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Analysis of irradiation in OptiTouch system with optical detection

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Abstract

As part of the research and development project, a multi-touch multimedia system was implemented, working exclusively on the basis of optical technologies. The model of device with a diagonal of 42” was developed and made with 4K TV image technology and simultaneous detection in near infrared. The control of individual system modules was carried out on RaspberryPi microcomputers without typical operating system. The functionality of a conventional large-format display with unlimited multi-touch, QR code scanner, and a document scanner has been achieved in one housing. Luminance distribution tests were carried out in accordance with ANSI requirements and infrared radiation for detection work.

1. Introduction

Touch vision screens have been known for many years and mainly use dedicated capacitive, resistive or ultrasonic overlays. On the one hand, the use of a touch overlay allows it to be used with any screen, but it changes or limits the optical properties of displays. Thus, the concept of designing and building an exclusively optical solution, insensitive to electromagnetic fields, which will additionally have an unprecedented function of scanning images on the entire surface of screen, was created [1].

The use of on-screen touch recognition in optical technology was tested by Microsoft in its proprietary “Surface” solution, based on systems with cameras, mirrors, infrared (IR) emitters and projectors, however, with the development of LCD display technology, Microsoft abandoned work on this project. Another solution in the area of optical multi-touch detection was Samsung “Pixel Sense” technology, in which the matrix pixels gained additional functionality. The “Pixel Sense” touch detection technology worked by building additional semiconductor elements into the LCD matrix and analysing the light reflected from objects placed on the screen matrix. This technology was very promising primarily due to the ability of the screen to recognize shapes and graphic codes placed on the screen surface. This technology, however, was very expensive to produce and had size limitations up to a 40” matrix. The market of touch screens with diagonals of 32” and larger has been dominated by the IR touch overlay technology. This technology is relatively easy to manufacture, reliable and allows you to build even very large touch screens without incurring high costs.

Currently, the market of large-format multi-touch screens uses the technologies described in Table 1. Based on the analysis of available touch-screen technologies, a solution called “OptiTouch” was proposed, which uses only optical technology to perform touch detection, as well as scanning and recognizing objects, using the control of the RaspberryPi microcomputer system.

2. Analysis of light flux emission in flat light guide

Modelling the distribution of light emitted from the side surface of an optical fibre is the basic problem which meets a constructor of an optical fibre with side emission. The balance of the light flux in a cylindrical fibre is shown in Fig. 1.

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Table 1.
Comparison of multi-touch technology in vision screens [1].

Multi-touch Technology	Advantages	Disadvantages
Resistive Tehnology	– the ability to be operated by hand or any other object that can be used to exert point pressure on the surface	– low resistance to mechanical damage, – low resistance to damage – surface hardness at the level of 3–4 H on the Mohs scale, – cannot be used for diagonals over 20” – permeability not more than 80–85%.
Capacitive Technology	– the possibility of making a monolithic screen surface, – easy to keep clean, – resistance to flooding and micro-scratches	– no recognition of objects other than the human body or special conductive styluses, – contact with an element generating an electrostatic field causes disturbances in operation, – relatively expensive technology, – surface hardness from 6 to 7 H on the Mohs scale, – the use of additional protective “overlays” or increasing the resistance to mechanical damage.
IR Technology	– relatively low price (compared to other technologies), – easy integration with LCD screens, – possibility of obtaining high mechanical resistance (tempered or glued glass), – reaction to any object placed on the surface: finger, pointer, etc.	– it is not possible to make a uniform surface of the screen (there is a frame on the perimeter of the glass that creates a recess for a circle of 12–15 mm), – difficult to keep clean and low resistance to flooding.
Projected Capacitive Technology	– the possibility of using any type of glass (including tempered or laminated), – continuity of the detection surface.	– relatively high price and great difficulty in integrating with devices, – screens very sensitive to electromagnetic and electrostatic fields.
Surface Acoustic Wave	– the ability to operate with a finger and other objects, – also works when the surface of the glass is scratched.	– low resistance to pollution and flooding, – used only for small diagonals up to 10”.
Pixel Sense Technology	– the ability of the screen to recognize shapes and QR codes placed on the surface of the screen.	– relatively the most expensive technology, – the ability to develop screens up to 40” diagonal.
Dispersive Signal Technology	– the ability to handle any object and support large diagonals.	– the need to use a strong touch, – problems with integration with screens, – relatively high price.

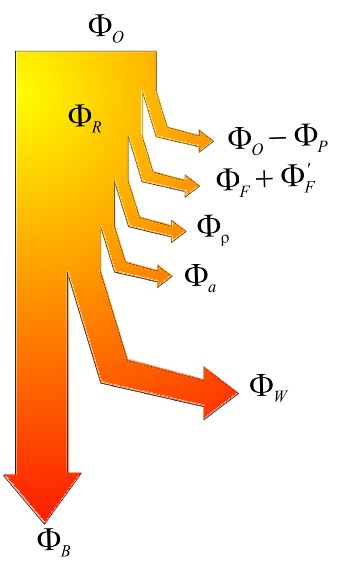

Fig. 1. Balance of the light flux in an optical fiber with side emission.

$$\begin{aligned} \Phi_o &= \Phi_P + \Phi_F \\ \Phi_R &= \Phi_P - \Phi_F = \Phi_P\left(1-\rho_F\right) \\ \Phi_R &= \Phi_W + \Phi_a + \Phi_\rho + \Phi_B + \Phi_F', \end{aligned} \tag{1}$$

where:
Φ_o – the total light flux of light source,
Φ_P – the light flux incident on input surface of an optical fibre,
Φ_F – the light flux reflected from input surface of an optical fibre in accordance with Fresnel law,
Φ_F' – the light flux reflected from output surface of an optical fibre in accordance with Fresnel law,
Φ_R – the light flux introduced into a fibre,
Φ_W – the light flux coming out from output surface,
Φ_a – the light flux absorbed in (linear absorption coefficient a),
Φ_ρ – the light flux lost in reflection from boundary surface core and cladding,
Φ_B – the light flux coming out of side surfaces of a fibre.

Calculation of the light emission in an optical fibre with side lighting, made based on the modified calculation method, uses Monte Carlo analysis [2]. Several characteristics were designed in a cylindrical fibre structure, containing diffuser cylindrical elements made of fluorine-doped glass in the core or in the core-cladding border. [3]. The Monte Carlo method allows the analysis of complex light-optical structures, considering the nature of light propagation in materials and its interaction on the surface (reflection). Compared to the classical method of elementary fluxes of light, it provides the possibility to quickly check the correctness of the optical model and with the use of many random samples it allows small calculation errors (less than 5%) to be obtained.

The following types of scattering may occur in the core-mantle boundary layer:

a) even,
b) directional.

The function describing the type of luminous flux scattering $f(\varepsilon)$ is related to the luminous flux by the following relations [4]:

$$
\begin{gathered}
I_\varepsilon = I_o f(\varepsilon) \\
d\Phi = 2\pi \int_0^{\varepsilon_g} I_\varepsilon \sin\varepsilon \cdot d\varepsilon \\
L_\alpha = \frac{I_\varepsilon}{dS\cos(\xi+\varepsilon)} = \frac{\tau \cdot E \cdot f(\varepsilon)}{2\pi\cos(\xi+\varepsilon)\int_0^{\varepsilon_g} f(\varepsilon)\sin\varepsilon \cdot d\varepsilon},
\end{gathered}
\tag{2}
$$

where I_ε – the surface luminous intensity dS as a function of angle ε, $d\Phi$ – the light flux falling on the element dS, ε_g – the limiting angle of light beam scattering.

Illuminance E caused by the luminous flux Φ incident on the dS (ΔS – real element) surface (Fig. 2), which can be determined as follows:

$$L = \frac{\tau E}{\pi}, \tag{3}$$

where τ is the transmittance coefficient of the jacket material.

Illuminance can be determined from the following relationship:

$$E = \frac{d\Phi}{dS} = \frac{\int_{Sw} d\Phi_f\left(dS_r\right)}{dS_r}, \tag{4}$$

where Sw – the surface area of the cylinder surface, $d\Phi$ – the elementary luminous flux incident on the surface, $d\Phi_f(dS_r)$ – the elementary luminous flux emitted from the elementary surface dS_r of the cylinder side surface.

The concept of building the OptiTouch optical table solution uses the IR radiation detection in order to obtain the possibility of multi-touch on any large surface, without the limitations introduced by typical technologies described in Table 1. The use of exclusively optical technology forces the introduction of IR and radiation spectrum on the one hand, visible for simultaneous scanning of documents and QR codes. According to the idea of OptiTouch detection shown in Fig. 3, the detection camera 7 must record images in both the IR and the visible bands. It is, therefore, necessary to achieve a high uniformity of irradiation intensity distribution over the entire surface of the outer glass 4 and, at the same time, to be able to register the touch point as energetic luminance [5]. On this basis, an analysis of the irradiance distribution of radiation emitted by the IR LED module was carried out.

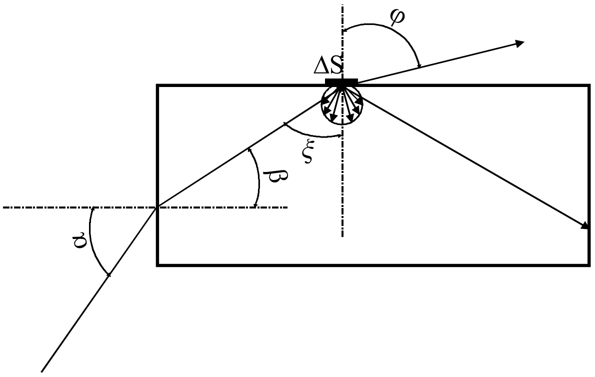

Fig. 2. Scattering of the light flux at the core-mantle boundary.

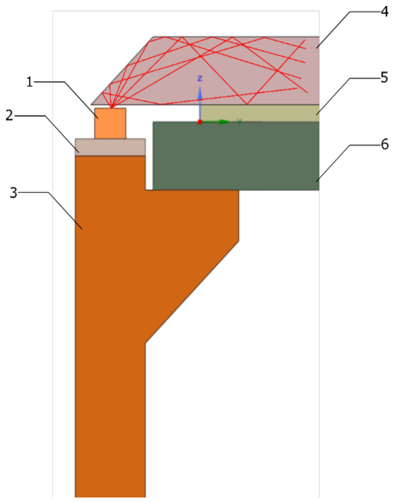

Fig. 3. IR illuminator structure: 1 – IR LED, 2 – printed cap, 3 – mounting strip, 4 – outer glass, 5 – LCD matrix, 6 – carrier glass.

The outer layer of the optical wafer is a glass with a low attenuation coefficient of near-IR radiation and a specially selected chemical composition. It is a kind of low-loss planar optical fibre inside which the propagation of IR radiation emitted by IR diodes placed at the edges of the table takes place. They use the phenomenon of total internal reflection and the IR radiation spreads throughout the entire volume of the glass. An LCD matrix is placed under the light-conducting layer, responsible for displaying images on the table surface. The conducted research has shown that it is almost transparent to IR radiation, regardless of the degree of control. The last layer is a load-bearing glass with a layer applied to disperse the white light coming from the illuminators placed at the bottom of the table.

3. The concept of OptiTouch technology

Standard designs of touch screens allow for touch points from 1 to 40 with a display size of up to 65”. The developed solution allows for multiplicative touch, depending on the number of modules supporting the section controller with a CCD camera over 40 touch points. In addition, the problem of screen recession has been eliminated due to the use of touch overlays. In the OptiTouch solution, the optical touch technology is built into the liquid crystal matrix and displays of any size can be almost "seamlessly" connected to each other, creating large-format images with a resolution limited by the liquid screen technology used. The developed solution involves decomposing the LCD matrix, arming it with additional layers responsible for optical touch and image detection.

The IR screen concept used is innovative. Infrared radiation was introduced along the longer edges of the glass. The placement of IR sensors in the edges was abandoned and digital cameras with a resolution above 2MPx, working with the RaspberryPi single-board computer system, became the IR sensors [6]. The cameras record the image in IR, and the image analysis allows to determine where the touch to the screen was made, how strong it is, and an additional advantage of this solution is the ability to record any image, decode tags or QR codes and cooperate with dedicated IR pens.

The outer layer of the OptiTouch screen is a planar IR illuminator made of glass with a low attenuation coefficient of radiation in the near-IR range (attenuation coefficient below 20% up to the wavelength of 1100 nm). It is a low-loss optical guide inside which the propagation of IR radiation emitted by IR diodes with a wavelength above 900 nm takes place. The technique of total internal reflection of IR radiation in the entire volume of light-guiding plate was used. A translucent LCD matrix is placed under the light guide layer, responsible for displaying images on the table surface. The last layer is a carrier layer with a coating that scatters the white light coming from the illuminators located at the bottom of the table.

Figure 4 shows the method of obtaining scattering on an optical guide layer, considering the detection with a wide-angle CCD IR camera. Finger touch detection on the table surface is carried out by a camera that detects an IR image on layers 3, 4, and 5, resulting from the scattering of IR radiation on the outer surface of the light guide plate. Scattered radiation caused by touching the outer layer passes through further structures: the LCD matrix and the carrier layer [7, 8], on which an image is created with a size proportional to the size of an object and its pressure on top plate. Part of this radiation is emitted towards the matrix of CCD cameras sensitive only to radiation in the IR range, above 900 nm, thanks to the use of dedicated bandpass filters in the 880–1000 nm range. The camera is surrounded by a printed circuit board with white light diodes arranged, which is necessary to display images through the LCD matrix [8]. One module covers part of a screen with its scope of operation, number of modules can be matched to a given screen size and depth of device, thanks to which such a solution does not introduce restrictions as to screen size of the designed device.

One of the advantages of this system is ability to estimate the pressure force based on size of light spot of any object placed or touched on a light-guiding layer. More pressure causes the spot to become larger, which is interpreted by software as more pressure. The RaspberryPi microcomputer software allows to calibrate the system each time the board is permanently scratched or soiled, or the optical properties

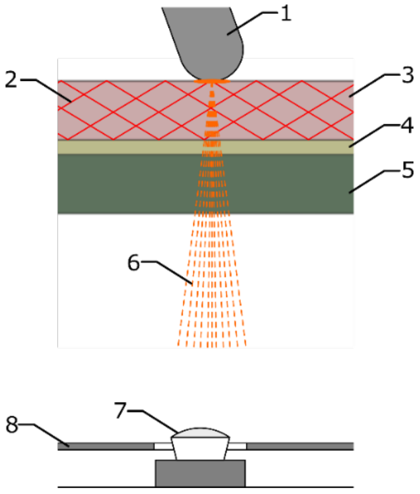

Fig. 4. The idea of touch detection in the OptiTouch solution: 1 – finger, 2 – light guide plate, 3 –IR radiation, 4 – LCD matrix, 5 – carrier layer, 6 – detected radiation, 7 – CCD camera, 8 – LED illuminator [9].

of this layer change. Due to the applied IR source with a wavelength of 900 nm and despite the use of an optical band-pass filter, it was not possible to completely eliminate IR radiation from the environment (from lighting fixtures in the room, from solar radiation penetrating through windows, etc.).

The main element of the multimedia table shown in Fig. 5. with a base diagonal of 42", responsible for touch detection, is a matrix of 12 wide-angle CCD cameras enclosed in a housing. The signal from each of cameras is processed by the RaspberryPi single-board computer, placed in a section controller with a LED illuminator [9, 10]. The viewing angle of the cameras was selected in such a way that the measuring fields of adjacent cameras completely covered the display surface. This eliminates the so-called "dead zones", where touch detection on the table surface is not possible. In addition, such a solution allows to reduce image distortions occurring at the boundaries of camera observation fields.

The block diagram of a multimedia table control system is shown in Fig. 6. Its main elements are lighting and detection blocks (1, 2, 3, 4). A single block consists of a driver based on a RaspberryPi single-board computer in version 3B+, a CCD camera with a wide-angle lens, drivers for IR emitters, and white LEDs (white light with the possibility of obtaining high colour rendering CRI over 85)

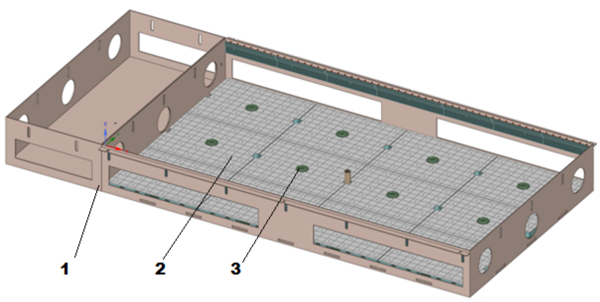

Fig. 5. Location of lighting modules and CCD cameras inside multimedia table: 1 – housing, 2 – LED illuminator section, 3 – CCD camera.

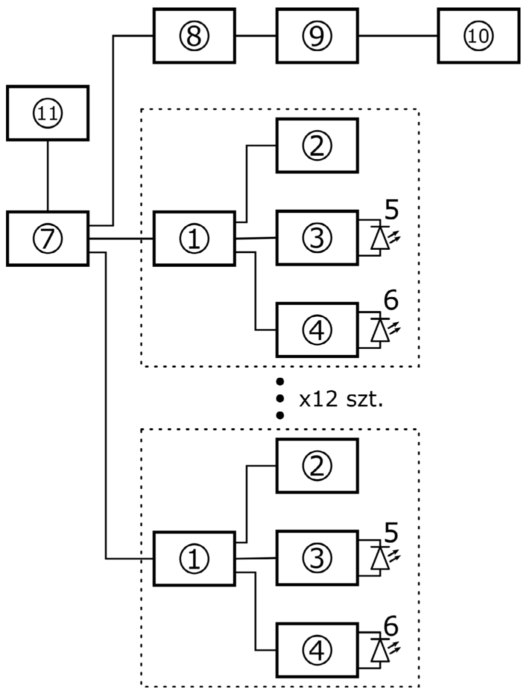

Fig. 6 Block diagram of the OptiTouch control system: 1 – RaspberryPi computer, 2 – CCD camera module, 3 – IR illuminator module, 4 – LED backlight module, 5 – IR emitters, 6 – white LED emitters, 7 – switch, 8 – scanner computer, 9 – scanner illuminator, 10 – scanner camera, 11 – OptiTouch main computer.

[11, 12]. 12 such modules were used in the developed OptiTouch system with a diagonal of 42”. An additional single-board computer system is responsible for controlling scanning field illumination and reading data from the scanner camera. All control systems are connected to a local network and supervised by a desktop computer with dedicated software.

Single board computers communicate with each other and with the main computer via a local Ethernet network using UDP protocol. For this purpose, one of table elements is a 16-port Gigabit Ethernet switch.

In terms of operation of the OptiTouch management and control system, the following assumptions regarding the touch point detection algorithm have been imposed:

1. to ensure smooth operation of device, the touch point detection time should be as short as possible,
2. the device should be resistant to power supply decays and accidental switching off.

Assumption 2 is difficult to meet for RaspberryPi microcomputers working under the control of Linux operating system: during an accidental shutdown, the file system on the microSD card, which is the mass memory of this microcomputer, is easily damaged. Therefore, the Ultibo environment (www.ultibo.org) was used, which creates code for RaspberryPi working without an operating system. Reading from the memory card is performed only once, when device is started, after which the card is no longer used and system does not need to be shut down.

Assumption 1 eliminates solutions based on cameras with a USB interface. The process of image compression, transmission, and decompression takes time and introduces noise into the image. The developed algorithms use cameras connected via the CSI bus and uncompressed data from the camera.

The developed table prototype contains 12 modules. The angle of view of cameras required to cover relevant part of screen is approx. 170 degrees. The touch point search algorithm, working on a single-board computer (prototype uses a RaspberryPi) consists of the following elements:

1. downloading image from camera,
2. reducing geometric distortions,
3. removing a fixed background image,
4. finding touch points,
5. converting the coordinates of found points into matrix coordinates,
6. sending data to the main computer.

Due to the need to ensure the lowest possible delays, some of the procedures have been written in assembly language. The reduction of geometric distortions is necessary due to the wide-angle lenses used. To avoid having to compute trigonometric functions, the function that performs this task uses a predefined array. The coefficients contained in this table were prepared using a program written for a PC.

In order to remove stationary background image, the program calculates a moving average of a large number (128–512) of frames – the value of said constant can be adjusted to obtain the best results of the procedure. The resulting fixed background image is subtracted from the current frame received from camera. As a result of this operation, we get an image in which bright touch points are visible against a dark background. Touch points are found using a procedure that, based on experimentally determined parameter values such as brightness and size of a given area, determines whether the screen was touched at a given point.

The coordinate conversion procedure also reduces keystone distortion caused by inaccurate camera mounting. In order to determine the parameters of this procedure, it is necessary to calibrate the OptiTouch table after its assembly. The results obtained thanks to the calibration procedure are then converted into data stored in the table.

The use of assembler and tables that avoid laborious calculations allowed for the processing time of one image not exceeding 30 msec. Further reduction of time operating will be possible after the use of RaspberryPi version 4. It has about three times more efficient processor, however, at the time of designing the OptiTouch table, the Ultibo environment was not yet available for this version.

The designed table also has a scanner module. This module is supported by a set consisting of a RaspberryPi microcomputer, a visible light illuminator, and a camera. The lens of camera was selected so that it covers an A4 sheet of paper with its field of view. When requested by the host computer, the image from camera is downloaded and then sent to the host computer. In this case, there is no need to optimize running time of procedures and the relevant code was written in Python.

One of design assumptions of the designed OptiTouch table was to recognize the objects (tags) placed on it, with a QR code. The basic problem in implementing this function was the focusing screen placed under matrix and necessary for its work. This screen diffuses image seen by the cameras. This is not very important when detecting touch points, but it limits resolution: individual code squares must have a side length of at least 3 mm. The second problem is the lack of IR lighting extending beyond the surface of the table, resulting from design assumptions.

4. Analysis of light distribution – measurements

As part of the research, simulations of light-optical systems were performed using a TracePro software. In the mathematical analyses, three configurations of the surface shown in Fig. 3 were adopted. The first version concerns shaping the bevelled surface at an angle of 45 degrees and polishing this surface (reflection coefficient 1.00). The second configuration involves shaping the bevel surface at an angle of 45 degrees and polishing this surface, assuming that the radiation does not go outside, and the reflection is specular (reflection coefficient 1.00). The third configuration concerns shaping the bevel surface at an angle of 45 degrees and giving this surface diffusion scattering. As part of the analysis of the light-optical system, the irradiance distribution was examined on the flat side surface of the plate, which will be illuminated with IR radiation with a wavelength of approximately 900 nm in order to detect touch and graphic codes. Figures 7–9 show the calculation results for the selected configurations.

Based on the analysis of the results of simulation calculations, it can be concluded that the highest level of irradiance occurs in the third configuration. The average irradiance value is 1044 W/m2. This solution also provides the highest efficiency in distributing the light flux from the IR sources to the light guide plate. Unfortunately, the uniformity of the radiation intensity distribution is the lowest. In the case of the first two versions with a bevel at an angle of 45 degrees and surfaces not deformed by forced scattering, average irradiance values were almost 50% lower but had greater uniformity. Therefore, the second solution was chosen for the imaging assessment of IR touch due to the uniformity of over 90% and the average irradiance value over 30% higher than in the first version. The CCD camera, operating in an extended radiation band (without an IR filter), is able to read the position touch point (area) and its shape and, at the same time, it is possible to record images in the visible band (scanning). In order to make the effectiveness of touch recognition as high as possible, a camera with a VIS filter should be used to completely eliminate the visible band and an independent CCD camera, e.g., with a 4K resolution, should be used for the process of scanning images in the VIS band.

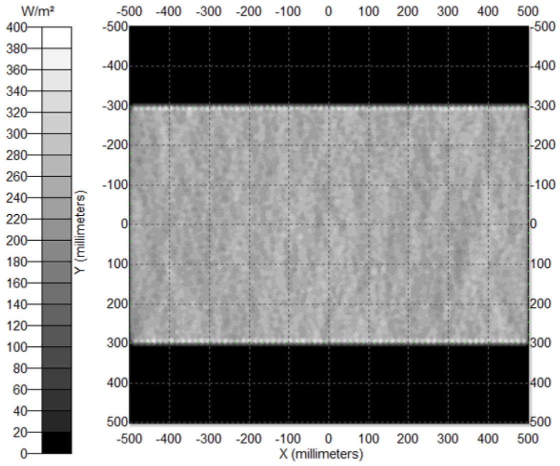

Fig. 7. Irradiance distribution on the surface of a planar illuminator with a 45-degree bevel and a polished bevel surface (version 1).

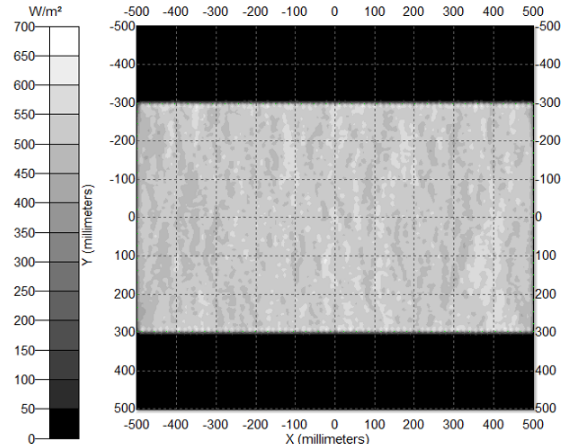

Fig. 8. Irradiance distribution on the surface of a planar illuminator with a 45-degree bevel and a mirror bevel surface (version 2).

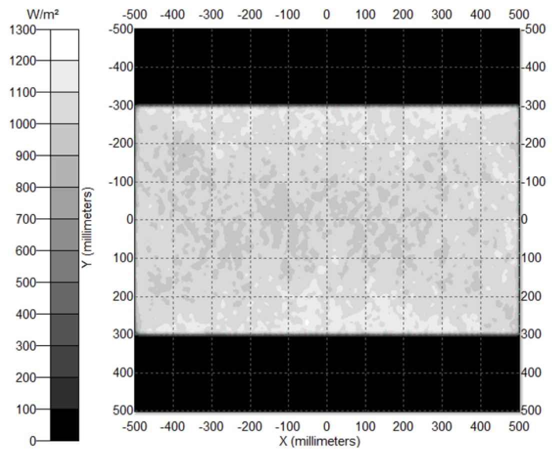

Fig. 9. Irradiance distribution on the surface of a planar illuminator with a 45-degree bevel and a diffusing bevel surface (version 3).

5. Discussion

Based on the analysis of the results of simulation calculations (Figs. 7–9), it can be concluded that the highest level of irradiance occurs in the third configuration. The average irradiance value is 1044 W/m^2. This solution also provides the highest efficiency in distributing the light flux from the IR sources to the light guide plate. Unfortunately, the uniformity of the radiation intensity distribution is the lowest. In the case of the first two versions with a bevel at an angle of 45 degrees and surfaces not deformed by forced scattering, average irradiance values were almost 50% lower but had greater uniformity. Therefore, the second solution was chosen for the imaging assessment of IR touch due to the uniformity of over 90% and the average irradiance value over 30% higher than in the first version. The CCD camera, operating in an extended radiation band (without an IR filter), is able to read the position touch point (area) and its shape, and, at the same time, it is possible to record images in the visible band (scanning) [13]. In order to make the effectiveness of touch recognition as high as possible, a camera with a VIS filter should be used to completely eliminate the visible band and an independent CCD camera, e.g., with a 4K resolution, should be used for the process of scanning images in the VIS band [14].

6. Conclusions

The developed solution of the OptiTouch multimedia table was also subjected to a strength analysis of the supporting structure and temperature distribution in chamber with electronic circuits with RaspberryPi and LCD matrix, camera and backlight systems to optimize their quality and strength.

To optimize the work and speed up the operation of camera modules for RaspberryPi, the Ultibo environment was used, which creates code for RaspberryPi working without an operating system. A proprietary touch detection module based on RaspberryPi cameras modified for IR recording was also developed, and image conversion procedures and deformation elimination were carried out quickly and efficiently by using the assembler. The RaspberryPi-based solution allowed for unification of the hardware platform that supports all multimedia table modules.

The functionality of the table allows it to be used, for example, in:

- medical facilities: independent recognition of touch points by each module allows, for example, for simultaneous work with the OptiTouch table by a doctor and a patient sitting on opposite sides of it,
- retail outlets to create large-area interactive advertising screens: the modular design allows the use of screens of any size, including those composed of many matrices,
- educational establishments: support for pens and tags allows to create educational applications and board games,
- offices: the touch table allows to handle interactive forms, and the built-in scanner module allows to scan paper documents.

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References

[1] Touch Screen Middle East. https://www.touchscreen-me.com/touchscreen-me.com/about-touch-screens.html#about (Accessed 20.01.2023).

[2] Dorosz, D. & Zajkowski, M. Optical Properties of Glasses For Sight Light Emission Waveguides. in *Proc. of XXI International Congress on Glass* (ICG, 2007).

[3] Dorosz, D., Kochanowicz, M., Zmojda, J. & Dorosz, J. Helical core optical fibre made of Nd3+/Yb3+-doped oxyfluoride silicate glass, *Proc. SPIE* **7721**, 77211B (2010). https://doi.org/10.1117/12.854766

[4] Zajkowski, M. Luminous flux emission calculation analysis in side light illumination optical fibres. *Proc. SPIE*. **5775**, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments III (2005). https://doi.org/10.1117/12.610742

[5] Żagan, W., Zalewski, S., Słomiński, S. & Kubiak, K. Methods for designing and simulating optical systems for luminaires. *Bull. Pol. Acad. Sci. Tech. Sci.* **68**, 739–750 (2020). https://doi.org/10.24425/bpasts.2020.134168

[6] Pi NoIR Infrared Camera Module for Raspberry Pi. https://www.raspberrypi-spy.co.uk/2013/10/pi-noir-infrared-camera-module-for-raspberry-pi (2023).

[7] Czyżewski, D. Comparison of luminance distribution on the lighting surface of power LEDs. *Photonics Lett. Pol*. **11**, 118–120 (2019). https://doi.org/10.4302/plp.v11i4.966

[8] Słomiński, S. Advanced modelling and luminance analysis of LED optical systems. *Bull. Pol. Acad. Sci. Tech. Sci*. **67**, 1107–1116 (2019). https://doi.org/10.24425/bpasts.2019.130886

[9] Błaszczak, U., Gryko, Ł. & Zając, A. S. Characterization of multi-emitter tuneable LED source for endoscopic applications. *Metrol. Meas. Syst*. **26**, 153–169 (2019). https://doi.org/10.24425/mms.2019.126332

[10] Błaszczak, U., Zajkowski, M. & Zając A. S. Selected Issues of Design and Quality Assessment of Lighting Devices with Semiconductor Sources. in *Problemy metrologii elektronicznej i fotonicznej 9* (ed. Mroczek, J) (Oficyna Wydawnicza Politechniki Wrocławskiej, 2018).(in Polish)

[11] Listowski, M. & Supronowicz, R. Color quality consideration when switching from FL to LED. *Photonics Lett. Pol*. **14**, 56–58 (2022). https://doi.org/10.4302/plp.v14i3.1159

[12] Piątek, P., Zajkowski, M., Budzyński, Ł., Kardasz, P. & Tyniecki, D. Multimedia table with optical multitouch. Patent application P.438796. (Aug. 23, 2021).

[13] Budzyński, Ł., Kardasz, P., Tyniecki, D. & Zajkowski, M. System OptiTouch z Detekcją Optyczną Sterowany Raspberry Pi. in *XXX Krajowa Konferencja Oświetleniowa i 2 Forum Technologii Oświetleniowych* 14 (2022). (in Polish) https://wydawnictwokreator.publuu.com/view/388/8235/page/14

[14] Czyżewski, D. Research on luminance distributions of chip-on-board light-emitting diodes. *Crystals* **9**, 645 (2019). https://doi.org/10.3390/cryst9120645