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Thermal navigation for blind people

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Abstract. This article presents a system of precise navigation for a visually impaired person which uses GPS navigation and an infrared sensor in the form of an infrared matrix. The presented system allows determining the orientation and distance of a blind person relative to a selected object, e.g. a wall or road edge. The application of the above solution facilitates a significant increase in the accuracy of determining the position of a blind person compared to the accuracy offered by commonly used ground satellite devices. The system uses thermal energy accumulated in the environment without the need to generate additional signals. The main parts of the system are a simple infrared matrix, data processing system and vibrating wristband. Messages and navigation warnings are sent to a blind person in the form of a vibration code. The article describes the method of determining the path of a specified width and distance from the wall of a building, curb, etc., along which a blind person should move. The article additionally describes the method of determining the orientation of a blind person depending on the selected object. Such a method facilitates verifying whether the visually impaired person is moving according to the indicated direction. The method can also be used to navigate mobile robots. Due to the use of natural energy for data registration and processing, the mobile navigation system can be operated for a long time without the need to recharge the battery.

Key words: blind/visually impaired person; GPS; infrared matrix; infrared sensors; low-energy measurement systems; mobile robots; satellite navigation; thermal navigation.

1. Introduction

It is currently estimated that there are 253 million people in the world with visual impairments, including about 36 million completely blind people [1]. The number of the blind is expected to increase three times by 2050 [2].

Currently, there are many solutions and finalized projects which are aimed at helping the blind to move safely in an urban environment. An interesting project is a solution enabling the navigation of the blind in an urban environment with the application of a combination of sensors [3], e.g. a gyroscope, camera, and GPS. Such a solution makes it possible to increase the accuracy of determining the position of a blind person to below 2 m. An illustrative solution is a system of navigation of a blind person by means of RFID tags [4] placed along a selected path. Another example is the use of ultrasonic sensors [5], e.g. placed in a white cane [7, 8] or on a blind person [8] to detect obstacles around them. Another approach to helping the blind is the solution described in article [9], which allows a caretaker to remotely navigate a blind person under their care by making use of the transmission of an image over the Internet to the caretaker from a video camera placed in front of the blind person, which is followed by transmitting voice messages to the blind person. Such a solution enables one caretaker to help a number of blind persons to move around. Most of the available solutions for the navigation of blind people are based on the GPS, which facilitates determining the position of a blind person with an accuracy of a few meters.

This accuracy is sufficient for healthy people to move around the city efficiently and safely. Such people, using their eyesight, can accurately determine their position in relation to the surrounding objects, such as roads or buildings. A blind person is not able to determine their exact position when moving. The proposed solution is to employ an infrared sensor in the form of a simple and small infrared matrix placed in a single casing in order to determine the position of a blind person in relation to the nearby building or pavement edge. The original idea of navigating the blind by means of infrared sensors has already been briefly described by the authors [10]. It allows us to determine the precise distance between a blind person and a selected object. The proposed solution, due to the use of an infrared sensor in the form of a simple infrared matrix, facilitates accurate determination of the distance between a blind person and an object. Additionally, with this solution, it is possible to determine two distances from a selected object, which would determine a path of a constant width, along which a blind person should move so as to maintain a constant and safe distance from the edge of the road or building. The application of an accelerometer and gyroscope additionally facilitates determining the orientation of a blind person in relation to a selected object and provides the information about the direction of movement in relation to the selected object (moving away or approaching the object). An additional feature of the temperature sensor is the

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possibility to detect a threat to a blind person, e.g. in the form of hot elements or fire [11].

Equation (1) describes the total radiated power measurement by the camera. The radiation received by the camera lens comes from three sources [12]:

- Emission from the object $\varepsilon\tau\sigma T_{obj}^4$,
- Reflected emission from ambient sources $(1-\varepsilon)\tau\sigma T_{amb}^4$,
- Emission from the atmosphere $(1-\tau)\sigma T_{atm}^4$,

$$W_{cam} = \varepsilon\tau\sigma T_{obj}^4 + (1-\varepsilon)\tau\sigma T_{amb}^4 + (1-\tau)\sigma T_{atm}^4, \qquad (1)$$

where:

ε – object emissivity,
τ – transmission through the atmosphere,
σ – Stefan-Boltzmann constant,
T_{obj} – the temperature of the object,
T_{atm} – the temperature of the atmosphere,
T_{amb} – the temperature of the ambience.

Objects encountered when moving, e.g. a road, wall, or pavement, are made of different materials, characterized by different emissivity factors, and often having different temperatures, so that the infrared sensor can determine the line separating two objects with different temperatures, i.e., the ground and the wall of the object/building. Then, knowing the position of the line on the image generated by the infrared matrix sensor and with the use of the geometry laws, it is possible to determine the position of a blind person in relation to the selected object. The use of infrared sensors to measure the distance enables the construction of a system that allows us to save energy in comparison with a system built based on a classic optical or laser sensor, at the same time facilitating the measurement of the distance. The thermal radiation of the ground and nearby objects is a measurement signal obtained absolutely for free. Therefore, no measuring signal generator is used. This means that we use a zero-energy generator which greatly reduces the total amount of energy consumed by a mobile device. This makes it possible to save a lot of the energy consumed by the emission of the measurement signal, e.g. a laser. As a result, the mobile device works longer without frequently recharging its battery. The proposed solution does not require any changes in the urban environment, is independent and can be used in numerous locations. The advantages of this solution are its low cost and easy implementation of the project.

Currently, there are a lot of solutions that allow people and objects to navigate without introducing adjustments in the environment with a particular solution in mind. In industry, AGV (Automated Guided Vehicle) is the term used to describe robots that move autonomously. These are vehicles that are fully independent of the environment in which they move around and that use only their own sensors for navigation purposes. At present, such solutions are also implemented in cars. They are integrated into systems called ADAS (Advanced Driver Assistance Systems), which enable more and more autonomous movement of vehicles using exclusively their own sensors. A good example is detecting pedestrians on the road at night with an infrared camera [13]. A similar solution has been implemented in AGVs to enable detecting pedestrians in the surrounding area.

2. Description of the navigation system for the blind

The navigation system for the blind consists of two basic modules: Sensor Module and Notice Module. The Sensor Module (Fig. 1) is responsible for collecting information about the surroundings and analyzing the collected data. The Notice Module (Fig. 2) is intended for generating warnings and messages for a blind person.

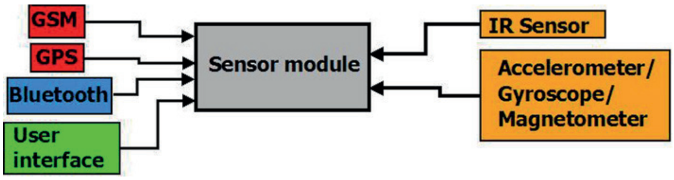

Fig. 1. The block diagram of the Sensor Module

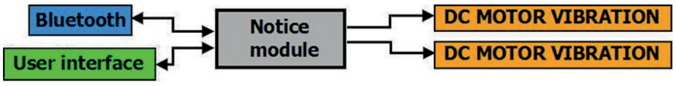

Fig. 2. The block diagram of the Notice Module

The Sensor Module consists of a GPS module for reading the position of a blind person and a GSM module for sending or receiving messages, e.g. from the caretaker of a blind person. To determine the distance between the blind person and the selected object, an infrared sensor matrix with a resolution of 160×120 and a FOV (Field Of View) angle of 25×19 is applied. Furthermore, to correct the image obtained from the IR sensor matrix, a 3-axis accelerometer with a 3-axis gyroscope has been employed. The communication between the Sensor Module and the Notice Module is based on Bluetooth technology. By means of this transmission, messages are sent to the Notice Module. In the Notice Module, messages are converted into appropriate signals generated by vibration motors placed on a wristband.

The position of the modules on the arm is illustrated in Fig. 3. The module sensor is placed on the blind person's arm so that the infrared sensor is directed quasi-perpendicularly to the selected object, e.g. a wall along which a person is moving. Currently, there are many available solutions for providing information to the blind.

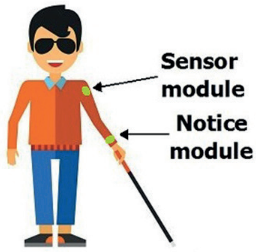

Fig. 3. The arrangement of the modules on the arm of a blind person

An example is a thermal tablet [14] from which a blind person can read the information. Another example is the transmission of the information to a blind person in the form of vibrations [15, 16]. The Notice Module was placed on the wrist. Thanks to the built-in vibration sensors, the blind person receives appropriate messages enabling them to move along the chosen route.

3. Method of distance measurement with an infrared sensor

By means of a matrix infrared sensor (hereinafter referred to as an infrared sensor) placed on the arm of a blind person, we can determine a safe path along which a human should move, for example, in relation to the edge of a road or the wall of a building. In order to determine this safe path, it is necessary to determine two border distances *D1* and *D2* from the selected object in relation to which the person should move. A blind person at the *D* distance from the wall is presented in Fig. 4.

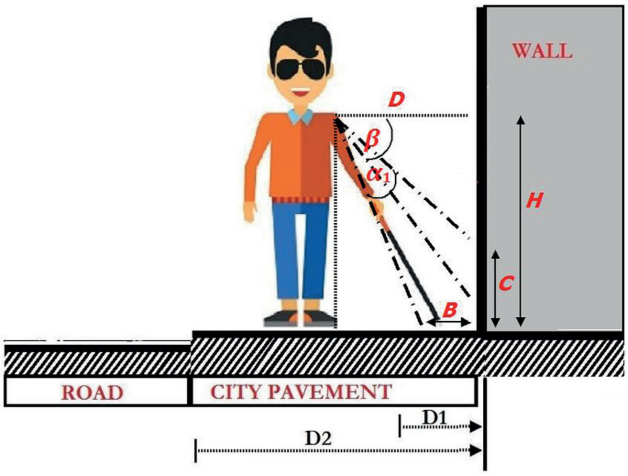

Fig. 4. The safe path for a blind person

In order to determine the above-mentioned distances, it is necessary to know the height of the sensor in relation to the ground surface H, the measurement angle of the infrared sensor α_1 and the angle of the sensor's inclination in relation to the ground β. Using Fig. 4, the following geometric dependencies are calculated:

$$\operatorname{tg}\left(\beta - \frac{1}{2}\alpha_1\right) = \frac{H - C}{D}, \tag{2}$$

$$\operatorname{tg}\left(90° - \beta - \frac{1}{2}\alpha_1\right) = \frac{D - B}{H}, \tag{3}$$

$$X = \frac{B}{C}, \tag{4}$$

where X is the ratio measured in the number of pixels from the infrared sensor image (Fig. 5).

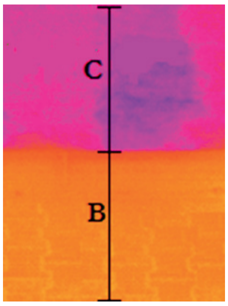

Fig. 5. The image from an infrared sensor with a resolution of 160×120 presents different temperatures or emissivity factors of the wall and the ground

Using Eqs. (2–4), we derive the equation:

$$D = \frac{H\left(X + \operatorname{tg}\left(90° - \beta - \frac{1}{2}\alpha_1\right)\right)}{1 + X\operatorname{tg}\left(\beta - \frac{1}{2}\alpha_1\right)}. \tag{5}$$

Assuming, for example, the resolution of the infrared sensor of 160x120, the angle $\alpha_1 = 19°$, the height of the sensor $H = 1.20$ m and the angle of inclination of the sensor in relation to the ground β, the minimum and maximum distance which may be measured with the sensor at certain parameters can be determined.

The theoretical measuring range of the infrared sensor for the specified β angles is illustrated in Fig. 6. For each of the β angles, we may read the minimum and maximum distance which can be determined at a given angle.

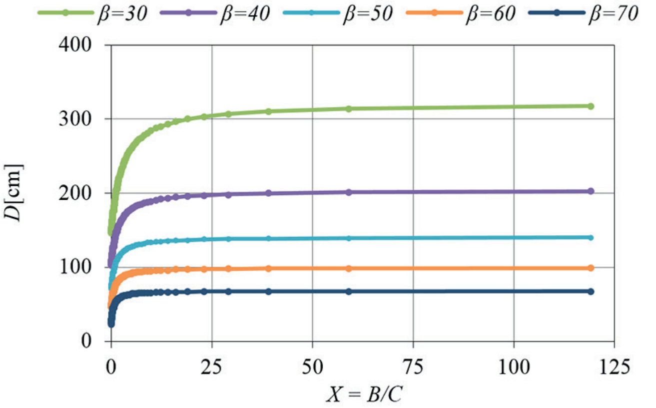

Fig. 6. The range of distance calculated from (5) for different β angles

By increasing the inclination of the sensor in relation to the ground, the maximum distance and the range of distances which can be measured are reduced and, at the same time, the minimum distance for a fixed angle is decreased, e.g. for the angle $\beta = 30°$, we measure a distance within the range of 145 cm and 310 cm and for $\beta = 50°$, a distance between 70 cm and 140 cm.

To increase the range of distance measurement for the fixed β angle, it is necessary to place the sensor at a higher height H or to use a sensor with a higher measurement angle FOV α_1. The use of a sensor with a larger FOV angle α_1 additionally allows us to measure smaller distances at a constant angle of inclination.

In order to determine a safe path for the blind along which they can move, e.g. $D1 = 50$ cm and $D2 = 90$ cm, it is necessary to determine the range from $X1$ to $X2$ resulting from the extreme distances $D1$ and $D2$. For this purpose, we transform Eq. (5) to calculate the value of X:

$$X = \frac{D - H\mathrm{tg}\left(90^\circ - \beta - \frac{1}{2}\alpha_1\right)}{H - D\mathrm{tg}\left(\beta - \frac{1}{2}\alpha_1\right)}. \tag{6}$$

Assuming that the sensor is placed at the height $H = 120$ cm, and at the angle $\beta = 60°$, the blind person should move between the distances $D1$ and $D2$ for the value $X \in [0.09; 4.14]$. The maximum range of X values for the specified angle of inclination and the range of X values for $D1$ and $D2$ are depicted in Fig. 7.

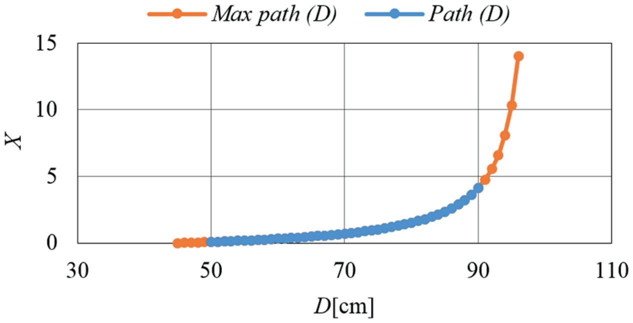

Fig. 7. X for a safe path (blue) and for the maximum safe path (orange)

4. Change of resolution with distance adjustment

As the distance between the sensor and the examined object increases, the value of X is increased by increasing the value of B and decreasing the value of C (Fig. 5). The variable B is defined as the number of pixels read from the infrared sensor images for which the substrate temperature is measured. The appropriate C value is the number of pixels for which the temperature of the object is measured. With a change of the distance and angle of inclination of the sensor in relation to the ground β, the resolution of the measurement changes. The relation between the measurement resolution and the value B for different angles of inclination of the sensor in relation to the ground β is presented in Fig. 8.

From Fig. 8, it can be seen that for the $\beta = 55°$ we obtain an almost constant increase in the distance with the increase of B by one unit (pixel). This increase is about 0.50 cm. This increase also means the measurement resolution at which we can determine the distance successfully. For the inclination $\beta < 55°$, an increase in the value B leads to a decrease in the measurement resolution. For an inclination $\beta > 55°$, the measurement resolution slightly increases with an increase in B.

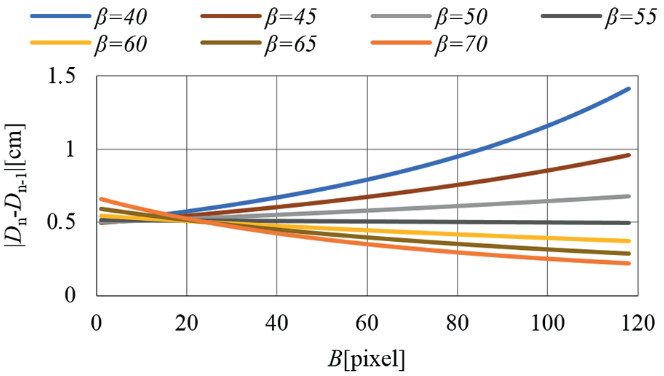

Fig. 8. The measurement resolution of the distance for different β angles

5. Correction the movement direction in relation to an object

To determine if a visually impaired person is moving parallelly to a building or road, an infrared image is applied. Two situations are presented in Fig. 9. Assuming that the infrared sensor is placed on the blind person's arm, in Case 1, the sensor is directed perpendicularly to the wall surface, which means that the blind person is walking parallelly to the wall. The temperature change line in the image obtained from the infrared sensor shows that the boundary between the object and the ground is horizontal. When distancing or approaching the object (Case 2), the line separating the ground temperature from the object temperature has an increasing (for moving away) or decreasing (for approaching) characteristic.

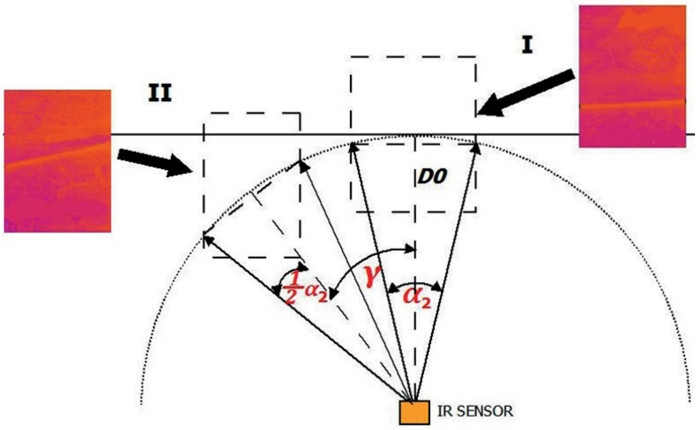

Fig. 9. The description of the movement the blind person direction in relation to an object; top view

For Case 2, Fig. 10 shows an infrared image in the case of a blind person moving away from the selected object. The method of determining the correction of the movement direction in relation to the object is presented in Fig. 10,

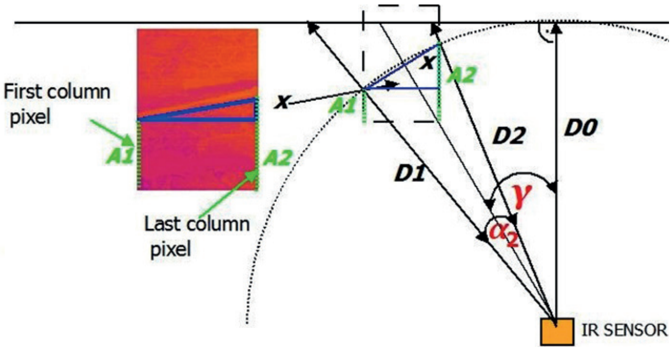

Fig. 10. The method for correcting the movement direction of the blind person in relation to the object by an infrared sensor

where

γ – the angle of the sensor displacement in relation to the selected object
α_2 – the measurement angle of the infrared sensor
$D0$ – the distance between the sensor and the object for $\gamma = 0°$
$D1$ – the distance between the sensor and the object for an angle: $\gamma + {}^{1}\!/_{2}\,\alpha_2$
$D2$ – the distance between the sensor and the object for an angle: $\gamma - {}^{1}\!/_{2}\,\alpha_2$
$A1$ – the first column of pixels at the infrared sensor image
$A2$ – the last column of pixels at the infrared sensor image

Based on Figs. 9 and 10, the distances *D1* and *D2* can be calculated:

$$\cos\left(\gamma - \frac{1}{2}\alpha_2\right) = \frac{D1}{D2}, \tag{7}$$

$$\cos\left(\gamma + \frac{1}{2}\alpha_2\right) = \frac{D0}{D1}. \tag{8}$$

Hence, from Eqs. (7–8), γ can be calculated:

$$\gamma = \operatorname{arctg}\left(\frac{D2 - D1}{D2 + D1}\operatorname{ctg}\left(\frac{1}{2}\alpha_2\right)\right), \tag{9}$$

where

$$D1 = \frac{H\left(\frac{B_1}{C_1} + \operatorname{tg}\left(90° - \beta - \frac{1}{2}\alpha_1\right)\right)}{1 + \frac{B_1}{C_1}\operatorname{tg}\left(\beta - \frac{1}{2}\alpha_1\right)}, \tag{10}$$

$$D2 = \frac{H\left(\frac{B_2}{C_2} + \operatorname{tg}\left(90° - \beta - \frac{1}{2}\alpha_1\right)\right)}{1 + \frac{B_2}{C_2}\operatorname{tg}\left(\beta - \frac{1}{2}\alpha_1\right)}. \tag{11}$$

In Eqs. (10, 11), the values of the distances *D1* and *D2* are calculated with Eq. (5). The numbers of pixels *B1* and *B2* are read as *A1* and *A2*, respectively, according to Fig. 11. The values *A1* and *A2* are read as the number of pixels in the first and last column from the infrared sensor image.

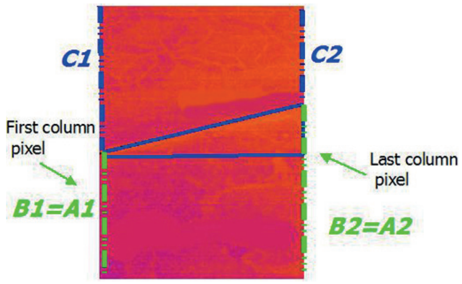

Fig. 11. An infrared sensor image with *B1* and *B2* marking

The plots in Figs. 12 and 13 were made for example data ($H = 100$ cm and $D = 80$ cm).

Figure 12 illustrates the dependence of *A1* and *A2* on the shift γ angle for method presented in Figs. 9 and 10. The variables *A1* and *A2* take the minimum value for $\gamma = \pm{}^{1}\!/_{2}\,\alpha_2$.

The difference the γ angle versus $\Delta A = A1 - A2$ calculated from (9) is provide in Fig. 13. Using the differences ΔA, we can calculate the angle between the blind person and the object

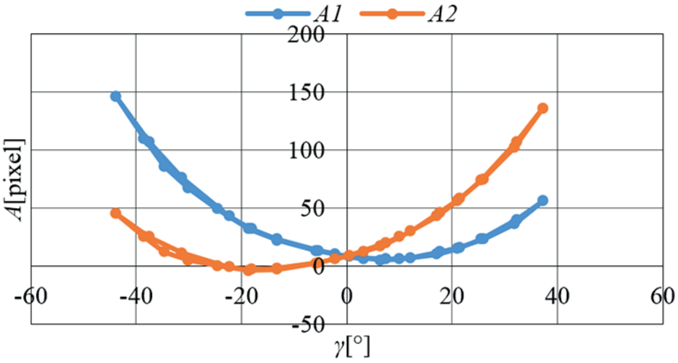

Fig. 12. The *A1* and *A2* dependencies on the γ angle from method described in Figs. 10 and 11

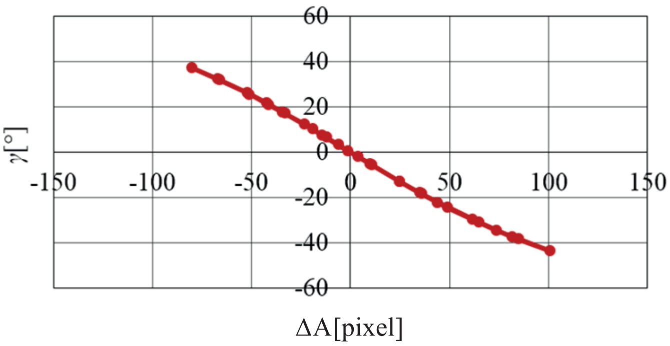

Fig. 13. The γ angle for the value obtained from the theoretical value

and determine if the person is moving parallel to the object, approaching it, or moving away. Assuming that the infrared sensor is set in an exactly perpendicular position to the object ($\gamma = 0°$), the value of ΔA should be equal to zero. For $\Delta A = 0$, the blind person sets and moves parallel to the selected object.

For $\Delta A > 0$, the blind person moves away from the selected object, and for $\Delta A < 0$, the blind person approaches the selected object.

6. Determination of the distance and the approach angle depending on the movement of the arm

We assume that the infrared sensor is placed on the arm of a blind person. In order to precisely determine the correction of the movement direction (γ) in relation to an object, it is necessary to determine the angle of inclination of the sensor resulting from the arm's movement forwards and backwards, performed cyclically during a walk or run. In Fig. 14, the sensor and the frame are directed perpendicularly to the ground surface.

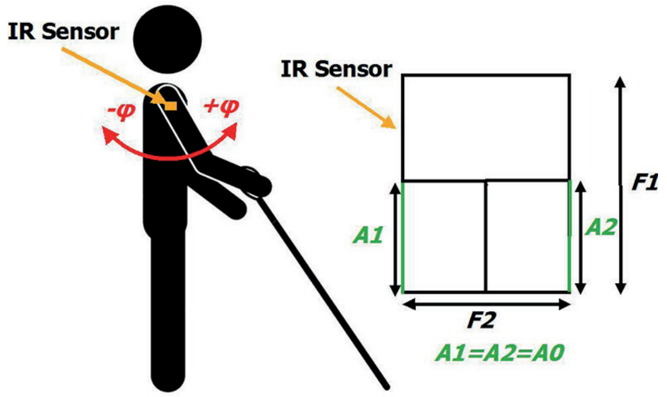

Fig. 14. The perpendicular position of the sensor and the arm to the ground surface

The values *A1* and *A2* are equal and the same as *A0*. *F1* and *F2* represent the resolution of the infrared sensor image and amount to 160 and 120 pixels, respectively. The value *A1* and *A2* depends on the φ angle and can be determined by Eqs. (12, 13):

$$A1 = A0 - \frac{F2}{2}\,\mathrm{tg}(\varphi), \tag{12}$$

$$A2 = A0 + \frac{F2}{2}\,\mathrm{tg}(\varphi). \tag{13}$$

As the arm moves forwards, the sensor leans out by an $+\varphi$ angle. For the backward movement of the arm, the angle is negative.

When the arm is leaned forwards (Fig. 15 on the left) with φ, the value *A1* is reduced and the value *A2* is increased according to the inclination angle.

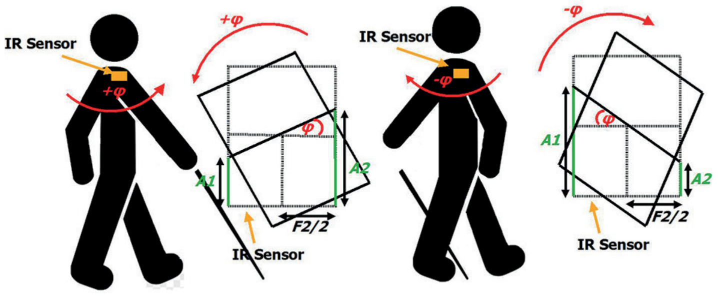

Fig. 15. Left – leaning the arm forwards, right – leaning the arm backwards

In Fig. 15 on the left, which presents the dependence of *A1* and *A2* on the γ angle, the forward movement of the arm can be observed by shifting the diagram *A2* upwards in relation to the diagram *A1*.

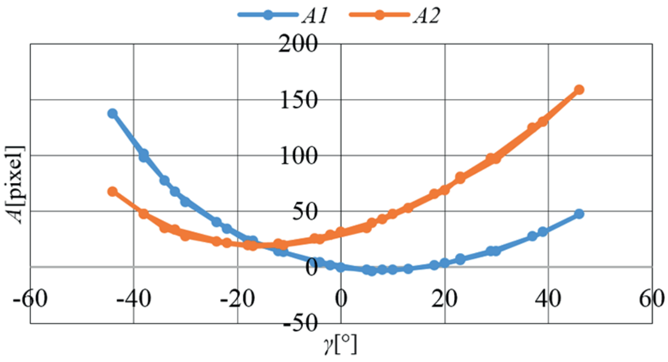

Fig. 16. Diagrams *A1* and *A2* for the arm leaning forwards

If the arm is leaned backwards (Fig. 15 on the right) at the $-\varphi$ angle, the value *A1* increases and the value *A2* decreases according to the inclination angle.

The values *A1* and *A2* depend on the φ angle and can be determined by Eqs. (14, 15):

$$A1 = A0 + \frac{F2}{2}\,\mathrm{tg}(\varphi), \tag{14}$$

$$A2 = A0 - \frac{F2}{2}\,\mathrm{tg}(\varphi). \tag{15}$$

The backward movement of the arm can be observed by shifting Diagram *A1* upwards in relation to Diagram *A2* in Fig. 17, which presents the dependence of *A1* and *A2* on the γ angle.

The sensor's inclination angle (φ) influences the estimation of the direction of a blind person's movement in relation to the object. In order to precisely determine the position in relation to the object and to estimate whether such a person is moving parallelly to the object, it is necessary to consider the position of the sensor in relation to the ground surface. Leaning the arm

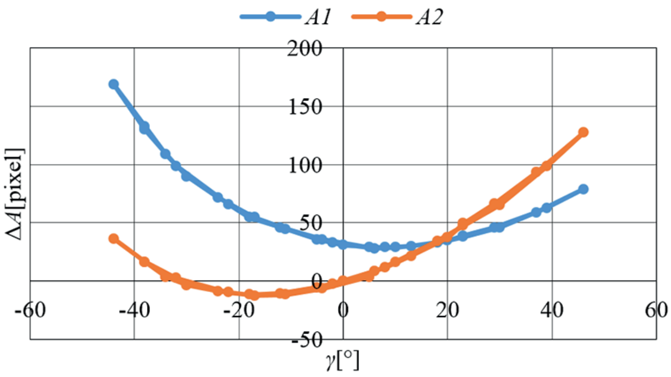

Fig. 17. Diagrams *A1* and *A2* for the arm leaning backwards

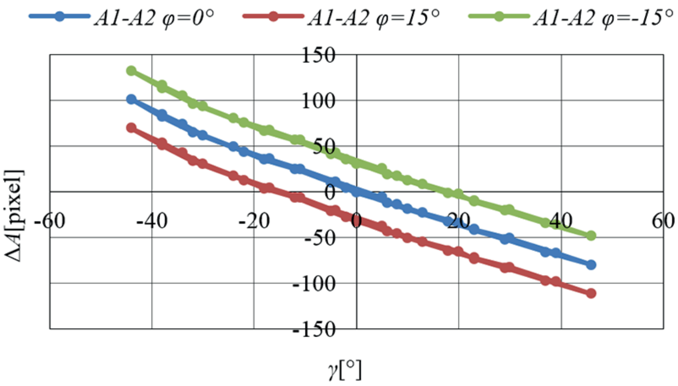

Fig. 18. ΔA for different φ angles

forwards or backwards causes a corresponding parallel shift of the diagram *A1-A2* downwards or upwards (Fig. 18). For the position of the sensor perpendicular to the ground surface, *A1-A2* is zero for $\varphi = 0$.

7. Testing and measurement results

Two photos taken while testing the proposed solution are presented in Fig. 19. The photo on the left shows the location of the modules on the human body when testing the navigation system. The photo on the right was taken with a thermal camera and shows the temperature difference between the ground and the object. For measurement, an infrared sensor matrix was used with a resolution of 160×120 and the FOV angle of 25×19. For correcting the infrared sensor's position, a 3-axis accelerometer and a 3-axis gyroscope were used.

The measurements below were made between the western wall (the object) and the pavement made of paving bricks (the ground). The conditions during the measurements were as follows: the temperature 6°C, heavy overcast, and daylight. During the measurements, the sensor was attached at the height of $H = 100$ cm and directed perpendicularly to the wall. The inclination angles and the angles of the arm's movement were corrected using an accelerometer and gyroscope in real time.

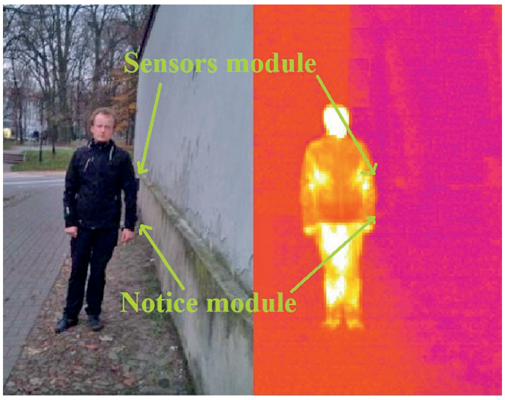

Fig. 19. Pictures taken during tests of the navigation system (on the left made with a video camera, on the right made with an infrared camera)

An electric circuit diagram and a photo of the notice module are shown in Fig. 20. An electric circuit diagram and a photo of the sensor's module are presented in Fig. 21.

7.1. Distance measurement using an infrared sensor. An overview of the distance D determined during the measurement for various β angles is shown in Fig. 20. The distances determined by the infrared sensor are marked with a continuous line and calculated using Eq. (5). The reference distances measured with a measuring tape with a resolution of 1 cm were marked with a dashed line. The average error in determining the distance for the obtained measurements equals 7.1 cm. Excluding the distance measurement for the angle $\beta = 30°$ as a gross error, the distance measurement error equals less than 6 cm.

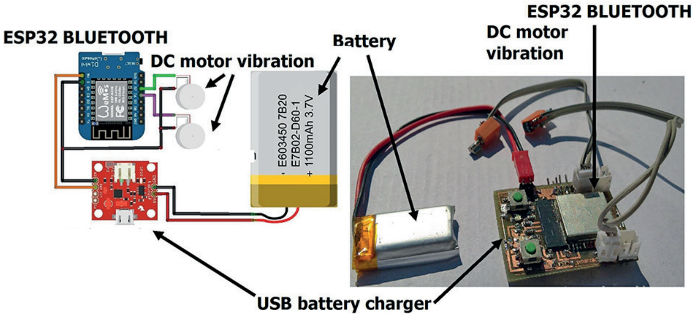

Fig. 20. Electric circuit diagram of the notice module

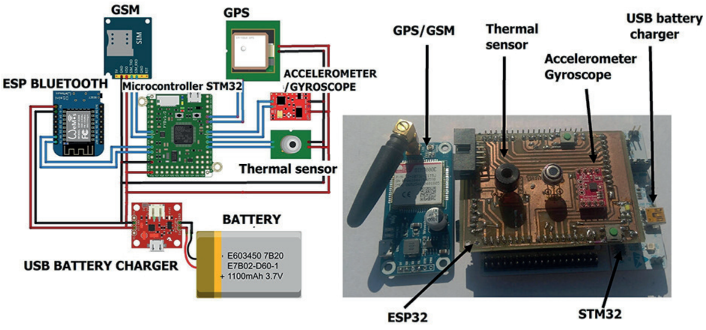

Fig. 21. Electric circuit diagram of the sensors module

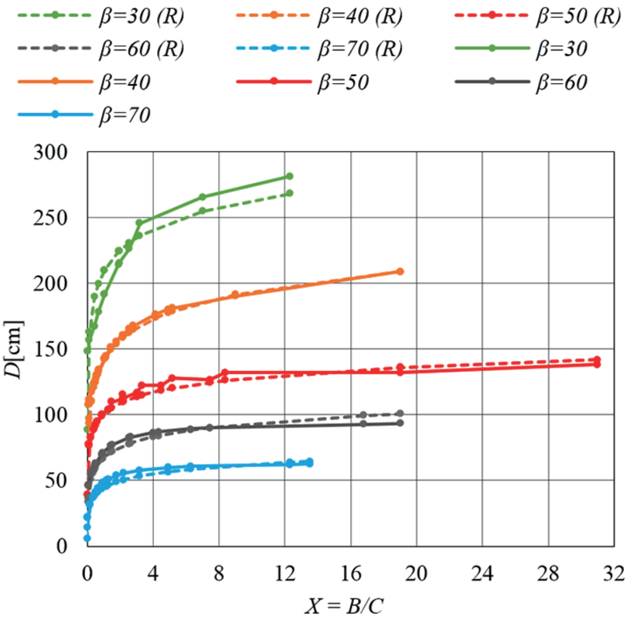

Fig. 22. The results of the distance D measurement, the continuous line – values determined by the infrared sensor, the dashed line – reference values

7.2. Direction measurement using an infrared sensor. The relation between the γ and the values of $A1$ and $A2$ is shown in Fig. 23. The plots in Figs. 23 and 24 were made for $H = 110$ cm and $D = 77.5$ cm. The γ angle was calculated using an infrared sensor.

A digital gyroscope with an accuracy of 1° was employed to measure the reference values of γ. The measurement was taken for the γ in the range from $-45°$ to $35°$. The relation between the γ angle and the value ΔA read from the infrared sensor for the data obtained during the measurements and the data calculated based on Eq. (9) is shown in Fig. 20. In addition, the figure includes a diagram of the difference between the γ angle determination for the data obtained during the measurements and the data calculated based on Eq. (9). The average error of determining the γ angle with Eq. (9) from the infrared sensor image ($A1$ and $A2$) is approximately 2°.

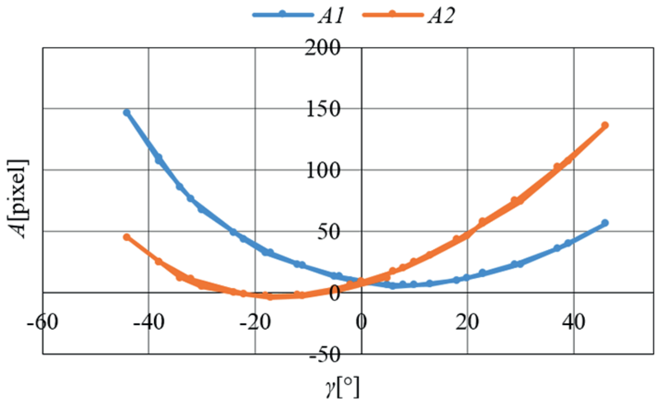

Fig. 23. The $A1$ and $A2$ for the data obtained during the measurements

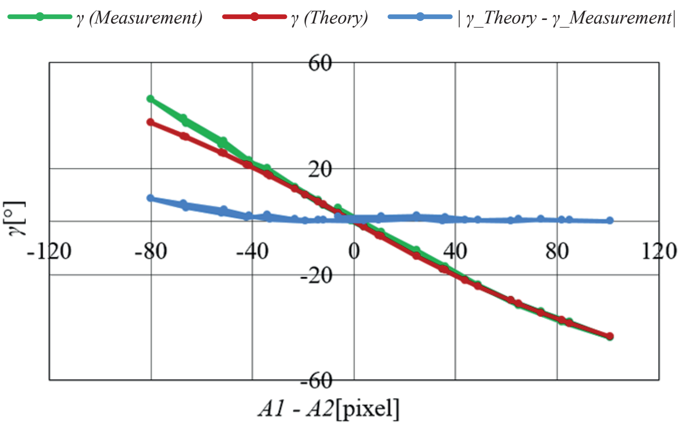

Fig. 24. The γ angle versus ΔA for the measurement data and calculated data from (12)

From Eqs. (9–11), it can be noticed that the value of γ does not depend on the height H of placing the sensor above the ground level. The dependence of ΔA on the γ angle for different heights of the sensor's placement above the ground for the data obtained from the measurements is shown in Fig. 20.

The γ angle depends on the distance between the sensor and the selected object and the β angle of the sensor's inclination in relation to the ground. ΔA is shown in Fig. 26 as a function

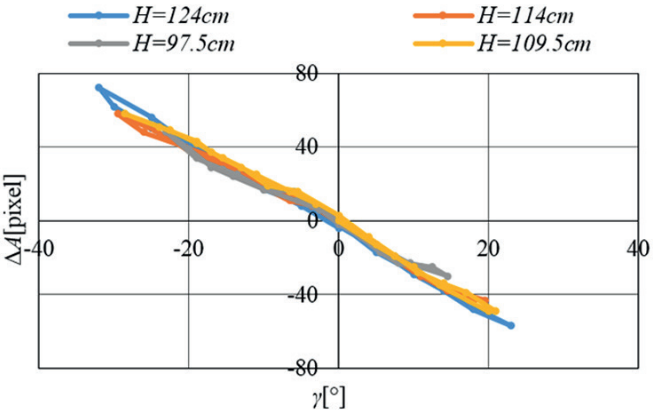

Fig. 25. ΔA versus γ for different H

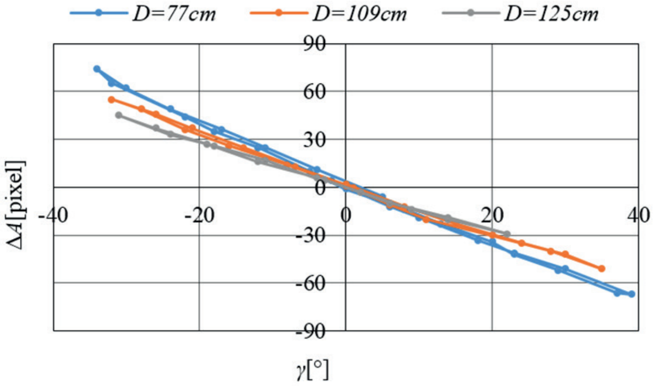

Fig. 26. ΔA with variation in the γ angle for different distances D

of γ for different distances D of the sensor from the selected object, for the data obtained during the measurements.

8. Assessing measurement performance for different weather conditions

To determine the environmental conditions under which the proposed method is applicable, a measuring station was built, enabling continuous measurement of the temperatures of the ground and the object. The temperature measurement was made with a contact temperature sensor (thermal conductivity) and with an infrared sensor (thermal radiation). The measurement was made for a number of locations throughout the whole day. In Figs. 27 and 28, a sample measurement of the temperature between the pavement made of paving bricks and the southern wall with a rough surface (dry surface) can be seen. The situation during the measurement when the day starts approximately at 7 am and ends at 4 pm, with the sky fully overcast is illustrated in Fig. 27A. Throughout the day, a temperature difference of approximately 0.5°C related to different emissivities of the measured materials could be observed. With an increase in the temperature during the day (Fig. 27B), the temperatures of the ground and the object also rose. The increase in the temperature of the ground was faster in comparison with that in the temperature of the ground, which was connected with the thickness and thermal conductivity of the materials of which the ground and the object were made.

With an increase in the temperature and the amount of light during daytime, the temperature difference Delta_PIR measured by infrared sensors increased to approximately 1°C.

The measurement illustrated in Fig. 28 was made in the same place as the previous measurement and the insolation of the object and the ground was even.

The temperature difference at night was equal to approximately 0°C, and for the infrared sensors it was approximately 0.5°C. During the day, a sudden increase in the temperatures of the object and the ground occurred, which was due to

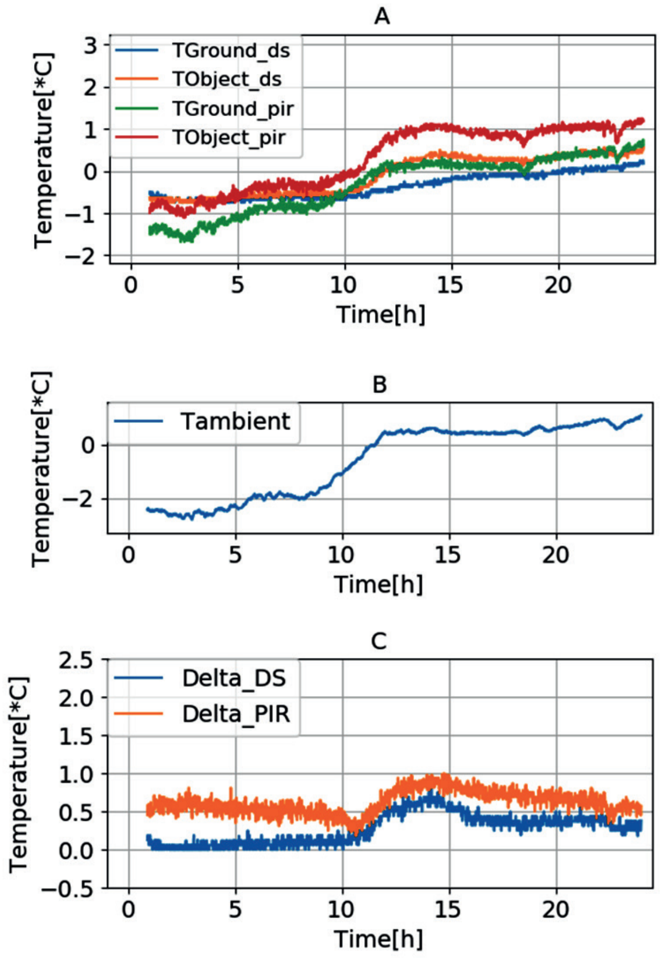

Fig. 27 Measurement of the temperature difference between the wall and the object by the measuring station on a cloudy day: A) Measurement of the temperature of the ground and of the object, using infrared sensors (pir) and temperature sensors (ds); B) Measurements of the air temperature; C) The temperature difference measured with the infrared sensors (Delta_PIR) and the temperature sensors (Delta_DS)

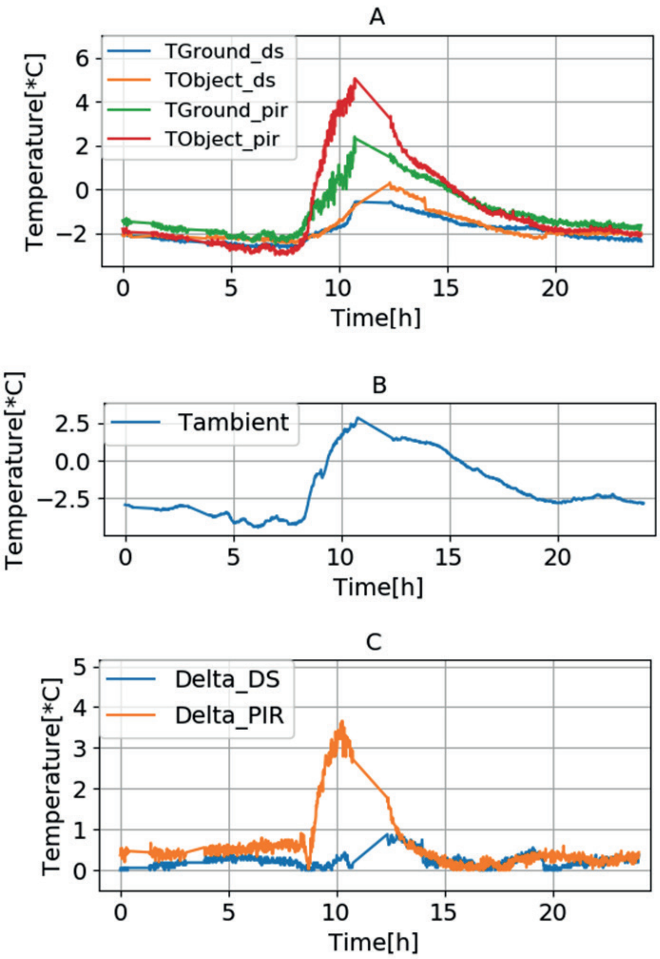

Fig. 28 Measurement of the temperature difference between the wall and the object by the measuring station on a sunny day: A) Measurement of the temperature of the ground and of the object, using infrared sensors (pir) and temperature sensors (ds); B) Measurements of the air temperature; C) The temperature difference measured with the infrared sensors (Delta_PIR) and the temperature sensors (Delta_DS)

direct insolation by sunlight. During the day, the temperature increases of the object measured by each of the sensors was much higher than that of the ground. A faster temperature rise of the object was caused by a lower thermal conductivity of the material of which the object was made. Based on the measurements made for different locations and objects, it can be concluded that, in most cases, there is a temperature difference measured by the infrared sensors and, provided that the air temperature during the day and night is constant, it is mainly due to different emissivities of the materials of which the object and the ground were made. The temperature difference Delta_PIR additionally increases if the temperature during the day changes or in the case of even insolation. Problems occur when the object is partly shaded or partly lit by sun rays, since a distance error appears, which is due to the occurrence of the temperature difference Delta_PIR between the well-lit and shaded areas. The suggested solution is to detect such spots with ambient light sensors and maybe to neglect such a measurement.

9. Power consumption

Table 1 presents a comparison of the average power supply for different types of sensors used for determining the distance and spatial orientation of a blind person. To be able to determine a safe distance between a blind person and a selected object, e.g. a wall, it is sufficient to make a single measurement of one constant distance, using two-point sensors described in [10], and therefore distance measurement with the application of two-point sensors is the most energy-efficient of all the methods included in Table 1. By vertically increasing the number of infrared sensors, we are able to obtain a more accurate linear measurement and a higher number of measuring points. A matrix consisting of 1×160 measuring points is sufficient to obtain an accurate linear measurement. Additionally, in order to consider a person's spatial orientation in relation to a selected object, it is necessary to add two vertical rows of measuring points, which leads to creating 3×160 matrices.

Table 1
Comparison of different types of distance sensor

Type of sensor	Average Power Consumption [mW]	Number of measurement points	Computational complexity
Infrared sensor (×2)	14	1	small
Time-of-Flight	53	1	small
Infrared array sensor	98	160	small
Ultrasonic distance sensor	75	1	Small
VGA camera	80	depends on the measurement method	Large
IR sensor (with LED-IR)	36 + 100 (LED-IR)	1	Small

Table 1 also presents the computational complexity required during the operation of each sensor. The highest computational complexity is required for image analysis in the case of a digital camera, and this solution also leads to a higher power consumption by the microcontroller. Using infrared sensor matrices, we obtain a filtrated infrared image void of unnecessary details (e.g. lettering, colours), which results in a lower computational complexity and a lower power consumption by the microcontroller. The commercially available 120×160 matrix consumes approximately 98 mA. Using a 3×160 pixel matrix, it is possible to obtain the level of 30 mA, which facilitates the construction of the most energy-efficient sensor characterized by the lowest computational complexity.

The whole system was designed so as to enable its operating on one charge for at least one day (approximately 10 hours). Table 2 presents the average power consumption by the notice module. Energy consumption mostly depends on the number of notifications received by the module. The minimum period between notifications is 2 seconds. Using a 520 mAh (3.7 V) battery with notifications sent every 2 seconds, we obtain the operating time per charge of approximately 10 h.

Table 2
Current consumption by the notice module

Elements	Normal (mA)	Sleep (mA)	Average consumption (mA)
DC vibration motor ×1	122	1	53
Esp32	78 (received)	3	

Table 3 illustrates the power consumption by the sensor module. The system sends up to one notification to the notice module every two seconds. The information about a blind

Table 3
Current consumption by the sensor module

Element	Normal (mA)	Sleep (mA)	Average consumption per element (mA)
ESP32	120 (transmit)	3	32
STM32	44	<1	44
Accelerometer/ gyroscope	3.7	<1	3.7
GSM	11 (idle)	1.48	2
GPS	30	6	30
IR sensor	98	2	26.5
Other elements	10	–	10
Total consumption			148.2

person is transmitted by a GSM network to the caretaker on request or periodically at certain time intervals. A cell of 3000 mAh in capacity used to supply the module with power allows for the module operation for approximately 19 h without recharging.

The operating times of the device that are presented above assume the highest energy consumption during navigation. In reality, it is possible to obtain 20–30% longer operating times if carefully selected power cells are used and the amount of the transmitted data is decreased.

10. Conclusion

The employment of an infrared sensor in the form of an infrared matrix allows determining the distance between a blind person and a selected object, such as a wall, with a resolution of less than 1 cm. The resolution depends on the infrared sensor applied and the angle of inclination of the sensor in relation to the ground. From the obtained measurements, it is possible to obtain the accuracy of determining the distance from the object of about 5.5 cm as the worst case. The use of generally available GPS navigation allows us to obtain an accuracy of the position above a few meters. It is an insufficient accuracy for our purpose. With an accuracy of a few meters, a blind person is not able to determine their exact position in the urban environment. Thanks to the combination of GPS navigation and an infrared sensor, it is possible to precisely determine the position, e.g. moving along a path or along a roadway. The precise determination of the position in an urban environment will provide better safety for the blind.

Additionally, the application of an infrared sensor allows us to determine the direction of the movement of a blind person in relation to a selected object. Analyzing the image from the infrared sensor can determine whether the blind person is approaching or moving away from the selected object. From the obtained measurements, it is possible to obtain an accuracy of 2° when determining the angle between the blind person and the selected object. Knowing the direction of the blind person's movement in relation to the selected object, vibration sensors can be used to direct the blind person in such a way that they move parallel to the selected point, e.g. a sidewalk curb or a building wall.

The system is coupled with a gyroscope and accelerometer that enable us to compensate the movement of the arm when the distance is being calculated by the infrared matrix. Unlike other sensors (e.g. an ultrasonic sensor, a laser sensor, etc.), the infrared sensor used employs infrared radiation generated by objects, which enables distance measurement. The infrared sensor does not generate any signals. As a result, the infrared sensor requires much less energy to operate and ensures a longer operation of the battery-powered system.

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