

Physical Field-Enhanced Intelligent Space with Temperature-Based Human Motion Detection for Visually Impaired Users

Jiaoying Jiang¹, Kok-Meng Lee^{1,2(✉)}, and Jingjing Ji^{1(✉)}

¹ State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China
kokmeng.lee@me.gatech.edu, jijingjing@hust.edu.cn

² Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, USA

Abstract. This paper presents a method utilizing temperature field to improve the indoor mobility of the blind/visually-impaired-people (Blind/VIP) in a physical field-enhanced intelligent space (iSpace) that takes advantages of the rapidly developing cloud-computing and personal mobile devices (generally built with sound, image, video and vibration alert capabilities) to share way-finding information among users. A method, which uses temperature fields and their gradients to detect face-orientation and analyze leg-postures for predicting the motion states of other humans in a traveling path, is introduced. The concept feasibility of the temperature-based human motion detection has been experimentally validated in a simulated school environment for the Blind/VIP where users are generally familiar with stationary objects but less confident in daily walking in a crowd where human motion is unpredictable. The experimental findings presented in this paper establish a basis for developing temperature field-enhanced iSpace.

Keywords: Temperature field · Motion detection · Blind/VIP

1 Introduction

Rapid advances of cloud-computing, along with the wide availability of personal mobile devices (capable of computing, communication and control, digital imaging, and global positioning) at affordable cost, offer potentials to enhance the global perception of the user's surrounds, particularly for people who lost the optical ability to interpret their surroundings. This paper explores the concept of a physical-field-enhanced intelligent space (iSpace) to help overcome some daily problems encountered in a typical school for the Blind/Visually-impaired-people (Blind/VIP). As the use of geomagnetic field effects on magnetic waypoints for way-finding has been discussed and experimentally validated in [1, 2], this paper focuses on developing an avoidance technique based on temperature fields to help the blind/VIP acquire the motion states of other humans along a traveling path around congested areas.

Methods on obstacle avoidance can be classified into human-generated (active) and nature-generated (passive) signals [3] categories for navigation. Active-signal methods

requires an emitter/receiver pair to generate/detect signals (like ultrasonic and sonar) to determine the existence of the obstacles and their locations [4]; they are less sensitive to environmental influences but have limited range of operation. Passive-signal methods (for example, the uses of thermal infrared or optical fields [5, 6] naturally emitted/reflected from the obstacles to estimate the obstacle information), in general, have a potential to offer a low-cost solution. High-resolution imaging systems with advanced algorithms are now widely available in personal digital assistant (PDA) at relatively low-cost. Blind/VIP can share images/videos captured by a wearable camera through internet permitting a remotely guided navigation [7, 8]. More recently, rapid developing social networks (such as Twitter, Facebook and RSS) further enhance the global perception of the surrounding environments [9]. However, these technologies are generally ineffective for close range way-finding by a VIP.

In environments such as a typical school for the Blind/VIP, users are generally familiar with stationary objects but less confident in daily walking in a crowd where human motion is unpredictable. The human body, as a natural heat source, is significant in the infrared thermogram. For this reason, we explore the uses of thermal infrared to develop a temperature-based human motion detection. Temperature field is also a widely available physical field in nature and can be measured using infrared thermal imager; Applications include nondestructive testing [10, 11] (for detecting cracks, delamination and other defects), temperature map for supersonic wind tunnel testing in field of aerospace [12], temperature field reconstruction for monitoring tool wears in cutting [13] and diagnosing diseases [14, 15] in medicine.

The remainder of this paper offers the following:

- The concept of physical field enhanced intelligent space for the Blind/VIP is presented, where physical information based on temperature and magnetic fields is embedded in a navigation map.
- A method for detecting human motion state by using the temperature fields and their gradients is proposed. The infrared band (instead of the visible light band) with physically intuitive heat transfer model is exploited to simplify the detection of the face orientation, which provides a basis to determine the motion states of other humans in a traveling path.
- The concepts of the temperature-based face-orientation detection and leg-posture analysis have been experimentally illustrated and validated in a test environment simulating a Wuhan blind school for the Blind. As will be shown, the method effectively detect four different orientations of the face from the measured IR temperature fields, and differentiate the motion states from the leg posture analyzed using image processing routines.

2 Filed Enhanced iSpace for Blind/VIP

Figure 1 illustrates the design concept of intelligent space (iSpace) where geomagnetic and thermal fields are used to enhance building floor maps and complement optical fields commonly used with digital cameras that are now widely available in smart phones. An immediate application of an iSpace is an enhanced environment that helps

the blind and visually impaired people (blind/VIP) users overcome problems encountered in daily way-finding. As an illustrative example and experimental setup, Fig. 1(a) shows the plan view of a teaching building in Wuhan Blind School and the path from the first floor to a classroom on the second floor through a corridor, where the trashcan①, water heater②, staircase handrail③ and iron fence④ along the path are existing ferromagnetic landmarks (or stationary magnetic waypoints) for identifying locations [1, 2]. The blind/VIP is generally familiar with common stationary objects (such as tables, chairs, etc.) in the room, but often find challenging to walk in a crowd; for examples, a person who moves in the same direction is unlikely an “obstacle”, but a person who stands still or moves in opposite or a different direction may likely interfere with his/her walking. An effective method to identify “real barriers” in a crowd, rather than treating everyone as an obstacle, is a common problem to the blind/VIP.

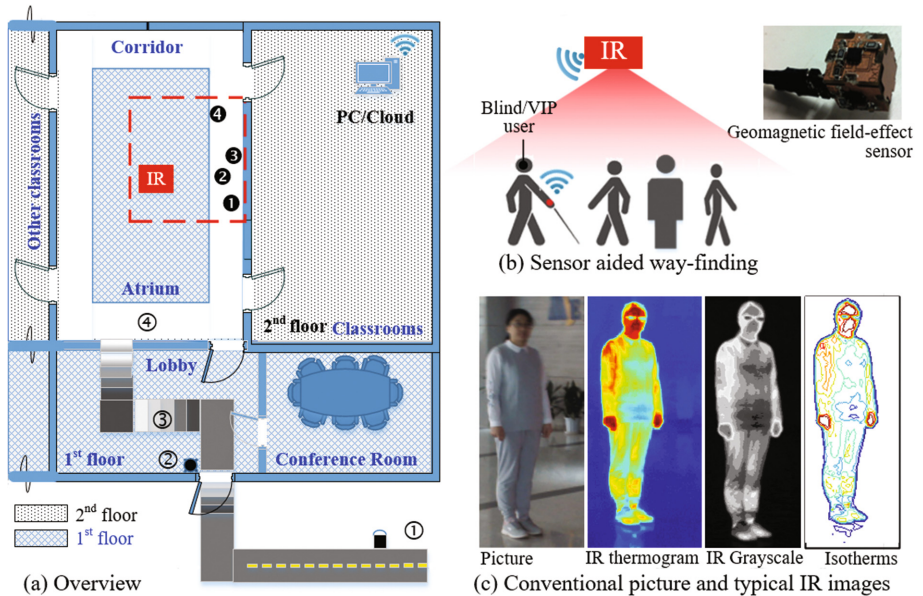


Fig. 1. Schematics illustrating iSpace

Figure 1(b, c) illustrates a real-time temperature-based method to improve the blind/VIP’s perception of the surrounding, where the thermal images were captured using an infrared sensor to identify human bodies and their motion states around the blind/VIP. Unlike a conventional image which includes many other details in the scene making human detection a difficult image-processing task, the thermal image (Fig. 1c) significantly reduces the difficulty of human detection by taking advantages of the fact that human faces’ temperature is generally much higher than the ambient as well as other objects in the surrounding, and can be used to determine his/her walking direction.

The iSpace being built for the blind and VIP users consists of a PC Cloud server (that includes floor maps enhanced with magnetic waypoints and navigation

algorithms) and several infrared (IR) thermal imagers mounted at strategic locations. Once entering the iSpace, the user (with a standard VIP-adapted smart phone and geomagnetic sensor shown in Fig. 1b) communicates with the Cloud server that processes IR images (Fig. 1c) and shares information of other human around the user (through voice or vibration in existing VIP devices) judgment on the surrounding environment. In this paper, a corridor of a Wuhan blind school has been selected for concept-feasibility studies using temperature fields to enhance an iSpace, where the detection of human directions is typical in a relatively clouded space environment. The IR Imager mounted perpendicular to the corridor provides information complement to image data (viewed in the direction of the corridor), which are now widely available in personal mobile device such as a smart phone.

The use of geomagnetic field effects on magnetic waypoints for way-finding has been discussed in [1, 2], this paper focuses on developing an avoidance technique for daily way-finding, which helps the blind/VIP acquire the motion states of other humans along a traveling path particularly around congested areas.

2.1 Infrared Head Temperature Imaging for Face Orientation

IR radiation that corresponds to a wavelength range between visible light and microwave ($0.75 \sim 1000 \mu\text{m}$) has a significant thermal effect. All object in the natural temperature above the absolute zero (-273°C) is constantly emitting infrared rays. The human body is essentially a natural bio-heat source producing heat to maintain the body temperature T at about 37°C with a small range of fluctuations. The normal dry skin of the human body is close to the ideal blackbody surface ($\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$) with an emissivity ε of 0.98 to 0.99, by Stephen-Boltzmann's Law, emitting infrared heat energy $E = \varepsilon\sigma T^4$ which can be received by a detector and converted into digital images representing the thermal characteristics of the human body. Figure 1(c) compares four representations of a human image captured by an IR imager; conventional grayscale "optical picture" that includes many surrounding details in the image background, and IR temperature field presented in pseudo-colors, IR field in grayscale and isotherms. Unlike the grayscale picture (1st from left in Fig. 1c) that requires often tedious and time-consuming filtering and segmentation to identify the human body, the presence of the human body in the IR thermos-gram (2nd from left in Fig. 1c) can be easily identified for subsequent image processing (last from left in Fig. 1c).

The heat transfer mechanism of biological tissue is extremely complex. Given in Eq. (1), the Pennes' heat conduction model 16 that bases on the following assumptions has been most widely used in the study of biological heat transfers: The tissue is a continuous medium; the blood flow is equal to the heat transfer and heat deposition (or heat source) of the tissue; and the local structure and blood flow velocity speed are neglected. Please note that the first paragraph of a section or subsection is not indented.

$$\rho_t c_t \frac{\partial T}{\partial \tau} = k \nabla^2 T + \rho_b w_b c_b (T_b - T) + q_m + q_r \quad (1)$$

In Eq. (1) which can be solved with appropriately defined initial conditions and boundary conditions, ∇^2 is Laplacian operator; (ρ_b , c_t and k) are the (density, specific heat and thermal conductivity) of the tissue; w_b is the blood perfusion rate; T_b is the arterial Blood temperature; ρ_b and c_b are the density and specific heat of the blood, respectively; q_m is the heat production rate of tissue metabolism; and q_r is the external heat source heat. The biothermal model (1) reveals that the surface temperature of the human body is influenced by subcutaneous blood circulation, local tissue metabolism, skin thermal conductivity, skin and environmental temperature and humidity exchange constraints [17, 18]. Thus, the metabolism of various parts of the human body and heat dissipation are different; for examples, the parts with more blood vessels distribution (such as mouth, forehead, sulci nasolabialis, eyes) has a higher temperature than the parts covered by hair [19]. Combined with the infrared thermogram, this feature can be used to identify and determine the face and hence the motion states of the human.

2.2 Motion State from Gradient-Based Face Orientation

The detection of a human consists of two parts; namely, human face, and shape/motion characteristics of the human posture. Because human face can be characterized by a specific temperature range, this can be used to distinguish a human face from other thermogenic objects in the IR image. Once the human face is identified, other body parts can be derived from the overall shapes and motion state of the human in the field of view.

Figure 2 illustrates the theoretical basis orientation using heat transfer models for detecting the face (and hence the motion state of the human). As shown in Fig. 2(a), the human head (particularly the forehead) has a significantly higher temperature than the other parts of the body, and thus can be readily located by means of image

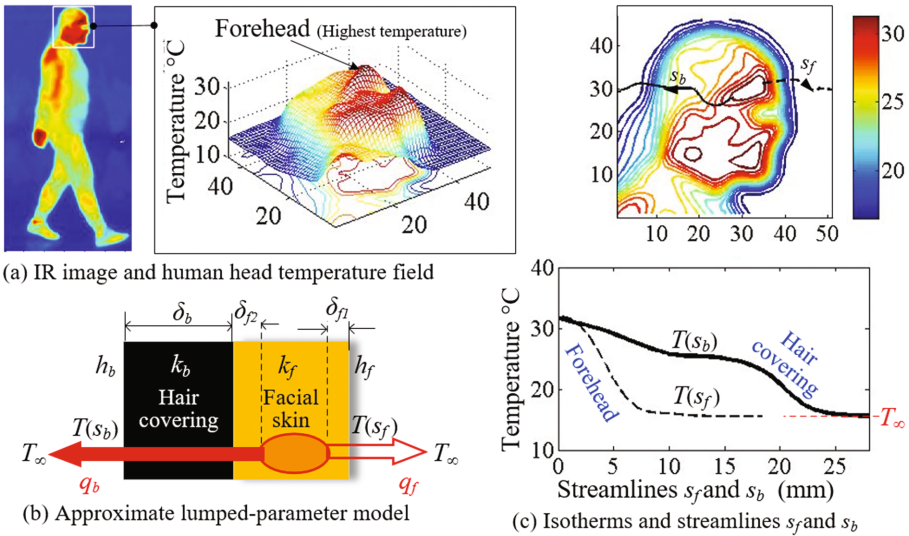


Fig. 2. Human head temperature model for detecting face orientation

segmentation with an appropriately selected temperature threshold. In modeling the human head temperature, the radiative heat transfer is neglected as compared to the conduction and convection heat transfer.

For finding the face orientation from the IR image, the steady-state heat transfer of the human head is approximated by a lumped-parameter model of two homogeneous (forehead facial and hair covering) regions as shown in Fig. 2(b), where the two heat fluxes (q_f and q_b) flow along two opposite paths (s_f and s_b) in the (same and opposite) directions of walking as shown in Fig. 2(c). The highest temperature region is treated as a bio-heat source from which (q_f and q_b) flows to the ambient environment at temperature T_∞ through the two paths:

$$T(s_f) - T_\infty = q_f \left[k_f^{-1} (\delta_{f1} - s_f) + h_f^{-1} \right] \text{ where } s_f \leq \delta_{f1}. \quad (2a)$$

$$T(s_b) - T_\infty = q_b \begin{cases} k_f^{-1} (\delta_{f2} - s_b) + k_b^{-1} \delta_b + h_b^{-1} & \text{where } s_b \leq \delta_{f2} \\ k_b^{-1} (\delta_b + \delta_{f2} - s_b) + h_b^{-1} & \text{where } \delta_{f2} \leq s_b \leq \delta_b + \delta_{f2} \end{cases} \quad (2b)$$

In (2a, b), s_f and s_b are the two paths starting from the highest temperature T_m contour; (k_f and k_b) and (h_f and h_b) are the (thermal conductivities and convective heat transfer coefficients) of the two regions; and δ_{f1} , δ_{f2} and δ_b are the lengths of the paths defined in Fig. 2(c), through which the heat fluxes flow. Equations (2a, b) offer some intuitive insights into the solutions to the face orientation detection from IR images that measure surface temperatures. The arguments are best illustrated numerically with Fig. 2(c) where the temperatures along the two streamlines (perpendicular to the equal-temperature contours) of the side-facing human are compared:

- Since the parametric values for (q_f, k_f, h_f, δ_f) and for (q_b, k_b, h_b, δ_b) are different, the temperature gradients along the two streamlines are expected to be different.
- For the same temperature drop ($T_m - T_\infty$), the temperature $T(s_f)$ along the streamline s_f through the forehead has a much steeper gradient than that $T(s_b)$ along the streamline s_b .
- Unlike $T(s_f)$ that linearly drops from T_m to T_∞ , $T(s_b)$ experiences more than one gradients for the same temperature drop.
- Similar reasoning can be made to differentiate between the front-facing and back-facing of the same human, where $T(s_f)$ and $T(s_b)$ are symmetric and have similar gradients, but the forehead will show a higher maximum temperature T_m than the hair temperature.

Once the face orientation is known, the motion state can be determined from the leg postures of the human using image processing routines. For the front- and back-facing orientation, an additional view in the orthogonal direction can be used to simplify the identification. The procedure to determine the motion state from the leg posture for a side facing orientation consists of three steps: (1) Obtain the binary image of the human from the IR grayscale image with a thresholding operation. (2) Using morphological

operations, reduce the image blob representing the human to a skeleton. (3) Compare the angle θ between the pair of legs with a threshold θ_{th} to determine the motion state:

$$State = \begin{cases} \text{In motion} & \theta \geq \theta_{th} \\ \text{Stationary} & \theta < \theta_{th} \end{cases} \quad (3)$$

3 Experimental Results and Discussion

Experiments were conducted to illustrate and evaluate the method to determine the motion state from the face orientation based on temperature gradients of the IR image and the leg-posture (using morphological skeleton processing of a binary image). The experimental results are given in Figs. 3, 4 and 5.

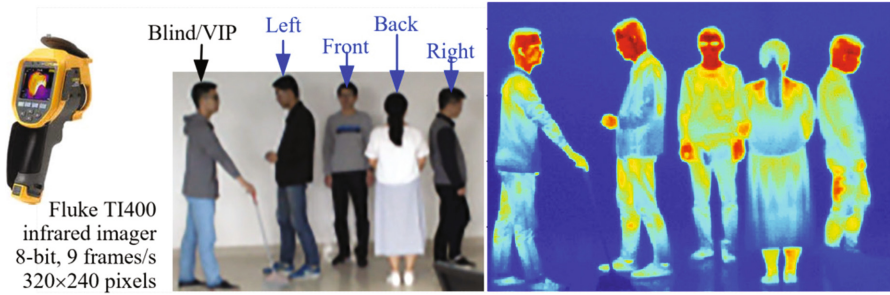


Fig. 3. Experimental setup (Image taken at a distance of 5.5 m)

Figure 3 shows the experiment setup simulating an environment commonly encountered in a daily walking in a crowd, where an 8-bit FLUKE Ti400 infrared thermal camera (320×240 pixels, 9 frames/s) was used to capture the scene at a distance of 5.5 m, where four peoples faced different directions in front of the blind/VIP to illustrate the face-orientation detection experimentally. The results demonstrating the face orientation detection based on temperature gradients are summarized in Fig. 4; each sub-figure shows the isotherms and temperatures along the two streamlines (on the left s_1 and right s_2) from the highest-temperature isotherm, and the temperature field.

The following are some observations drawn from Figs. 3, 4 and 5:

- For all the four different peoples (including Fig. 2c), the foreheads have the highest temperature (approximately 35°C) where the starting points of the two streamlines (s_1 and s_2) can be clearly defined. On the other hand, the back of the head (primarily covered by hairs) exhibits a lower (but more uniformly distributed) temperature than the forehead; thus, the starting points of the two streamlines (s_1 and s_2) for the back of the head are arbitrarily defined.

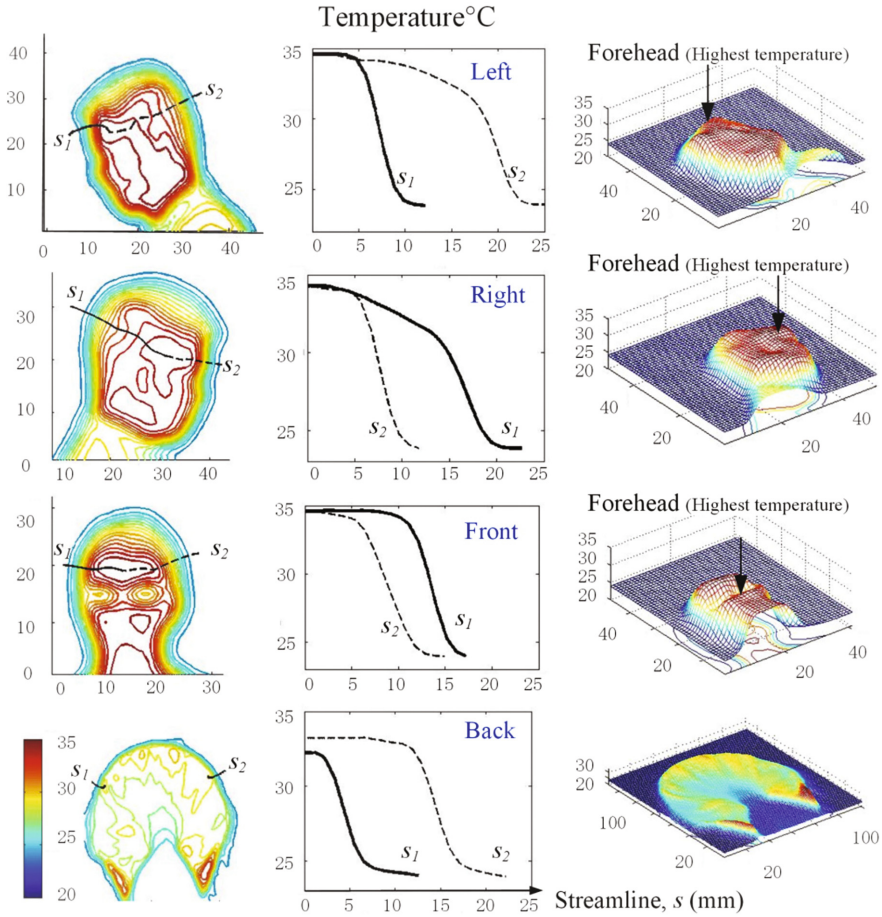


Fig. 4. Experimental results (isotherms and temperatures along streamlines)

- Unlike the front/back facing, the streamline-temperature for the side-facing is non-symmetric. The forehead temperature drops monotonically from 35 °C to the ambient temperature (24 °C) within a short distance of approximately 5 mm. On the other hand, two distinct temperature gradients (over a distance of 20 mm) can be observed along the path of conduction heat transfer on the hair-covering back. As compared in Fig. 4 (between the top two rows), the temperature field of the right-oriented face is opposite to that of the left-oriented face.

Figure 5 shows the results of the motion-states determined from the leg-postures for a side-facing orientation. As illustrated in Fig. 5(a), the procedure begins with a binary image obtained using a thresholding operation from the IR image; the image blob representing the human is then reduced to a skeleton by means of a morphological operation; next, straight-line segments are found by Canny edge detection followed by Hough transform; and finally the angle θ between the two legs is computed using inner

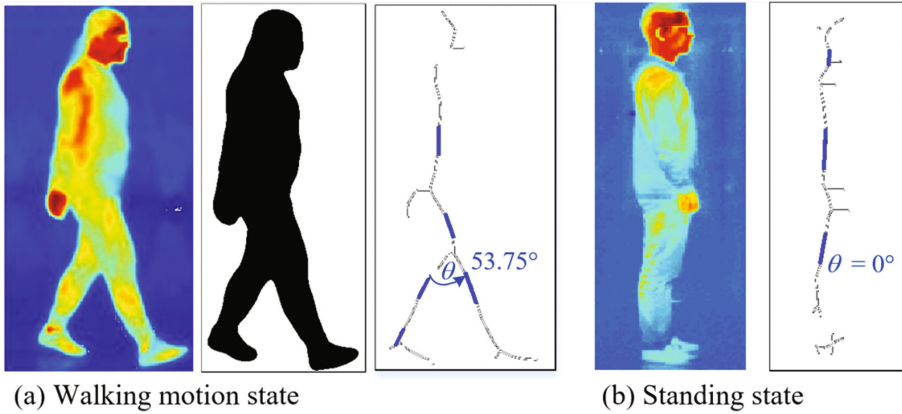


Fig. 5. Motion state detection

product and compared with a threshold ($\theta_{th} = 45^\circ$ is used in this study). Figures 5(a, b) compare two different leg-postures with the same face orientation, $\theta = 53.75^\circ$ walking and $\theta \approx 0^\circ$ for standing.

4 Conclusion

The concept of multi-physics intelligent space for the Blind/VIP has been presented, where physical information from the geomagnetic field-effects and temperature fields are used to effectively enhance the traditional navigation map. The procedure for detecting the human head, face orientation and leg posture from the temperature-based images has been detailed. The concept feasibility of the method has been experimentally validated using a test setup that simulates a typical environment in the Wuhan Blind School.

The experimental findings presented in this paper have been encouraging, which will help establish a basis for developing temperature filed-enhanced iSpace in the future. Research is being directed towards integrating other physical fields in the experimental iSpace testbed and its practical implementation.

References

1. Lee, K.-M., Li, M.: Magnetic tensor sensor for gradient-based localization of ferrous object in geomagnetic field. *IEEE Trans. Magn.* **52**(8) (2016)
2. Lee, K.-M., Li, M., Lin, C.-Y.: Magnetic tensor sensor and way-finding method based on geomagnetic field effects with applications for visually impaired users. *IEEE/ASME Trans. Mechatron.* **21**(6), 2694–2704 (2016)
3. Dakopoulos, D., Bourbakis, N.N.G.: Wearable obstacle avoidance electronic travel aids for blind: a survey. *IEEE Trans. Syst. Man Cybern. Part C: Appl. Rev.* **40**(1), 25–235 (2010)

4. Ando, B., Baglio, S., Marletta, V., Valastro, A.: A haptic solution to assist visually impaired in mobility tasks. *IEEE Trans. Hum.-Mach. Syst.* **45**(5), 635–640 (2015)
5. Ando, B.: A smart multisensor approach to assist blind people in specific urban navigation tasks. *IEEE Trans. Neural Syst. Rehabil. Eng.* **16**(6), 592–594 (2008)
6. Bourbakis, N., Makrogiannis, S.K., Dakopoulos, D.: A system-prototype representing 3D space via alternative-sensing for visually impaired navigation. *IEEE Sens. J.* **13**(7), 2535–2547 (2013)
7. Garaj, V., Hunaiti, Z., Balachandran, W.: Using Remote Vision: The Effects of Video Image Frame Rate on Visual Object Recognition Performance. *IEEE Trans. Syst. Man Cybern. Part A: Syst. Hum.* **40**(4), 698–707 (2010)
8. Hunaiti, Z., Garaj, V., Balachandran, W.: An assessment of a mobile communication link for a system to navigate visually impaired people. *IEEE Trans. Instrum. Meas.* **58**(9), 3263–3268 (2009)
9. Xiao, J., Joseph, S.L., Zhang, X., Li, B., Li, X., Zhang, J.: An assistive framework for the visually impaired. *IEEE Trans. Hum. Mach. Syst.* **45**(5), 635–640 (2015)
10. Jin, G.F., Zhang, W., Song, Y.J., Yang, Z.W., Wang, D.D.: Numerical simulation of ultrasonic infrared thermal wave detection with curvature structure crack. *Sci. Technol. Eng.* **13**(3), 776–779 (2013)
11. Serra, C., Tadeu, A., Prata, J., Simões, N.: Application of 3D heat diffusion to detect embedded 3D empty cracks. *Appl. Therm. Eng.* **61**(2), 596–605 (2013)
12. Cardone, G., Ianiro, A., Ioio, G.D., Passaro, A.: Temperature maps measurements on 3D surfaces with infrared thermography. *Exp. Fluids* **52**(2), 375–385 (2012)
13. Ji, J.J., Lee, K.M., Huang, Y., Li, C.Y.: An investigation on temperature measurements for machining of titanium alloy using IR imager with physics-based reconstruction. In: *IEEE/ASME AIM2015*, Pusan, Korea (2015)
14. Zhang, Y., Mahemuty, D., Jiang, S.C., Zhang, X.X.: Numerical simulation and heat transfer in A and therapy in Uyghur medicine. *J. Zhongnan Univ. (Med. Sci.)* (2010)
15. Li, K.Y., Dong, Y.G., Chen, C., Zhang, S.P.: The noninvasive reconstruction of 3D temperature field in a biological body with monte carlo method. *Neurocomputing* **72**(1–3), 128–133 (2008)
16. Pennes, H.H.: Analysis of tissue and arterial blood temperatures in the resting human forearm. *J. Appl. Physiol.* **85**(1), 5–34 (1998)
17. Kundu, B.: Exact analysis for propagation of heat in a biological tissue subject to different surface conditions for therapeutic applications. *Appl. Math. Comput.* **285**, 204–216 (2016)
18. Jones, B.F.: A reappraisal of the use of infrared thermal image analysis in medicine. *IEEE Trans. Med. Imaging* **17**(6), 1019–1027 (1999)
19. Zhang, D.: Surface temperature distribution and infrared image analysis of normal human body. *Laser Infrared* **17**(3), 52–56 (1994)