war in Ukraine. Almost every day, there are multiple air raid alerts, which force students and personnel to move to the shelter. During the period of recording, there were two air raid alerts: from 1:35 AM to 8:36 AM and from 1:49 PM to 2:21 PM. These periods will be displayed on the graphs as two highlighted regions.

Pedestrians flow. First, we will consider a graph of number of detected objects over time – Fig. 2.

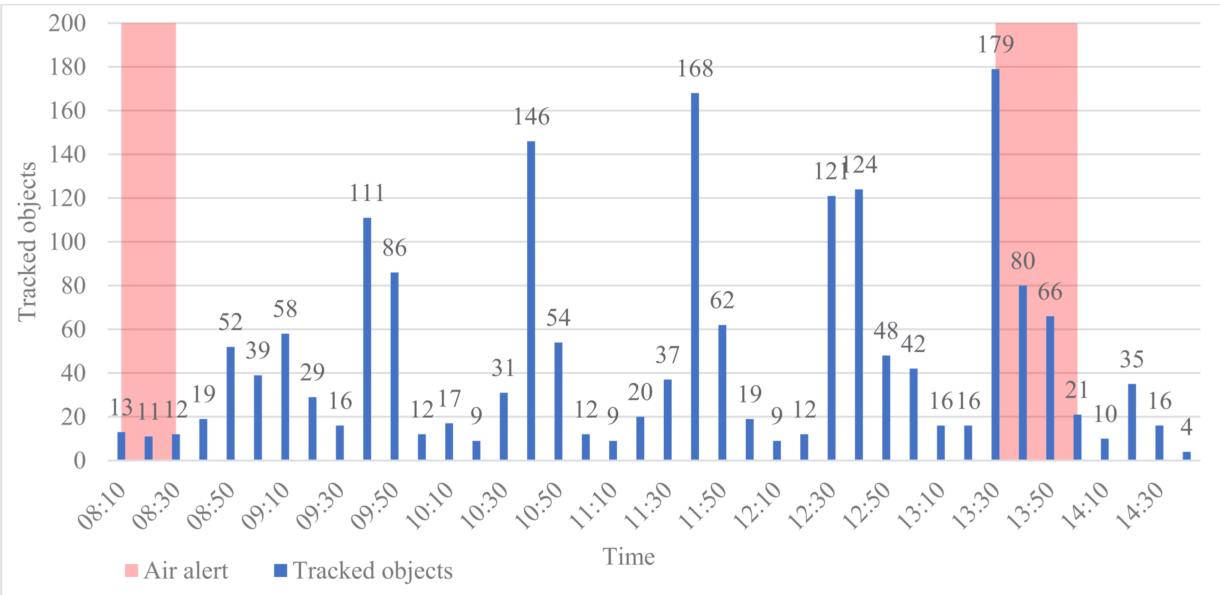

Fig. 2. Detected objects over time

The proposed detection method identifies objects in each frame and is capable of tracking them across consecutive frames. However, there are instances when an object becomes temporarily occluded for several frames – for example, when it is obscured by other objects. In such cases, the same pedestrian might be treated as multiple tracking objects, potentially inflating the values shown in Fig. 1. Nevertheless, this approach enables visualization of pedestrian dynamics and allows for comparative analysis of pedestrian flow over time. Importantly, this issue does not significantly affect the calculations of the average estimated speed, which will be discussed in subsequent sections.

In Fig. 2, distinct spikes are observed every hour at approximately 40 minutes. This can be attributed to 15-minute breaks between lessons. The lowest pedestrian flow values are recorded at the beginning of each hour, corresponding to the start of lessons. The first air raid alert occurred prior to the beginning of the video recording, resulting in minimal movement until the alert ended. During the second air raid alert, pedestrian movement towards the shelter is evident, indicating the highest number of detected objects overall period of observation, with movement decreasing to its lowest value at 14:10.

Average speed. The graph in Fig. 3 contains average pedestrian speed data during observed time, and the graph on Fig. 4 displays the average speed distribution.

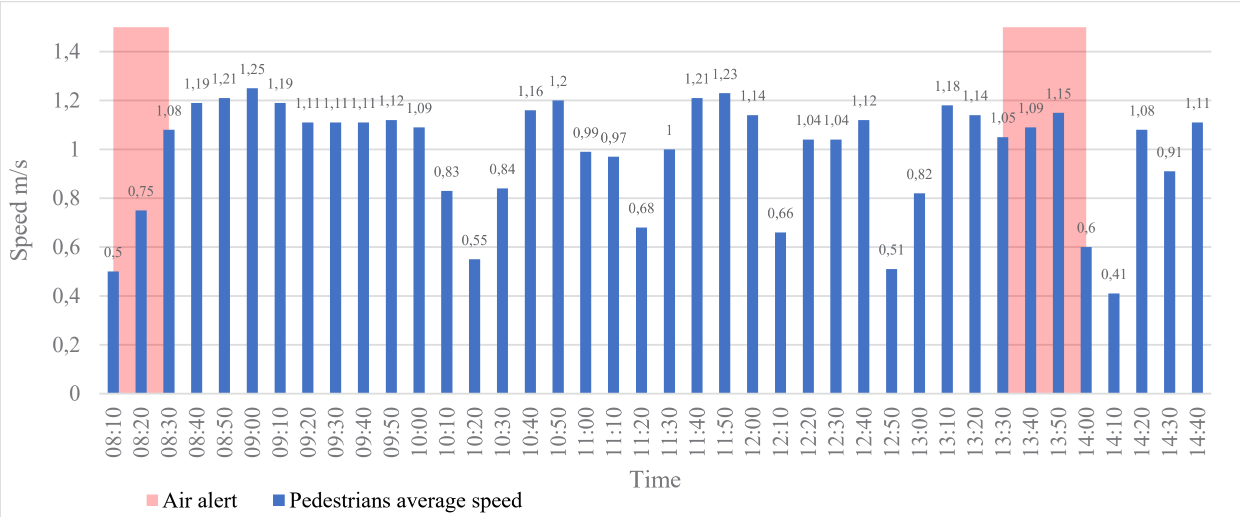

Fig. 3. Average speed over time

The graph illustrates the average median speed of pedestrians, calculated over 10-minute intervals. This approach was chosen based on the characteristics of the algorithm employed, which estimates the distance between the tracked objects' positions across consecutive frames. In certain instances, portions of a pedestrian's body may be obscured from the camera view by other pedestrians or objects. This occlusion can result in abrupt shifts ("jumps") in the detected pedestrian position as the detection algorithm continues to identify and track the individual. Considering that pedestrian movement is generally uniform and accounting for these detection nuances, the median speed per pedestrian was used as a more robust measure. Subsequently, the average speed was calculated based on these median values to generate the presented graph.

As observed, there are several periods where the average speed approaches its maximum value of 1.25 m/s. The highest speeds are recorded during breaks between lessons and at the onset of air raid alerts. In contrast, the lowest speeds are observed during lesson times. This reduction in speed during lessons can be explained by two factors: a smaller number of detected pedestrians and a cabinet within the video frame where individuals remain stationary for extended periods. These factors contribute to noticeable drops in the average moving speed.

The average detected speed is 1.15 m/s, which agreed with the research of M. Giannoulaki and Z. Christoforou [7], where authors gathered different previous researches on pedestrian speed and claim that pedestrians' speed varies from 0.78 to 2.79 m/s depending on conditions, with an average value of 1.26 m/s.

The correlation coefficient between the average speed and the number of pedestrians is 0.36, which is a weak to moderate value. In the social sciences, where human behavior is researched, such a value is considered sufficient. So, in our experiment, the higher the number of pedestrians, the higher their average speed, which might be counterintuitive. However, in our case, there was no crowding, and people moved freely. In the case of bottlenecks, moving speed would obviously decrease significantly with the rising size of the crowd.

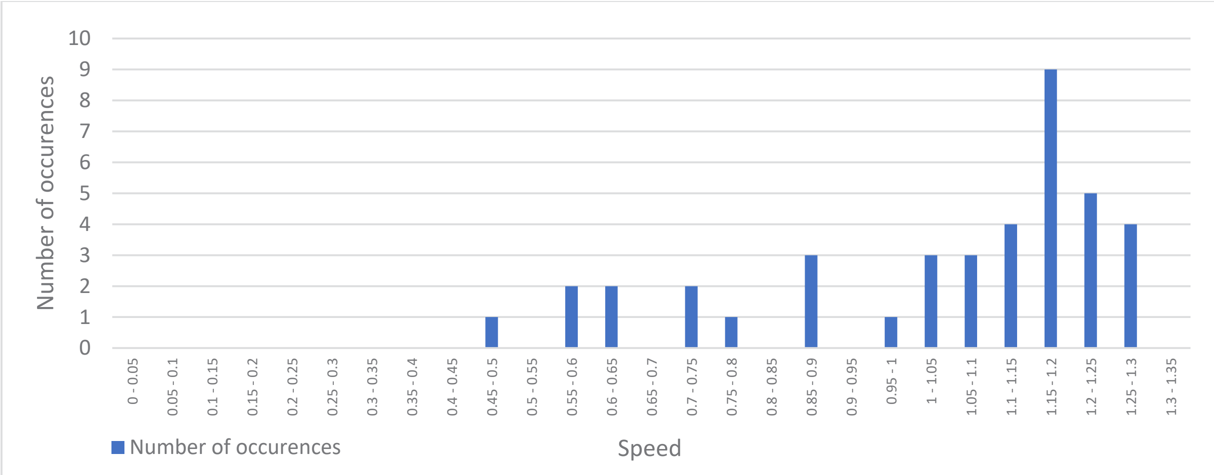

Fig. 4. Speed distribution

Groups and single pedestrian dynamics. In this section, we will consider the dynamic of pedestrians walking within a group and single pedestrians. Fig. 5 displays the average speed of single pedestrians and within a group along with a number of such founded objects for 10-minute intervals. A pedestrian is considered as one walking within a group if its frame intersects someone else's frame at least in 50% of frames the pedestrian has been detected.

Fig. 5. Groups and single pedestrians dynamics

This chart confirms the previous conclusion about the positive correlation between a number of detected objects and their speed. In most cases, people in groups move faster than single pedestrians.

To formalize dependency, we will calculate the Effect size coefficient – η^2, indicating the impact of the independent variable, in our case, the type of movement – single pedestrian or the pedestrian within a group, on the dependent variable, average speed.

The results are next: $\eta^2_{group} = 3.53\%$, $\eta^2_{single} = 4.25\%$. Both values indicate a small effect size of the moving type on the average speed.

Conclusions. This study made it possible to evaluate the proposed method for estimating pedestrian gait speed [10] under real-world conditions by visualizing the obtained data after processing and generating statistical summaries. A 6.5-hour video recording was captured in a school corridor and analyzed using an artificial neural network (ANN)-based model for object detection and tracking, along with the developed approach for movement speed estimation. The analysis facilitated a comprehensive statistical examination of pedestrian dynamics, including pedestrian flow, temporal variations in average speed, speed distribution, and the influence of walking alone versus in a group on movement speed.

A total of 1,841 pedestrian trajectories were detected, with an average walking speed of 1.15 m/s. The obtained data clearly demonstrate a correlation between the number of pedestrians and their walking speed with the presence of breaks between classes, which confirms the validity of the proposed method. While walking in a group versus alone did not exhibit a statistically significant effect on movement speed, a slight influence of this factor was still observed.

Next steps. The implemented method enables the processing of recorded video footage. The speed estimation algorithm is analytical, relying on mathematical operations that are computationally efficient, allowing for real-time execution. However, the primary limitation of the current implementation lies in the detection and tracking stage, which operates relatively slowly and is not suitable for real-time applications.

Overall, the current implementation [8] is effective for extracting data for subsequent analysis. Further optimization is required to achieve real-time processing capabilities. Once real-time operation is achieved, the approach can be effectively utilized for recognizing critical situations and as a component of video analytics in decision support systems for emergency scenarios.

Bibliography:

1. A. Boroomand, G. Shaker, P. P. Morita, A. Wong and J. Boger, "Autonomous gait speed estimation using 24GHz FMCW radar technology," 2018 IEEE EMBS International Conference on Biomedical & Health Informatics (BHI), Las Vegas, NV, USA, Apr 2018, pp. 66–69. https://doi.org/10.1109/BHI.2018.8333371.
2. B. Kannadasan and K. Yogeswari, "ANN-based traffic planning model using adaptive YOLOv5-aided object counting from surveillance videos". *Asian Journal of Civil Engineering*, vol. 25, pp. 4771–4788, May 2024. https://doi.org/10.1007/s42107-024-01079-9.
3. B. Y. Wang, A. Bochkovskiy, H. Y. M. Liao. "YOLOv7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors," In CVPR, New Orleans, LA, USA, 2022, pp. 7464–7475. https://doi.org/10.48550/arXiv.2207.02696.
4. DBN V.1.1-7:2016, Fire Safety of Building Structures, Ministry of Regional Development of Ukraine, Kyiv, 2016. URL: https://e-construction.gov.ua/files/new_doc/3019922918881626107/2023-01-20/5c73ab5e-fc7d-4433-8bcf-6f78978113b6.pdf.
5. H. Ghomashchi, J. Paterson, A. C. Novak, and T. Dutta, "Estimating pedestrian walking speed at street crossings using the YOLOv4 and deep SORT algorithms: Proof of principle," *Applied Ergonomics*, vol. 119, Article 104292, Apr. 2024. https://doi.org/10.1016/j.apergo.2024.104292.
6. M. F. M. Ali, M. S. Abustan, et al., "A Case Study of Malaysian Pedestrian Walking Speed at Shopping Malls in Kuala Lumpur, Malaysia using Human Behaviour Simulator (HBS)," *International Journal of Integrated Engineering*, vol. 11, no. 4, pp. 225–230, Aug. 2019. https://doi.org/10.30880/ijie.2019.11.04.025.
7. M. Giannoulaki, Z. Christoforou, "Pedestrian Walking Speed Analysis: A Systematic Review," Sustainability, vol. 16, no. 11, Article 4813, Jun. 2024. URL: https://translate.google.com/website?sl=en&tl=uk&hl=uk&prev=search&u=https://doi.org/10.3390/su16114813.
8. M. Tishkov. Pedestrian speed estimation. 2024. URL: https://github.com/MaksymTishkov/pedestrian_speed_estimation.
9. M. W. Park, S. G. Chung, J. Beom, K. S. Kim, J. Kim, and C. H. Park, "Minimum Required Distance for Clinically Significant Measurement of Habitual Gait Speed," Research Square, 2024. https://doi.org/10.21203/rs.3.rs-5403357/v1.
10. O. L. Tymoshchuk, M. O. Tishkov, V. G. Bondarenko, "Crowd navigation monitoring during emergencies," System research and information technologies, no. 4, pp. 43–54, Dec. 2024. https://doi.org/10.20535/SRIT.2308-8893.2024.4.03.
11. P. Shrivastav and A. K. T. Andu, "Integrated Approach for Real-time Human Counting, Tracking, and Direction Estimation using Advanced Algorithms," 2024 15th International Conference on Computing Communication and Networking Technologies (ICCCNT), Kamand, India, Nov. 2024, pp. 1–6. https://doi.org/10.1109/ICCCNT61001.2024.10726257.
12. S. Mirzaei, "Dual-Camera Intersection Monitoring: Detection, Tracking, and Predictive Safety Alerts for Road Users," M.A.Sc. thesis, Dept. of Mechanical Eng., McMaster Univ., 2024. http://hdl.handle.net/11375/30193.
13. X. Peng and J. Shan, "Detection and tracking of pedestrians using Doppler LiDAR," *Remote Sensing*, vol. 13, no. 15, Article 2952, Jul. 2021. https://doi.org/10.3390/rs13152952.
14. Y. Liu, W. Zhang, L. Cao and D. Wei, "Ped-Mag-ODO: Indoor Pedestrian Motion Speed Estimation Method Based on Dual Magnetometers," *IEEE Internet of Things Journal*, Dec. 2024. https://doi.org/10.1109/JIOT.2024.3512504.