

Application of an Electronic Cane for Blind People - Analysis and Evaluation

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Abstract – This study examines various methods, criteria, and technological approaches used to evaluate parameters associated with the mobility of individuals with disabilities, with particular emphasis on the development of an electronic guidance and monitoring system integrated into a cane for visually impaired users. The proposed engineering solution includes an electronic module based on an ESP32-S3 microcontroller, tested in laboratory and real conditions. Methods for determining distance and signal processing have been analyzed, and a methodology for creating algorithms for working with the HC-SR04 ultrasonic sensors and the TF-LUNA infrared sensor has been developed. The influence of the mounting angle on the measurement accuracy with the infrared sensor has been studied, and the measurement process has been modeled with an emphasis on error assessment and minimization. The results obtained confirm the effectiveness of ultrasonic scanning in avoiding obstacles in the course of movement. Criteria for reliability and accuracy of measurements are presented, as well as an algorithm for processing sensor data using regression models, providing adaptive user guidance through tactile or sound feedback. In conclusion, a structural and principal diagram of a comprehensive electronic system to support the orientation and safety of blind people in an urban environment has been synthesized.

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Keywords – Cane, electronic control system, blind people, ultrasonic sensors, infrared sensor.

1. Introduction

The contemporary advancement of medical engineering is inextricably linked to the development and modernization of electronic systems aimed at assisting people with disabilities. The creation of innovative electronic solutions can significantly contribute to the social integration and quality of life of individuals in unequal circumstances. Technological progress in nearly every scientific field has led to considerable improvements in life quality.

A thorough examination of current electronic solutions includes an extensive survey of the available literature on diverse devices, patents, and products designed for individuals with visual impairments. Identifying the functional focus of these systems and the ways in which they support user interaction, either by compensating for or partially substituting visual perception, offers valuable insight into the everyday challenges faced by visually impaired individuals and underscores the societal significance of such technologies. Effective progress in this area requires coordinated efforts from both governmental institutions and the scientific community, ensuring that people with disabilities are provided with the means to lead fuller and more independent lives [1]. The review of available data and the subsequent analysis indicate a notable absence of reliable statistical information regarding the number of individuals with visual impairments in Bulgaria, which poses a significant obstacle to developing and implementing effective state policies in this field.

Numerous electronic systems have been developed to assist the orientation and mobility of blind individuals [2], [3]. Most of the existing devices are based on various combinations of sensors, among which ultrasonic, infrared, photosensitive, moisture and flame sensors are most common, as well as accelerometers and gyroscopes [4], [5], [6]. However, existing solutions are often limited to detecting static objects within a limited range, without covering the possibility of recognizing dynamic obstacles, which creates prerequisites for the occurrence of accidents [7], [8].

The conducted in-depth review of the scientific literature and patent base showed that although there are various technological solutions, there is still no optimized system that combines a specific selection of sensors and indications that would provide timely and reliable feedback to the user [9], [10]. In response to this need, this study proposes an individually configured electronic control system for blind people cane, which has not been presented in a similar form in existing developments.

The developed concept is based on a systematic analysis of available technologies and takes into account the real needs of end users. The article justifies the choice of element base, presents the algorithms for the operation of the sensors and evaluates the effectiveness of the system in the context of its applicability as a navigation tool for blind people.

The purpose of this publication is to present an electronic system for controlling peripheral parameters in disadvantaged people – a cane for blind people, with a view to improving their living environment.

2. Methodology

This chapter outlines the methodology used to develop the electronic control system for a cane intended for visually impaired users, along with the associated control algorithms and the criteria applied for its design and evaluation.

2.1. Analysis and Compensation of Errors in Determining the Range

The Time-of-Flight (ToF) technique is the most widely used ultrasonic measurement approach. In this method, the transmitter emits simple, single-frequency sequential pulses, while the receiver analyzes the returning echo to determine the propagation time of the ultrasonic waves. The distance is then calculated by combining this time information with the known speed of sound.

Accurate extraction of the time parameter is crucial for the ToF method, and it is typically accomplished using amplitude-threshold detection, envelope estimation, or correlation-based techniques.

The sources of range-measurement errors can generally be grouped into two categories. The first consists of systematic errors, which arise from inaccuracies in capturing the ToF signal itself. The second category includes errors introduced by external environmental factors, such as variations in the speed of sound caused by changes in temperature or humidity.

2.1.1. Error Sources in Signal Acquisition and Correction Methods

The acquisition of the ultrasonic ToF signal depends on both the quality of the echo and the specific processing technique applied. When the processing method remains constant, higher echo quality directly contributes to more accurate ToF measurements.

One major source of error arises from noise present in the ultrasonic echo. Applying signal-filtering techniques, such as Kalman filtering [11], helps eliminate irrelevant components and improves the signal-to-noise ratio (SNR). Additionally, increasing the intensity of the transmitted pulse enhances the amplitude of the received echo, thereby reducing ToF estimation errors caused by noise.

Secondly, range-measurement errors tend to increase with distance due to the significant attenuation of the echo signal as it propagates through air. To address this, a gain compensation module [12], [13] is incorporated into the receiving circuit to amplify the echo and counteract the energy loss of the ultrasonic waves. The compensation principle described in [12] (Figure 1) ensures that the echo signal maintains a consistent intensity across different distances, thereby reducing ToF measurement errors caused by variations in signal amplitude during subsequent processing.

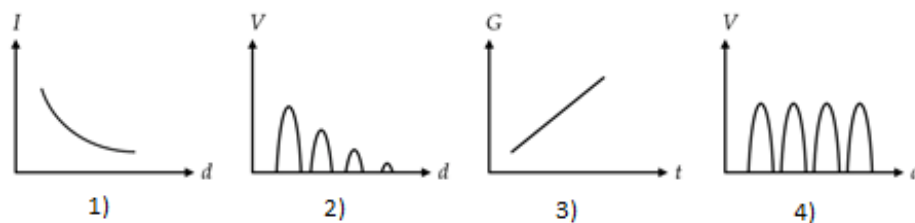


Figure 1. Gain compensation

(1) Variation of sound intensity with distance, (2) Relationship between received signal intensity and distance, (3) Compensation coefficient, (4) Received signal intensity after applying compensation

Measurement errors may occur due to the beam propagation angle, θ . Depending on the relative positions of the target and the transducer, as shown in Figure 2, the distance errors differ, highlighting the influence of angular alignment on the accuracy of the ToF measurements.

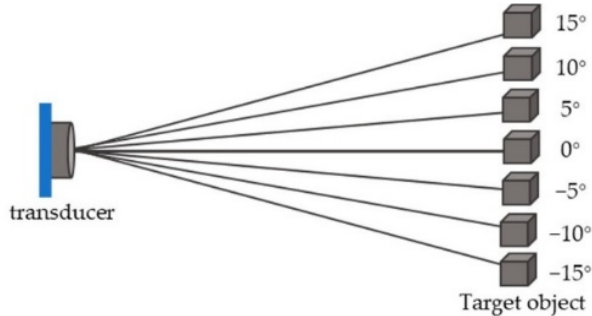


Figure 2. Angular range of object detection

The larger the angle, the greater the error in determining the range [12], [14]. The waveform of an ultrasonic signal deviates from the ideal shape when it moves away from the centerline of the main beam, making the precise identification of the echo timing more challenging. To address this, the detection angle must either be controlled, or the resulting error can be corrected using a compensation algorithm derived from pre-measurements with sensors positioned at various angles. As reported in [15], applying angular compensation improved measurement accuracy from 12.24 mm to 3.4 mm at a distance of 1 m for a 60° beam angle.

2.1.2. Influence of Environmental Conditions and Compensation Methods

The speed of sound is influenced by various environmental factors, such as temperature, humidity, and pressure. It depends nonlinearly on these parameters, as well as on the concentration of CO₂:

$$c = f(t, p, x_{\omega}, x_c), \quad (1)$$

where t is the temperature in Celsius, p is the air pressure, x_{ω} is the mole fraction of water vapor, and x_c is the mole fraction of carbon dioxide.

Temperature has the greatest influence on the speed of sound, which can be expressed by the formula [17]:

$$c = 331.45 \times \left(\sqrt{1 + \frac{t}{273.15}} \right) \quad (2)$$

In this context, 331.45 m/s corresponds to the speed of sound in dry air at 0 °C, with t representing the temperature in degrees Celsius. The speed of sound increases as the temperature rises. Equation (2) can be expressed using a Taylor series expansion as follows:

$$c = 331.45 + 0.607 \times t \quad (3)$$

For each 1 °C rise in air temperature, the speed of sound increases by approximately 0.607 m/s. The effect of humidity on the speed of sound is less pronounced than that of temperature and can be expressed as [18]:

$$c^2 = \gamma \frac{RT}{M} \left(1 + \frac{2pB}{RT} \right), \quad (4)$$

where c is the speed of sound; T is the temperature on an absolute scale; γ , p , R , M , B represent the ratio of specific heat, pressure, universal gas constant, molecular mass and second virial coefficient respectively.

The speed of sound is higher in moist air than in dry air. The variation of the speed of sound with respect to temperature and relative humidity is shown in Figure 3.

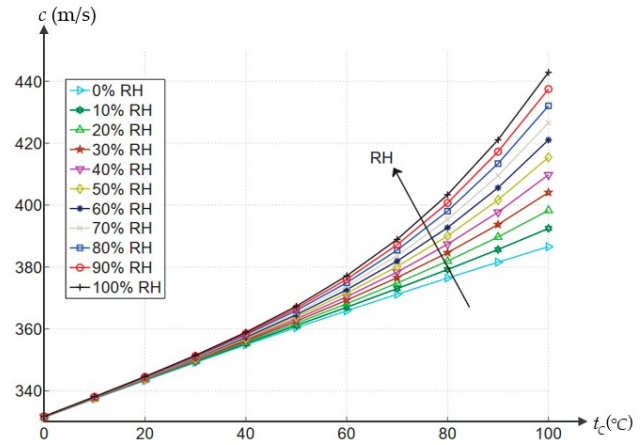


Figure 3. Effect of temperature and humidity on the speed of sound

Changes in air pressure and CO₂ concentration exert only a minimal influence on the speed of sound, which is largely overshadowed by the effects of temperature and humidity. Even at extreme humidity levels (100% RH), the resulting impact on sound speed remains relatively small. The maximal impact of air pressure on the speed of sound occurs under conditions of high humidity, with the relative variation of sound speed due to air pressure reaching 0.67% at 30 °C and normal CO₂ concentration ($X_c = 0.000383$). The effect of CO₂ concentration is even smaller, causing a relative variation of only about 0.06% at 19 °C for a 0.2% change in the CO₂ mole fraction [16], [19], [20], [22].

In practice, the system compensates for sound speed errors caused by temperature and humidity. Integrated sensors measure environmental parameters in real time, allowing the ToF signal to be used to calculate the actual sound speed [21]. This approach corrects for multiple environmental effects simultaneously but increases the system's size and footprint.

2.2. Methods and Criteria for the Work and Evaluation of the Developed Electronic Cane for Blind People

Based on an analysis of visual impairments, the necessity of developing advanced assistive systems for visually impaired individuals is emphasized. The proposed electronic control system for a blind person's cane enables the detection and avoidance of obstacles using ultrasonic and infrared signals. Preliminary research and conducted experiments determined that the developed electronic control system is based on an ESP32_S3 microcontroller and includes three HC-SR04 ultrasonic sensors and one TF-LUNA infrared sensor (Figure 4).

Ultrasonic sensors at the cane's base detect obstacles up to 2 m, while a mid-mounted infrared sensor identifies stairs and their orientation. A vibration module in the handle provides feedback on stair presence and direction.

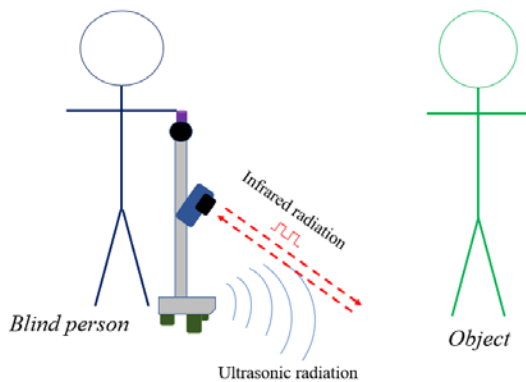


Figure 4. Schematic representation of the operation of the electronic control system for blind people cane when detecting an object

According to the literature review (Figure 5) it was found that the standard angle of stairs varies between 30° and 45°. Exit stairs are built with a shallower angle in the range of 30...35°, while industrial stairs have steeper angles, ranging from 40° to 70°.

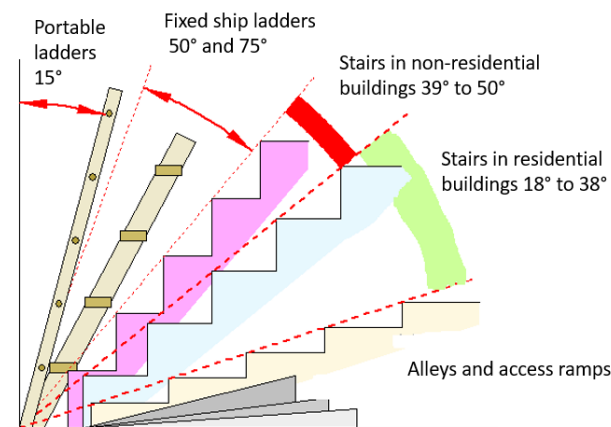


Figure 5. Standard stair angles [23]

2.2.1. Methods of Sensor Operation

Two working methods are synthesized, related to the infrared sensor (Method 1) and the ultrasonic sensor (Method 2).

Method 1: Climbing: When climbing, the sensor needs to be closer to the foot with each subsequent step. If the sensor is placed at an angle, it will measure decreasing distance as it moves up.

Descending: When descending, the distance will increase because the sensor will detect the edge of the lower step.

The operation of the TF-LUNA infrared sensor which is used to determine the direction of movement on the stairs based on the change in distance schematically present when climbing (Figure 6a) and when descending stairs (Figure 6b). This then activates a vibration motor with different frequencies depending on whether a person is going up or down the stairs.

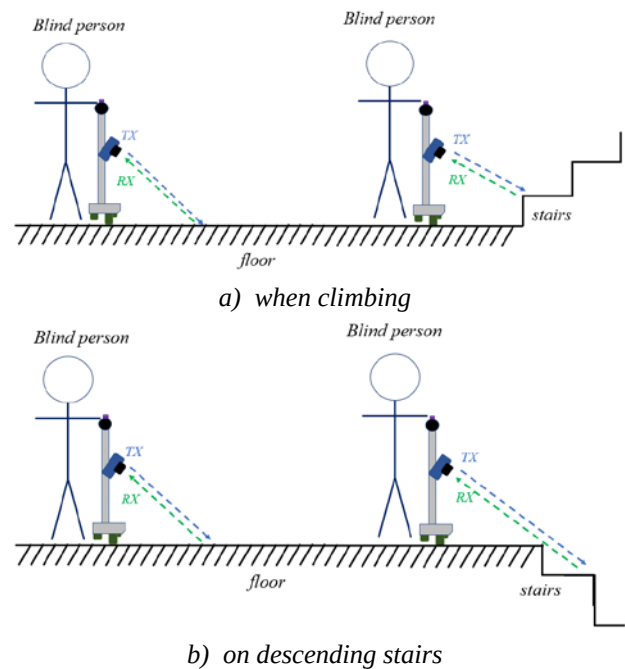


Figure 6. Schematic representation of the operation of the TF-LUNA infrared sensor

Method 2: The ultrasonic sensor operates by first emitting a 10 μ s probing pulse, generating a high-level output, followed by an ultrasonic packet consisting of eight pulses at 40 kHz. The pulse frequency and packet structure allow the receiver to distinguish transmitted signals from ambient noise. After transmitting this probing packet, the system monitors the returning echo. If no echo is detected within 38 ms, the system registers the absence of obstacles within the sensor's range. When a reflected signal is received within 150 μ s to 25 ms, the system detects an object and calculates its distance based on the duration of the received pulse [24].

The speed of sound is 340 m/s. The echo pulse represents the time taken for the signal to travel to the object and return, allowing the distance to be calculated using the standard formula, with the measured time divided by two to account for the round trip.

2.2.2. Criteria for the Performance of the Developed System and Evaluation of Measurements

Based on the research conducted, preliminary tests performed and described methods, criteria for the operation of the developed system and an evaluation of the measurements have been synthesized.

Criterion 1: The required field of view angle of an ultrasonic sensor in the horizontal plane is 42.8° .

Based on a developed and researched methodology for the accuracy of sensor measurements [25], an ultrasonic sensor HC-SR04P with a range of 42.8° was selected under the assumed hypothesis of a horizontal plane of the field of view with a coverage angle of up to 160° .

Criterion 2: The number and arrangement of the fields of view of the ultrasonic sensors is three without overlapping of the individual zones to achieve the overall field of view of the device.

Criterion 3: The optimal mounting angle of the TF-LUNA infrared sensor to ensure balanced and accurate readings when climbing and descending stairs is 35° .

For optimal coverage when detecting stairs and to determine the configuration for the placement of the infrared sensor when a blind person using a cane moves, the system was tested at different angles and positions, (Figure 5), with the degrees of the stair angle tested between 18° and 38° .

Criterion 4: Adaptive control of the sound signaling by changing the frequency depending on the measured distance for close objects the frequency is 0.1 s and for distant objects it is 1 s.

The algorithm (Figure 7) provides adaptive control of the sound signaling by changing the frequency of the sound pulses depending on the measured distance. At smaller distances, the warning is every 0.1 s or 0.5 s, while at medium distances the signal is every 1 s. In this way, the sound indication adapts to and effectively increases the user's warning of the presence of obstacles, with decreasing distance leading to an increase in frequency.

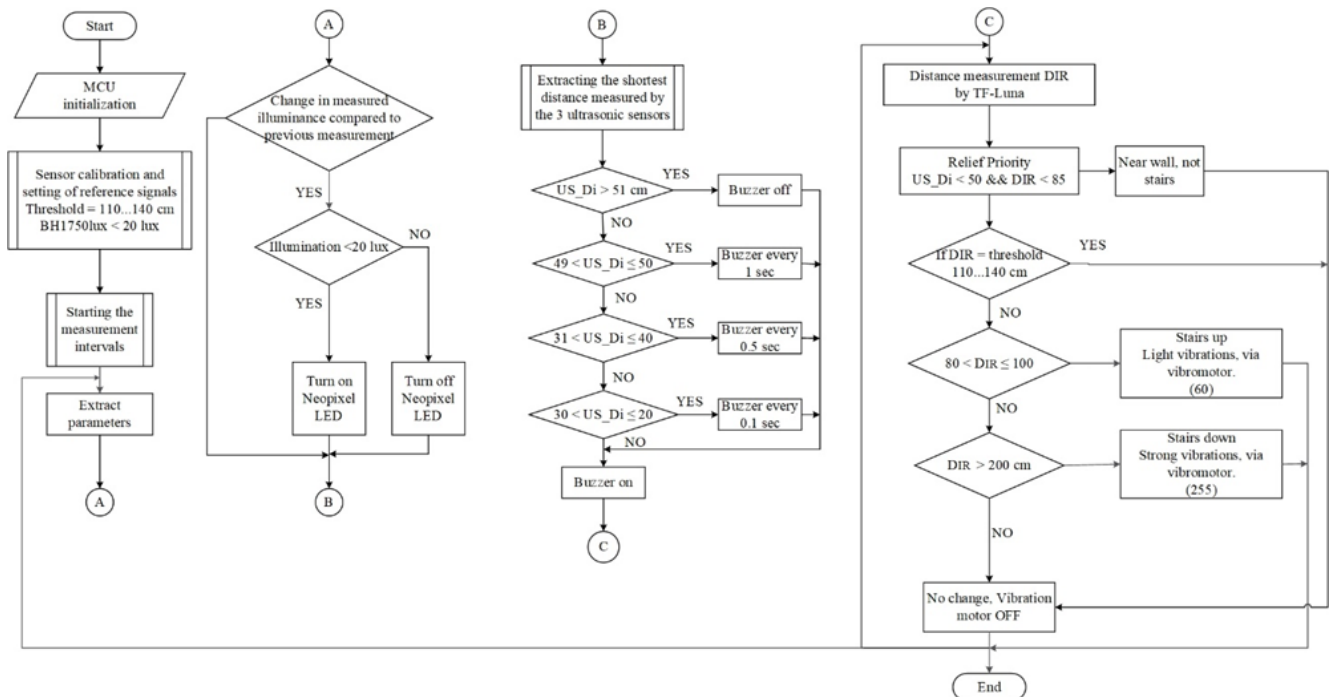


Figure 7. Algorithm of operation of the electronic control system for blind people cane

2.3. Structure and Operation of an Electronic System for Analyzing and Controlling an Electronic Cane for Blind People

Based on the synthesized criteria and the defined methods, the operating algorithm of the electronic system was synthesized.

The synthesized prototype of the electronic control system for blind people cane is presented in (Figure 8) in all stages of its development, with the location of the individual sensors marked.

Calibration of individual sensors and setting reference signals allow for personalization of the cane and is performed once.

Sensor monitoring is then carried out continuously at intervals of 1 s.

Microprocessor initialization prepares the electronic system for operation by loading the initial data and starting the cane's functionality.

The HC-SR04 ultrasonic sensors (Figure 8a) and (Figure 8b) measure the distance to obstacles, enabling their detection and avoidance. The sensors emit pulses of 10 μ s, and upon receiving the reflected signals, the microcontroller processes the information to determine the presence of an object and trigger the corresponding indication.

The BH1750 light sensor module (Figure 8a) and (Figure 8b) measures ambient brightness and intensity, comparing the readings with a predefined threshold. When the output voltage exceeds this threshold, LED lighting is activated to signal the presence of a visually impaired user to other road participants.

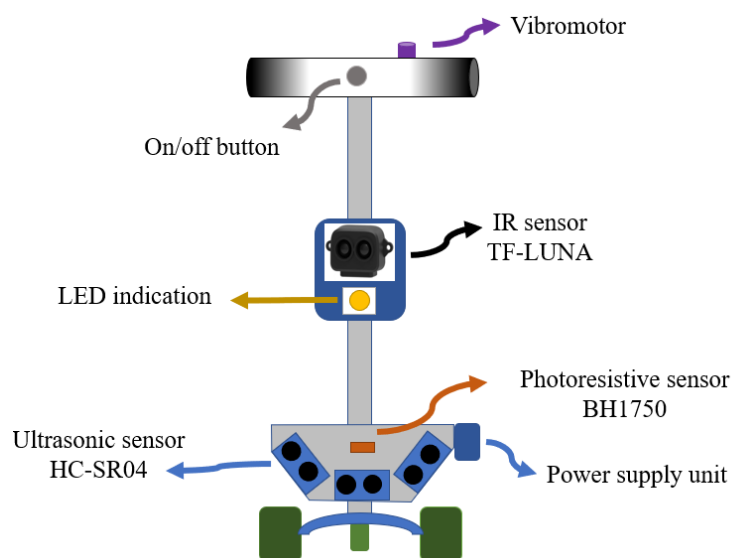
The TF-Luna infrared sensor (Figure 8a) and (Figure 8b) employs the Time-of-Flight (ToF) principle to measure distances by periodically emitting modulated near-infrared waves ($\lambda \approx 850$ nm). It determines the time of flight by measuring the phase difference between the emitted and reflected waves, which is then used to calculate the relative distance to objects.

The printed circuit board with the location of the ultrasonic sensors and the control – PCB1 (Figure 8c) and the printed circuit board of the TF-LUNA sensor – PCB2 (Figure 8d), was synthesized.

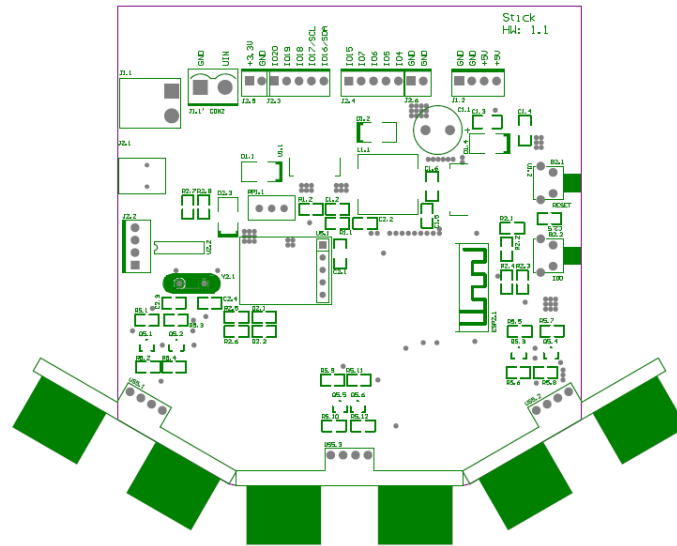
The developed electronic cane for blind people is presented in (Figure 8e).



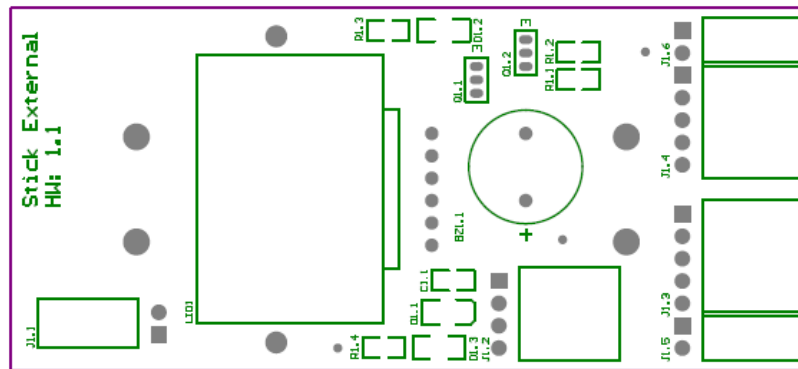
a) Structure diagram



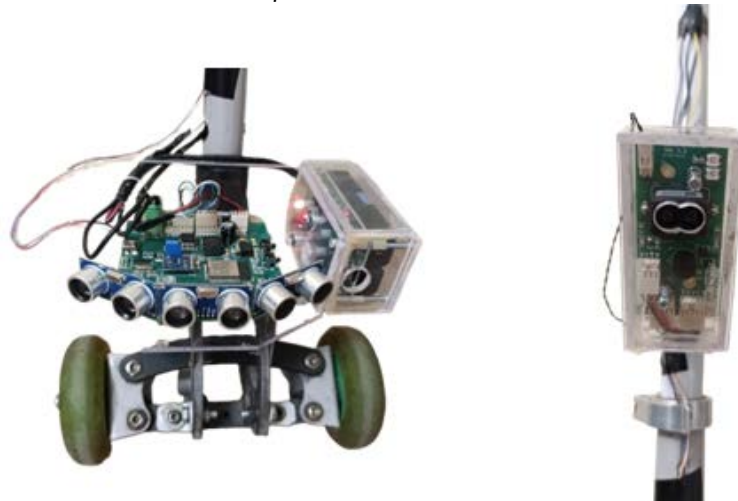
b) Schematic representation of the cane



c) PCB1: The printed circuit board with the location of the ultrasonic sensors and the control



d) PCB2: The printed circuit board of the TF-LUNA sensor



e) Visual representation of PCB1 and PCB2 on the cane
Figure 8. Prototype of an electronic cane for the blind

The electronic system is powered by two lithium-ion batteries with a capacity of 2850 mAh each, connected in series, which provides a total voltage of 7.4 V. These batteries are favored for autonomous devices because of their high energy density and extended lifespan.

The calculations performed show that the system can operate for up to 5.7 h at a load of 500 mA, which for people in an unbalanced situation is fully comparable to their lifestyle and time away from home.

3. Results and Discussion

This section describes the operation of the developed electronic control system for a blind person's cane and presents the results obtained from its testing under real-world conditions.

Between 2023 and 2025, a series of experimental studies were conducted in both laboratory and field settings to validate and practically demonstrate the theoretical findings, focusing on the anticipated improvement in the performance of the synthesized electronic system for monitoring and controlling peripheral parameters in individuals with disabilities. The aim of the experimental studies is to assess the role of extreme situations and to build an algorithm for assessing movement with a cane for blind people.

3.1. Stages of the Experiment

First stage: The first stage is related to the placement of the ultrasonic sensors in a horizontal plane [25]. The need for this stage of initial research is justified by the visual field of a sighted person and transferred to this field on the tasks of the cane and its sensors.

Second stage: In this stage of the research, simulation models are used to test the accuracy of the sensors used [25]. Using a combination of input data, the accuracy of the ultrasonic sensors is simulated, followed by the development of a prototype ultrasonic-based electronic cane system for visually impaired users employing a single sensor. Experimental studies are then conducted to evaluate the field of view determined by the sensor configuration.

Third stage: The third stage of the experimental research is related to the analysis of the quantitative and qualitative indicators of the proposed methodologies and the developed electronic system by evaluating the selected basic parameters. The quantitative analysis of the amplitude-temporal indicators provides information about the movement of the blind person using a cane.

3.2. Statistical Research and Evaluation of Ultrasonic Sensors

Statistical estimation of gross errors is essential for improving the accuracy and reliability of ultrasonic sensor measurements and distance sensing. Gross errors, often the result of unforeseen circumstances, can lead to serious data biases.

The objective of this study is to examine the influence of ambient temperature on distance measurements obtained with the HC-SR04 ultrasonic sensor through a statistical evaluation of gross measurement errors.

The experimental setup includes measurements at two fixed temperatures: 22.1°C and 3°C, at two predefined reference distances: 100 cm and 200 cm.

By repeatedly conducting measurements $y_i=20$, the aim is to identify gross errors and assess deviations. The need for such analysis is essential, since the requirements for high accuracy and reliability in modern engineering applications are an extremely important task.

The measurements taken are systematized and processed to estimate gross errors. In the context of a statistical study, gross errors are estimated by selecting values from the four samples that are furthest from the reference distances of 100 cm and 200 cm. The selection is justified in order to identify potential anomalies in the measurements.

In view of the presented samples of measurements ($y_i=20$), a suitable criterion is the Grab criterion, which is applicable to a smaller number of measurements ($y_i=3\div35$). The results of the observations are presented in increasing variation order, determining either the smallest $y_{\min}$ or the largest $y_{\max}$ values of the observed sample. For the needs of the study, the most visibly different values from the reference 100 cm at a temperature of 22.1°C are 98.66 cm, and at 3°C it is 101.25 cm, and at the reference 200 cm at a temperature of 22.1°C it is 200.88 cm, and at 3°C it is 203.91 cm. A null hypothesis is raised that the observation does not contain a gross error if:

$$G = \frac{|y_i - \bar{y}|}{S} < G_{kp}, \quad (5)$$

where: G_{kp} is the critical value of the Grab criterion, $\bar{y}$ is the arithmetic mean value, and S is the standard deviation, which are calculated according to the following relationships:

$$\bar{y} = \frac{\sum_{i=1}^n y_i}{n} \quad (6)$$

$$S = \sqrt{\frac{\sum (y_i - \bar{y})^2}{n-1}} \quad (7)$$

The verified (questionable) result is excluded from the calculations. The determined value of G is compared with the critical value of the criterion G_{kp} , the final results are presented in Table 1, at a significance level of $\alpha=0.05$. The null hypothesis is accepted if $G_{kp} > G$.

The critical value of the Grab criterion at $y_i=19$ and a significance level $\alpha=0.05$ is $G_{kp}=2.681$. This means that the null hypothesis is accepted and no gross errors are isolated at a reference distance value of 100 cm and an ambient temperature of 22.1°C and 3°C.

Table 1. Gross errors

temp = 22.1°C, dist = 100 cm	
$G_{22.1}^{\circ C} = \frac{ 98.66-98.85368 }{0.171924} = 1,127$	
$G_3^{\circ C} = \frac{ 101.25-101.0995 }{0.075607} = 1,99$	
temp = 3°C, dist = 100 cm	
$G_{22.1}^{\circ C} = \frac{ 200.88-200.7874 }{0.064191} = 1,44$	
$G_3^{\circ C} = \frac{ 203.91-203.5668 }{0.061739} = 5,56$	

With a reference distance of 200 cm and an ambient temperature of 3°C, a gross error is isolated. This necessitates a check of the observations for $y_{18,19}=203.66$.

$$G_3^{\circ C} = \frac{|203.66-203.56|}{0.056} = 1,79 \quad (8)$$

From the obtained results for the evaluation of the measured value 203.66 cm, it is concluded that the critical value of the Grab criterion at $y_i =$ and a significance level $\alpha=0.05$ e $G_{kp} = 2.620$. This means that the null hypothesis is accepted and no gross errors are isolated at a reference value of the distance of 200 cm and an ambient temperature of 3°C, i.e., the sample size is kept $y_i=19$.

3.3. Research on the Developed Prototype of an Electronic System for Controlling Peripheral Parameters in Blind People When Moving up Stairs

The next section presents the study of the developed prototype of an electronic system for controlling peripheral parameters in blind people when moving up stairs. The performance of the infrared sensor at different angles of the staircase and the influence of lighting on the sensor's performance are studied.

3.3.1. Study of the TF-LUNA Infrared Sensor Operating Algorithm

According to the study it was found that the exit stairs are built with an angle in the range of 30...35°. In order to determine the most suitable mounting angle of the TF-Luna LiDAR sensor when used in a system to assist blind people in climbing and descending stairs, a series of measurements were conducted at different mounting angles of the sensor.

The results obtained determined the two most suitable mounting angles: 30° and 35°, the others did not meet expectations and turned out to be unsuitable for the specific environmental conditions.

The purpose of the measurements is to establish which of the angles provides the most accurate recognition of the stair structure (stairs), by measuring the distance to objects at different positions – first, middle and last step, both when ascending and descending.

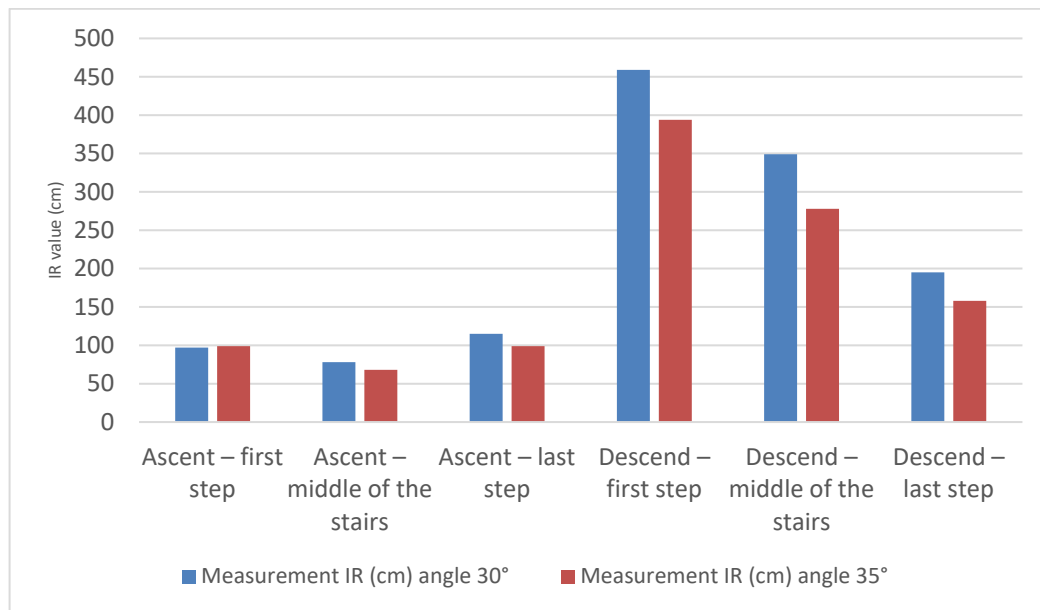
The results obtained are systematized which includes the measured values and the calculated relative error. These data allow conclusions to be drawn regarding the accuracy and reliability of each mounting angle.

Additional observation from the experiments shows that when the sensor is mounted at an angle of 35°, there is no interference in the measurements caused by reflective surfaces (windows) located opposite the path of movement. This suggests that this angle offers higher resistance to parasitic reflections in a real architectural environment.

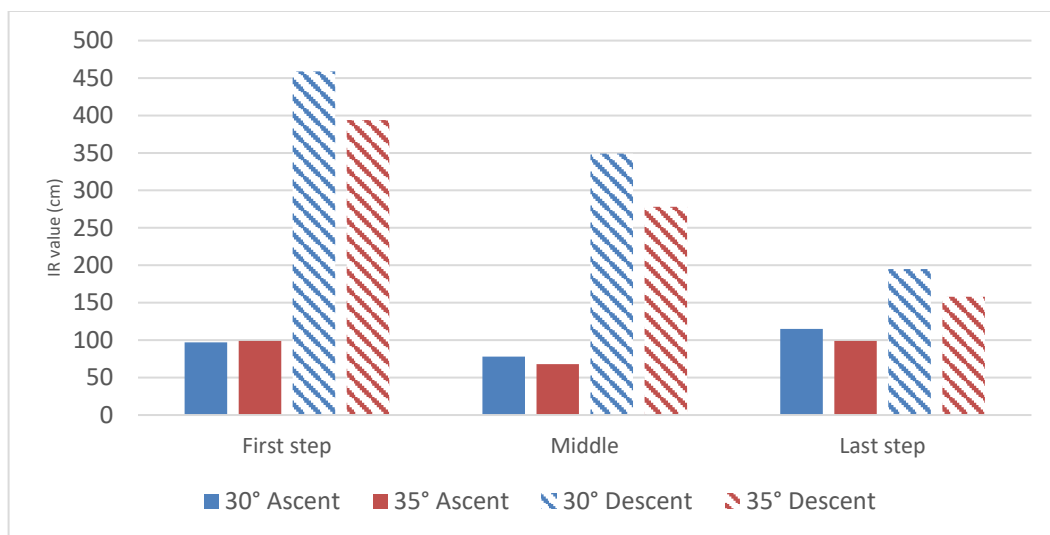
12 tests were conducted, 6 for each mounting angle, covering three stages of movement:

- Ascent: first, middle and last step;
- Descent: first, middle and last step.
- For each position, the following were measured:
- DIR – the measured distance from the sensor;
- Actual measured distance – measured by a calibrated device;
- Relative error.

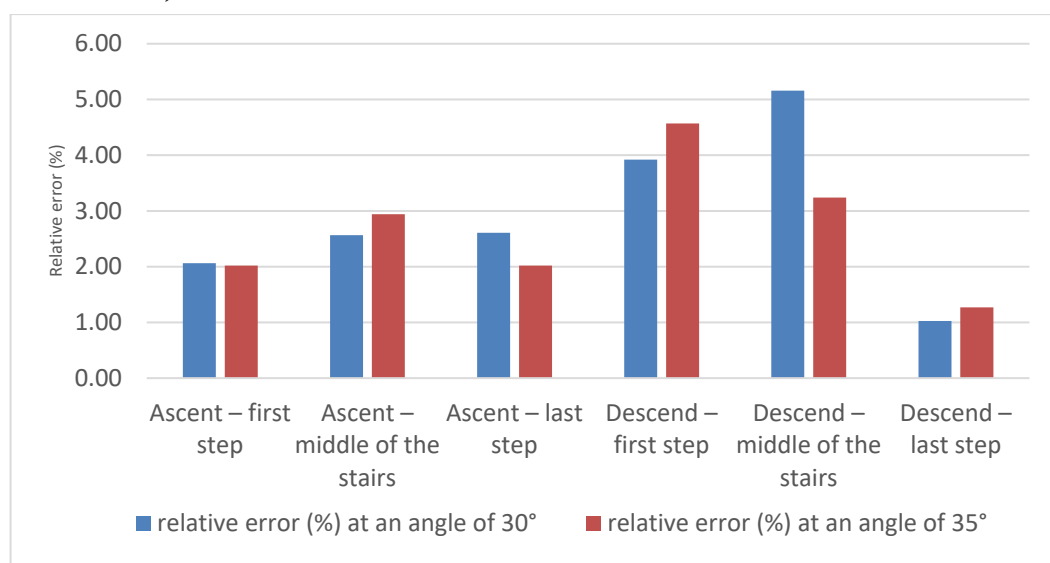
The results show a clear difference in the sensor behavior at the two mounting angles. The measured values of the infrared sensor from the test are visualized as follows: Comparison of IR values at 30° and 35° (Figure 9a); Distinction between ascent and descent at both 30° and 35° inclines (Figure 9b) and Comparison of relative error at 30° and 35° (Figure 9c). Mounting at 35° leads to more consistent and even values, especially when climbing. At 30°, larger fluctuations are observed, especially over long distances (descent – over 3 m).



a) Comparison of IR values at 30° and 35°



b) Distinction between ascent and descent at both 30° and 35° inclines



c) Comparison of relative error at 30° and 35°

Figure 9. Test measurement values of the infrared sensor

In all test measurements, Figure 9.b, the measured distance when descending is significantly greater than when ascending, which is logical due to the observation geometry – the sensor “looks forward”, and when descending the beam falls into the empty space between the steps. This difference allows for reliable classification of the type of movement.

The comparison of the relative error between the two angles by means of average values shows: (i) Average error at 30°: 3.04%; (ii) Average error at 35°: 2.88%. The maximum error at 30° is recorded in the “descending – middle of the stairs” position and reaches 5.16%, while at 35° the highest error is 4.57%. This shows that the 35° mounting provides better stability and accuracy in the measurement, especially in complex geometric conditions.

Discussion and conclusions: Analysis of experimental data shows that the TF-Luna sensor provides sufficient accuracy to distinguish movements on stairs, with mounting below 35° resulting in lower relative error and more consistent results in repeated measurements.

The geometry of the descent creates a clear but measurable increase in distance, which is a suitable indicator for creating an indication for the blind user.

The 35° angle provides a better balance between accuracy and stability, with the distinction between ascent and descent being more reliable at 35°.

According to the technical specification of the TF-Luna sensor, the measurement accuracy for distances over 50 cm is ± 6 cm, and for distances over 1 m – the relative error is within $\pm 2\%$.

The obtained results confirm these data, and in most tests the error values fall within the permissible range.

3.3.2. Study of the Influence of Illumination on the Performance of the TF-Luna Sensor

The TF-Luna sensor uses infrared (IR) laser triangulation to measure distance to objects. While it has built-in ambient light compensation, the manufacturer (Benewake) notes that extreme levels of light, especially direct sunlight, can lead to reduced accuracy, interference, or signal loss.

The objective of this study is to assess the effect of varying illumination levels (lx) on the accuracy and stability of measurements obtained using the TF-Luna sensor. The measurements were performed at fixed distances at different levels of illumination (lx), calculating the relative error between the real distance and the value reported by the sensor. The illumination was varied by conducting tests under different atmospheric conditions: shaded areas, cloudy weather and direct sunlight.

Discussion and conclusions: The results show (Figure 10) that the TF-Luna sensor works reliably at illuminances up to about 15,000 lx. At higher values, an increasing error is observed, reaching over 12% in direct sunlight (60,000 lx).

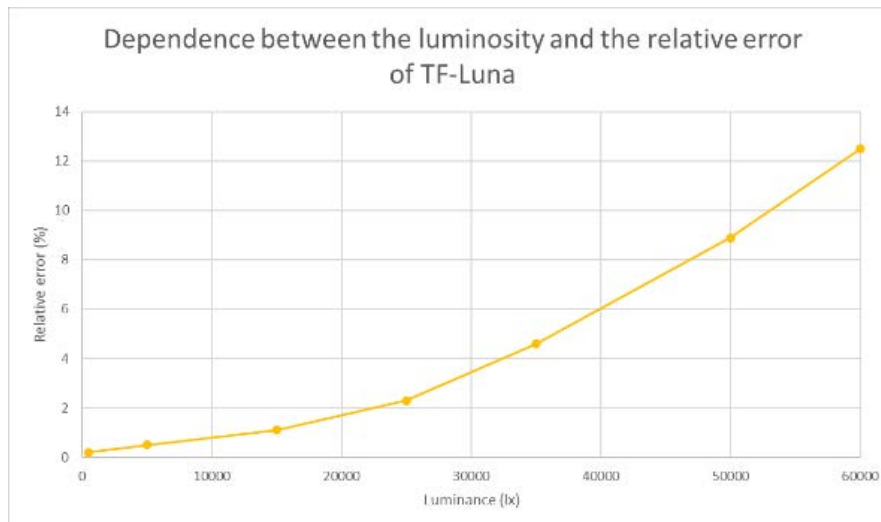


Figure 10. Dependence between illumination and relative error of TF-Luna

Although the conducted measurements indicate that higher illuminance levels increase the measurement error of the TF-Luna sensor, the actual effect of ambient light is highly dependent on the sensor’s mounting angle and orientation.

During the tests, in which the TF-Luna sensor was mounted at an angle of 35° to the horizontal surface, it was found that:

(i) Direct sunlight does not fall directly on the sensor optics, which significantly reduces optical interference;

(ii) Measurement errors remained within acceptable limits even at external illumination above 30,000 lx, while with vertical mounting in the same conditions, sharp fluctuations and false values were observed.

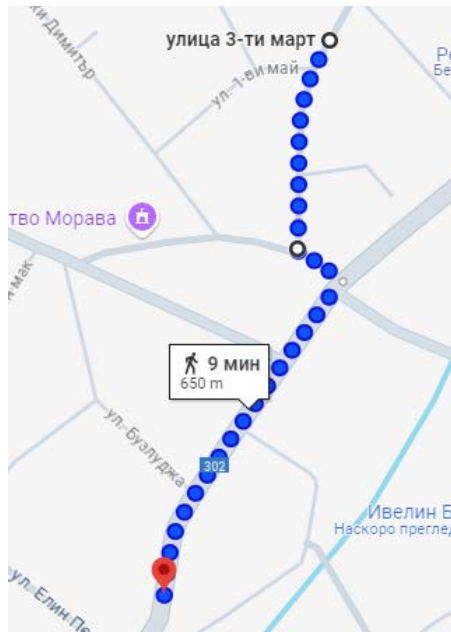
These results are consistent with practical observations in the technical documentation and user community, where it is recommended to avoid direct IR interference when working outdoors. Therefore, mounting at a 35° angle not only helps distinguish between climbing and descending stairs, but also contributes to the system's robustness in high-light conditions.

At illuminances up to 50,000 lx, the absolute error at 35° mounting does not exceed 18 cm, even in complex scenarios (descent).

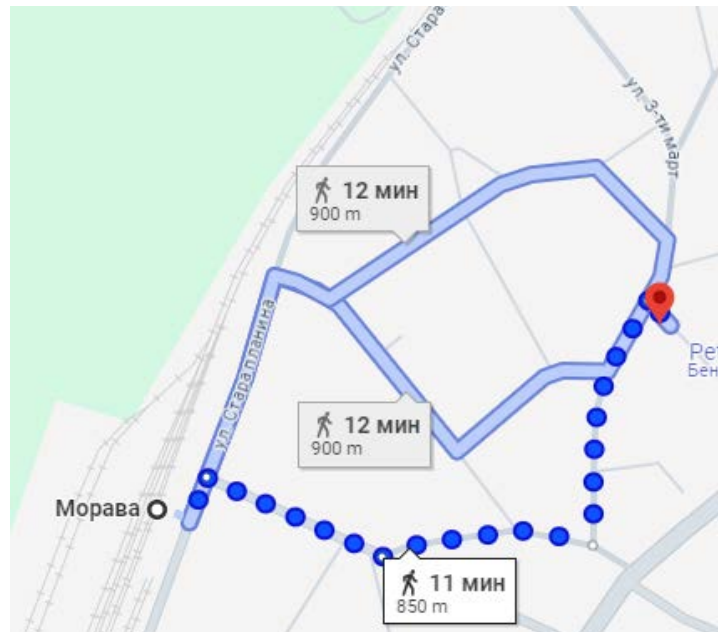
At the same light, vertical or frontal mounting leads to pulsating values or zeroing of readings, proven in field conditions.

3.4. Methodology for Testing the Cane for the Blind in an Open Room

The study of the electronic control system for blind people cane in field conditions is carried out on the basis of a pre-synthesized experimental route in an urban environment in the village of Morava, Svishtov municipality, Veliko Tarnovo region – experimental Route 1 with a distance of 650 m (Figure 11a) and experimental Route 2 with a distance of 850 m (Figure 11b).



a) Experimental Route 1 with a distance of 650 m from home to Primary School “St. St. Cyril and Methodius”



b) Experimental Route 2 with a distance of 850 m from the Primary School “St. St. Cyril and Methodius” to the Railway Station

Figure 11. Experimental routes

The Table 2 presents data from experimental testing of locomotion using a cane (i) and with an assistant in an open room (ii). The aim is to compare the transition time between different start and end points with two different methods of orientation assistance – cane and assistant – for two users.

The data are structured into three routes of different lengths and clearly distinguished conditions.

Table 2. Testing the electronic cane in an open room

Test	Starting point	Endpoint	Distance [m]	Time User 1 [min]	Time User 2 [min]
(i) With the help of a stick					
1	Living room	Bathroom	7.48 m	0.28 min	0.35 min
2	Living room	Corridor	4.85 m	0.13 min	0.15 min
3	Bedroom 1	Living Room	8.19 m	0.32 min	0.42 min
4	Toilet	Bedroom 2	5.00 m	0.18 min	0.22 min
(ii) With the help of an assistant					
1	Living room	Bathroom	7.48 m	0.32 min	0.40 min
2	Living room	Corridor	4.85 m	0.18 min	0.21 min
3	Bedroom 1	Living Room	8.19 m	0.37 min	0.48 min
4	Toilet	Bedroom 2	5.00 m	0.22 min	0.27 min

The analysis shows that the time for moving with the help of an assistant is noticeably shorter compared to the electronic cane for longer routes (650 m and 850 m). The average time reduction is 2.01 min for 650 m and 3.79 min for 850 m, respectively. This suggests that the assistant significantly facilitates navigation on more complex routes.

Discussion and conclusions: Urban environments pose serious challenges to the effective use of technologies such as the electronic cane for the blind. Poorly maintained infrastructure – including uneven and difficult-to-walk street surfaces, absent or poorly marked pedestrian crossings, missing or narrow sidewalks – significantly limit the possibility of safe and autonomous mobility.

In the analysis of times for movement with an electronic cane and with an assistant, a clear interaction between the nature of the environment and the method of assistance used is observed. Empirical data show that:

- For familiar routes (e.g., home - school), moving with a cane is relatively efficient, thanks to tactile and sound indication, as well as the routine habits of the user. This is confirmed by the fact that the differences in times between the cane and the assistant on the 300 m route are minimal.
- In unfamiliar or noisy environments (e.g., school - train station), navigating with an assistant leads to a significant reduction in time. Real-time verbal communication, as well as the assistant's ability to interpret dynamic obstacles, contribute to more efficient navigation.
- On routes with complex elements and increased risk, such as longer distances (850 m), the assistant provides not only higher speed, but also greater safety, making this approach recommended in such conditions.

The developed system incorporates a TF-LUNA infrared sensor, enabling reliable detection of stairs under real-world conditions. By analyzing the distance and angle of the reflected infrared beam, the system not only detects the presence of stairs, but also distinguishes their direction - ascending or descending. This significantly expands the functionality of the assistive device by providing vital information in situations with an increased risk of falling, which are often not recognized by conventional ultrasound systems. Such adaptive signaling significantly improves the user's safety and contributes to their independence in daily mobility.

A key advantage of employing an electronic control system for a blind person's cane is the enhanced independence and autonomy it provides for orientation and mobility in urban environments. This assistive device not only supports physical mobility but also positively influences the psychological well-being of its users.

Building confidence through the systematic use of a cane helps to overcome social isolation and encourages active participation in public life. As a result, the need for constant help from third parties is limited, and the daily life of people in disadvantaged situations acquires greater variety and meaning.

4. Conclusion

As a result of the research, effective methodologies and algorithms for working with three ultrasonic sensors and one infrared sensor in an electronic orientation system for blind people have been substantiated and experimentally confirmed.

The developed prototype of the electronic control system for blind people cane with a basic ESP32-S3 microcontroller demonstrates high accuracy and reliability in determining the distance to objects, both in controlled laboratory and real field conditions.

It has been confirmed that the correct mounting angle (35°) of the TF-LUNA infrared sensor significantly improves the system's robustness by detecting stairs.

The combination of ultrasonic and infrared technologies, coupled with adaptive data processing, allows for the construction of an intelligent system with tactile and audible feedback that supports the safe movement of blind people in an urban environment.

The conclusions drawn and the developed principle and structural solutions create a basis for future expansion of the functionality and integration of such systems into smart city infrastructures.

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