The concept of information technology for ensuring accessibility to art objects for the visually impaired persons

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Abstract
The current challenge is to ensure accessibility to art objects for the visually impaired persons by developing information technology, that provides converting 2D images into 3D models and generating descriptions for them in Braille. The brain of a blind person is able to convert tactile information into visual images, so tactile paintings created using 3D modeling and 3D printing technologies will allow blind people to "see" artistic masterpieces with their fingertips. The variable height of volumetric elements when creating tactile graphics for blind people can effectively and intuitively transmit various types of information, so when developing information technology for ensuring accessibility to art objects for the visually impaired persons, an important and urgent task is to recognize a 2D image and its 3D modeling (building up the relief to obtain an image of a three-dimensional object, as well as a mathematical model that describes the structure of the object, the location of its points in space, and a mathematical description of the object's surfaces). The analysis of the known methods and tools for 2D image recognition and their 3D modeling has shown that the methods and tools for rendering art objects (paintings) in 3D models are currently underdeveloped. The proposed information technology for ensuring accessibility to art objects for the visually impaired persons automates (in order to simplify the implementation) the transformation of a 2D picture into its 3D model, ready for printing on a 3D printer, and also generates a description of the picture in Braille, ready for printing on a typhloprinter.

Keywords
Visually impaired persons, tactile information, compensation for visual impairment, Braille, 2D image, 3D model, image rendering, information technology

1. Introduction

Vision is one of the most important human senses, as the visual analyzer provides more than 90% of the information sent to the brain from all receptors [1]. Vision is a multi-chain process

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that begins with the projection of an image on the retina, followed by the excitation of photoreceptors, the transmission and transformation of visual information in the neural layers of the visual system, and visual perception ends by the decision of the higher cortical areas of the visual system about visual images.

It is not uncommon for people to lose all or part of their vision. Blindness or serious visual impairment can be caused by various factors. These include injuries and diseases that damage the eyes, optic nerves, or brain.

In 2015, there were approximately 253 million people with visual impairments worldwide, including 36 million blind people and 217 million with moderate to severe visual impairment [1].

In 2020, there were already approximately 295 million visually impaired people worldwide, including 43.3 million blind people and 251.7 million with moderate to severe visual impairment [2].

In general, by 2050, there may be about 703 million blind people or people with moderate to severe visual impairment in the world [2] – Fig. 1. According to statistics, there are currently about 70 thousand blind people in Ukraine, but according to unofficial data, there are three times as many.

People with visual impairments use tactile relief dot writing, which was invented by the blind French teacher Louis Braille in 1824 [3].

To represent letters, the inventor used six dots arranged in two columns, 3 in each. According to his system, the text is written from right to left, then the page is turned, and the text is read as usual, from left to right. When writing, dots are pierced. Since you can only read convex dots, you have to "write" the text on the back of the page, in a "mirror image". Currently, the Braille information space is being created all over the world (especially in the European Union, the United States, Canada, and Japan), which includes the development of electronic devices with Braille, the production of various Braille publications, Braille inscriptions on product packaging and labels, labeling elevator buttons, making information signs, etc. [4].

The ratified UN Convention on the Rights of Persons with Disabilities also imposes an obligation on Ukraine to create the necessary environment and opportunities for the development of people with disabilities as part of the country's sustainable development [5].

In particular, Article 30 of the Convention obliges the state to ensure that people with disabilities:

- accessibility of television, movies, theater performances and other cultural events
- accessibility of cinema buildings, museums, libraries and other institutions where cultural events are held
- creation of opportunities for creative development of people with disabilities
- accessibility of cultural works for people with different types of disabilities
- adaptation of art objects for people with visual impairments without violating copyright

For many centuries, the idea of a blind person as an inferior personality has been formed in everyday consciousness, a blind person was seen as a completely different person, and the possibilities for the development of such a person, his or her participation in cultural life were considered extremely limited.

But, of course, this opinion is wrong. Two-thirds (66.9%) of people with visual impairments in Ukraine consider art and participation in cultural life important in their lives: 42% strongly agree with this statement, and almost a quarter (24.9%) rather agree [6].

Almost two-thirds of people with visual impairments (62%), similar to all Ukrainians, consider it the duty of the state to ensure equal rights for people with disabilities in the field of culture [6].

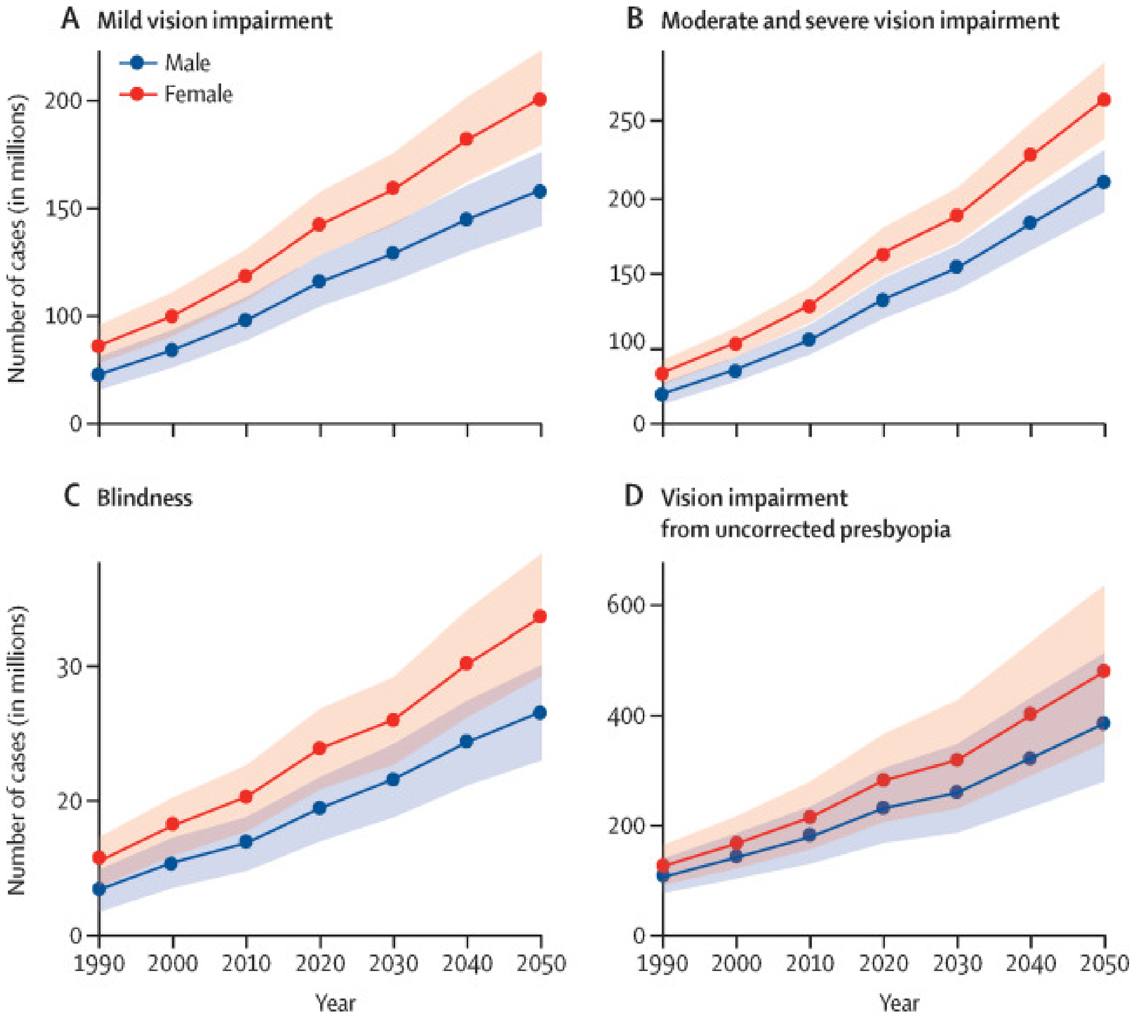

Figure 1: Forecast of number of people affected by mild vision impairment (A), moderate and severe vision impairment (B), blindness (C), and vision impairment from uncorrected presbyopia (D), all ages by sex, 1990–2050 [2].

Currently, in Ukraine, and in the world in general, art such as painting and drawings are practically inaccessible to visually impaired people. There are very few relief paintings, although there are some attempts to introduce visually impaired people to art objects. For example, the Prado Museum in Madrid has opened a unique exhibition of copies of famous paintings that were created specifically for the visually impaired.

The exhibition includes five paintings: "Touchy" by Correggio, a version of the famous "Mona Lisa" written by a pupil of Leonardo da Vinci, "Umbrella" by Goya, still-life painter of the Renaissance Van der Amen, "Apollo in the Forge of Vulcan" by Diego Velazquez and "Knight with hand on chest" by El Greco. Using 3D printing technology, these paintings were made in the form of reliefs, which allows even the blind to "see" the painting techniques and strokes of Correggio and other artists in their own way.

In addition to the paintings, visually impaired visitors are provided with texts in Braille and audio guides, and sighted visitors can ask for opaque glasses to experience the same sensations [7].

In addition, in 2023, the Dnipro Museum of History also implemented an accessibility project. In particular, the museum made a mnemonic scheme that helps visually impaired people navigate the institution, published a tour of the museum in Braille (15 copies) and a book on the history of Dnipro in Braille (50 copies).

The Resource Center "Barrier-Free Ukraine" offers a tactile art album "Cultural Treasures. The World" for the blind in Braille, which is quite expensive (from 14200 UAH). Wider use of this approach will make art objects accessible to all people.

Therefore, *the current challenge* is to ensure accessibility to art objects for the visually impaired persons by developing information technology, that provides converting 2D images into 3D models and generating descriptions for them in Braille (e.g., a description of the color scheme, a brief description of what is depicted in the painting, etc.) as a STEAM project for solving the real-world problem that requires the integration of cross-disciplinary knowledge and connections.

2. Neurophysiology of sensory processes and means of compensation for visual deficiency

Before proceeding to the creation of the aboved information technology, let's consider the basics of the neurophysiology of sensory processes and means of compensating for visual impairment in visually impaired people.

The main functions of sensory systems are [8]: signal reception; conversion of receptor signals (both from distant receptors (visual) and contact receptors (tactile)) into impulse activity of nerve pathways; transmission of nerve activity to sensory nuclei; conversion of nerve activity in sensory nuclei at each level; analysis of signal properties; identification of signal properties; classification and recognition of signals. The better the sensory systems work, the more accurate the information the brain receives.

From the neurophysiological point of view, sensation is a reactive response to the action of a stimulus, a reflection of certain properties of objects and phenomena under direct influence on the analyzer. Sensation (reception) is a cognitive mental process of reflecting in the brain certain properties of objects and phenomena of the surrounding world that currently act on the human senses (visual sensations – photoreception, tactile sensations – mechanoreception). The physiological basis of sensation is a nervous process that occurs when a stimulus acts on the corresponding analyzer [9].

Perception is necessarily associated with perceptual actions and is an active process. The basis of perception is a system of intra-analytical and inter-analytical connections that ensure the identification of stimuli and the consideration of the qualities of an object as a whole. The perception of information is a reflection in the human mind of objects and phenomena of reality under the direct influence of their analyzers as a whole [9].

Imagination is a mental process that consists in creating new images by processing the material of perceptions and ideas gained in previous experience. The emergence of imaginary images is the result of the activity of the human brain, namely the cerebral cortex. The complexity of the structure of imagination and its connection with emotions suggests that the physiological mechanisms of imagination are located not only in the cortex, but also in deeper parts of the brain. Such a part of the brain is the hypothalamic limbic system (the hypothalamus in its connections with the ancient cortex and subcortical areas that create a limb around the front of the brain stem at the entrance to the cerebral hemispheres) [9].

The formation of a socially significant personality can take place on an extremely limited sensory basis, even with the loss of the leading sensation, vision. Tactile, vibration, auditory, and olfactory senses become the leading senses in the formation and development of personality in these conditions.

Sighted people have more neurons in the cerebral cortex area responsible for processing visual signals than in the areas of hearing and touch. This is why sighted people analyze their environment primarily with their eyes. As a person loses their vision, the visual cortex no longer receives incoming signals [10].

Long-term experience of perceiving the world without the use of vision, affecting the morphological structure of certain parts of the brain, leads to a restructuring of the entire system of receiving information through the preserved analyzers. Such changes occur in the course of life, i.e. in the process of development, blind people develop new ways of perceiving and analyzing reality, orientation in space, which plays a leading role in their cognitive activity.

If the loss of vision occurred in adulthood, the person thinks in the same way as sighted people, but receives information about them through other senses. If a person lost their sight in childhood, after the age of five, then their visual memory is poorly developed, and their perception is based mainly on hearing and touch. In people who lost their sight in early childhood, the visual information processing center in the brain begins to process auditory, verbal or tactile signals. In people who have been blind since birth, the area of the brain responsible for converting visual information into images does not work at all [8, 11].

Tomograms of blind participants showed obvious differences from those of participants with normal vision. Blind people had increased connections between some parts of the brain. Significant changes were found not only in the occipital cortex (which is responsible for vision), but also in the areas responsible for memory, language, and sensorimotor functions [11].

Research on blindness and neuroplasticity (the brain's ability to adapt under the influence of experience) has shown that blindness can change the way the brain processes information. Different parts of our brain can reorganize to compensate for different sensory areas. The brain of a blind person can "reprogram" areas normally responsible for vision to improve, for example, auditory or tactile sensitivity.

Visual areas in the brains of blind people are comparable in size to those of healthy people, but non-visual areas are larger than normal. If the brain does not receive information from any sense organ, it can reorganize itself to enhance the functions of other senses (hearing, smell, touch), as evidenced by a lot of evidence. Even in the case of complete blindness, the brain "reshapes" itself to make the best use of the information at its disposal and interact more effectively with the external environment, so the potential for adaptation of a blind person is quite large [10].

This phenomenon is called compensation. Compensation is the restoration of underdeveloped or impaired mental functions by using the preserved or restructuring of partially impaired functions. From a physiological point of view, the basis of the compensatory process is the mobilization of significant reserve capabilities of higher nervous activity. In blind people, the lost function of the visual analyzer is compensated for by the active activity of the preserved analyzers – auditory, motor, tactile, etc. (for example, compensation of the mental functions of the visual analyzer in a blind child occurs mainly through tactile development).

In this case, there is an intra-systemic compensation, in which the restructuring of functions is carried out using the mechanisms of this functional (sensory) system. The physiological mechanism of compensation is based on the normal functioning of the preserved systems and on the reflex activity of the body. The inclusion of compensation mechanisms is unconditionally reflexive, automatic, and the further development of compensatory devices is a conditionally reflexive activity [8, 9].

Touch is of great importance in the perception and cognition of reality for visually impaired people. Tactile perception provides a complex of various sensations and helps to determine the shape, size of a figure, and establish proportional relationships. As a result, blind people can perfectly develop the tactile perception of spatial features (shape, size, etc.) and spatial relations, which allows them to use a kind of tactile "eye gauge" for approximate estimates of size and dimensions.

When touching, a person can perceive an object only in separate parts. Due to the fact that touch perception is carried out at a lower speed compared to visual perception, the tactile image of an object is formed more slowly, so a large size of an object that is studied by touch by a visually impaired person will be a significant obstacle. For blind people, touch is extremely important because it is directly involved in the reflection of objects and phenomena of the environment, physical and mechanical properties of the surrounding space. For a blind person, touch is the main way of object cognition of the environment.

The results of studies conducted in [8] indicate lower tactile sensitivity in people with late blindness, but not in people with early blindness, compared to the corresponding control group, regardless of gender and age. The results indicate that neither sensory compensation nor the slow development of the tactile sensory system is sufficient to explain changes in somatosensory after sensory loss, but rather a complex interaction of effects is existing.

The results of studies [9] showed that blind people outperformed their sighted counterparts in tactile tasks. The improvement in tactile acuity that accompanied blindness occurred in all groups of blind people (congenital, early, and late). However, improvements in tactile distinction of three-dimensional shapes occurred only in the early and late blindness groups; performance in the congenital blindness groups was no better than that of the sighted control groups. The results of this study demonstrate that blindness does lead to an enhancement of tactile abilities, and early visual experience may play a role in facilitating the tactile discrimination of three-dimensional shapes.

So, the brain of a blind person is able to convert tactile information into visual images, so tactile paintings created using 3D modeling and 3D printing technologies will allow blind people to "see" artistic masterpieces with their fingertips. Of course, blind people will perceive the paintings differently than sighted people, but they will have the opportunity to feel not only the composition, but also the drawing technique characteristic of a particular artist. The variable height of volumetric elements when creating tactile graphics for blind people can effectively and intuitively transmit various types of information [12], so when developing information technology for ensuring accessibility to art objects for the visually impaired persons, an important and urgent task is to recognize a 2D image and its 3D modeling (building up the relief to obtain an image of a three-dimensional object, as well as a mathematical model that describes the structure of the object, the location of its points in space, and a mathematical description of the object's surfaces).

3. Survey of known methods and tools

Let's consider the known methods and tools for 2D image recognition and 3D modeling, as well as approaches to 3D visualization.

The study [13] is devoted to evaluation of image quality with the purpose of finding the higher performance methods for evaluation of stereoscopic image quality. In the study, two Convolutional Neural Network-based methods for evaluation of stereoscopic image quality, which considering the semantic features of stereoscopic images. Convolutional Neural Network was used for evaluation of stereo image quality. The proposed models have relatively low computational time but high computational memory consumption.

The study [14] is investigated to the potential biometric recognition in 3D imaging in medicine. Authors consider various 3D imaging techniques in medicine and their advantages and disadvantages: magnetic resonance imaging (MRI), 3D ultrasound imaging, 3D near-infrared (NIR) imaging, computer tomography (CT) scans. Major disadvantages are the insufficient using the deep-learning-based approaches, insufficient data availability, and the absence of standardized benchmarking databases for this research.

Authors of [15] survey methods of facial analysis, including modeling clinical face phenotype spaces, statistical shape modeling, etc., because the computational analyses of 2D and 3D images helps to researchers and clinicians in detecting and describing facial mechanical, structural, and affective abnormalities.

The paper [16] proposed the metasurface nanostructures-based snapshot hyperspectral image sensor for obtaining the high-precision hyperspectral information of the detected face (combining RGB, depth, and infrared cameras), and proposed the 3D high-quality face recognition system using this sensor.

Authors of [17] proposed the method involves extracting image phase information using 2D Gabor filters and applying it to dense optical flow estimation based on polynomial approximation and semi-global block matching for obtaining robust 3D image measurements. Then the support vector regression is used for performing hyperplane fitting of the original images for improving the smoothness of the 3D images.

Study [18] is investigated to creating the historical timeline starting with the Old City of Jerusalem old drawings (beginning of the 18th century) and ending with present-day photographs with using computer vision, GIScience approaches, and deep learning. The proposed method based on several key components for the analyses: a 2D location recommendation engine, which detects an approximate location in the image of 3D landmarks;

2D landmarks to 3D conversion; and 2D polygonal areas to 3D GIS polylines conversion. This method provides examination of the landscape development throughout the last three centuries.

Authors of [19] proposed the method for rendering 2D images of 3D face meshes directly controlled by a single 2D reference image, using GAN disentanglement [20]. This method involved an input of a 3D mesh and a reference image, where encoders extract geometric features from the mesh and appearance features from the reference image. These features control the StyleGAN2 generator for obtaining the generated image that preserves the 3D mesh's geometry and the reference image's appearance.

Paper [21] developed a low cost and rapid method for converting any 2D rotational angiogram ("spin") into a 3 dimensional (3D) video, which no requiring the altering acquisition techniques or additional hardware, using the property that rotational angiograms are composed of images acquired from multiple angles. The resulting 3D videos convey anatomical depth that is not apparent from viewing the 2D images alone.

Paper [22] proposed the method for a stereoscopic visualization of a patient's individual abnormal vascular anatomy based on 2 independent photographs, obtained from traditional anaglyph procedures. This method consists of 3 basic procedures: volume rendering, image capture, and image fusion. Volume renderings is created using a free DICOM (Digital Imaging and Communications in Medicine)-reader.

Authors of [23] proposed the advancing 3D content creation tool HyperDreamer with several key properties: full-range viewable – creation of 3D models from a full range of observation points; full-range renderable – semantic-aware arbitrary material estimation; full-range editable – efficiently edit the texture with text-based guidance.

Research [24] proposed the method for reconstructing the transparent objects without manual assistance. This method represents two key technologies: volume rendering-based method that estimates object silhouettes by projecting the 3D neural field onto 2D images, and transparent object optimization through differentiable refraction rendering with the neural SDF field.

Paper [25] developed the animatable 3D-aware GAN that generates portrait images with controllable head pose, facial expression, and shoulder movements. It is a generative model trained on unstructured 2D image collections without using 3D or video data. So, method, trained on unstructured 2D images, generates diverse high-quality 3D portraits with desired control over different properties.

Authors of [26] presents SceneDreamer tool, which is unconditional generative model for unbounded 3D scenes, which synthesizes large-scale 3D landscapes from random simplex noise. This framework is learned from in-the-wild 2D image collections only, without any 3D annotations. The neural volumetric renderer, learned from 2D image collections through adversarial training, is employed to produce photorealistic images.

Paper [27] proposes a complete workflow of the automatic 3D reconstruction of objects from frontal RGB images (on the example of guitars). The guitars from the image are detected and segmented with convolutional neural networks-based semantic segmentation methods. Next, the final 3D reconstruction of the guitar is performed by warping the rendered depth maps of a fitted 3D template in 2D image space to match the input silhouette. Experimentally proven, that method automatically generates high-quality 3D object reconstructions from frontal images using various segmentation and 3D reconstruction techniques.

The conducted analysis of the known methods and tools for 2D image recognition and their 3D modeling, and approaches to 3D visualization has shown that, despite a number of available tools for rendering 2D images into 3D models, the methods and tools for rendering art objects (paintings) in 3D models are currently underdeveloped.

4. The Concept of information technology for ensuring accessibility to art objects for the visually impaired persons

Let's develop the concept of information technology for ensuring accessibility to art objects for the visually impaired persons (as a set of processes that use methods and tools of accumulating, processing and transmitting primary information to obtain information of a new quality (information product)).

The principles of design and operation of such information technology are [28-30]:

1. the principle of development and phasing – the possibility of updating and expanding the functions of information technology without disrupting its previous functioning
2. the principle of efficiency – achieving maximum effect while minimizing the cost of information technology
3. the principle of automation of information flows processing – automation at all stages of information flow from primary information to obtaining an information product
4. the principle of adaptability – operational restructuring of information technology if necessary to solve new problems
5. the principle of openness of information – ensuring the accuracy, truthfulness and reliability of information
6. the principle of compatibility – the availability of a communication mechanism for the interaction of information technology with users and with other technologies and systems
7. the principle of systematicity – basing information technology on a single methodological approach
8. the principle of legality – compliance with the current laws of Ukraine

Let's develop a context diagram A-0 of the functional model of information technology for ensuring accessibility to art objects for the visually impaired persons (Fig. 2).

The developed context diagram A-0 of the functional model of information technology for ensuring accessibility to art objects for the visually impaired persons reflects information flows and stakeholders, and makes it possible to understand the environment of such information technology.

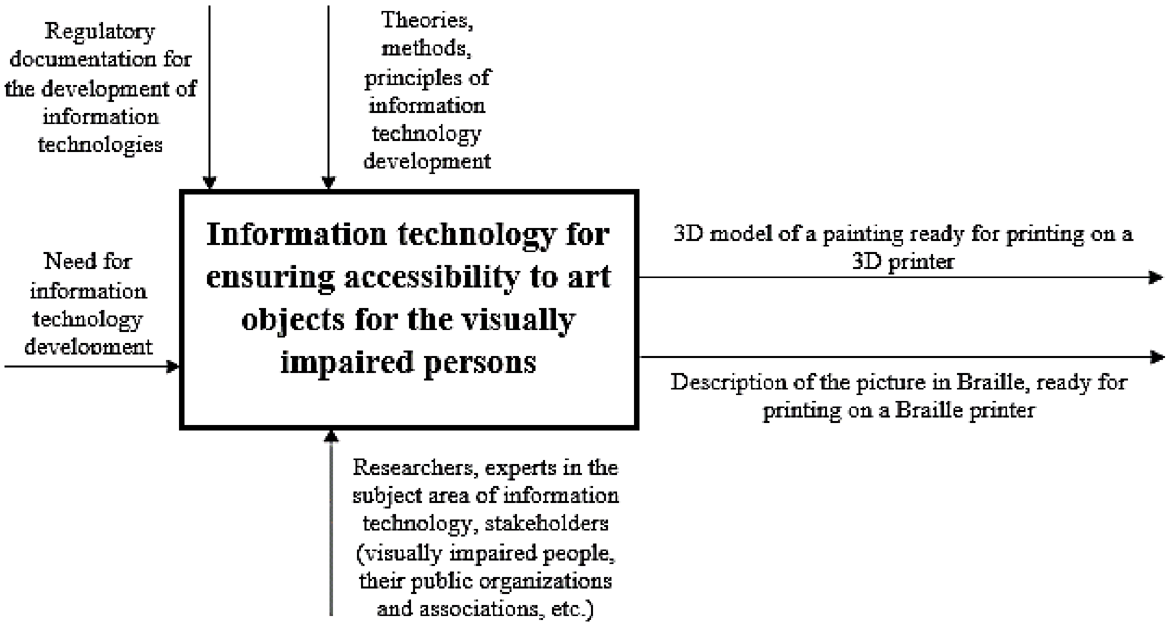

Figure 2: Context diagram of the functional model of information technology for ensuring accessibility to art objects for the visually impaired persons.

Taking into account the proposed principles of design and operation, the developed contextual diagram of the functional model of information technology for ensuring accessibility to art objects for the visually impaired persons, let's develop the structure of information technology for ensuring accessibility to art objects for the visually impaired persons (Fig. 3).

The proposed information technology for ensuring accessibility to art objects for the visually impaired persons automates (in order to simplify the implementation) the transformation of a 2D picture into its 3D model, ready for printing on a 3D printer, and also generates a description of the picture in Braille, ready for printing on a typhloprinter (Braille printer).

The main source of information, and therefore the primary information, in the information technology of ensuring accessibility to art objects for the visually impaired persons is a 2D picture, as well as answers to the questionnaire about the color scheme and content of the image in the picture.

The resulting 2D color picture is stored in the data section of the knowledge base and is processed by changing the depth, converting to a black and white image, detecting and segmenting the image, volumetric rendering, and 3D reconstruction by curving the rendered depth maps and building up the relief, resulting in an information product – the 3D model of the painting, ready for printing on a 3D printer, which is also stored in the data section of the information technology knowledge base.

At the same time, answers to the questionnaire about the color scheme and content of the image in the painting are collected and stored in the data section of the knowledge base, a textual description of the color scheme and content of the image is created in accordance with the recommendations for describing images for visually impaired people using the rules from the rules section of the knowledge base, and an information product is created – the description of the painting in Braille for the purpose of further printing on a braille printer, which is also stored in the data section of the information technology knowledge base.

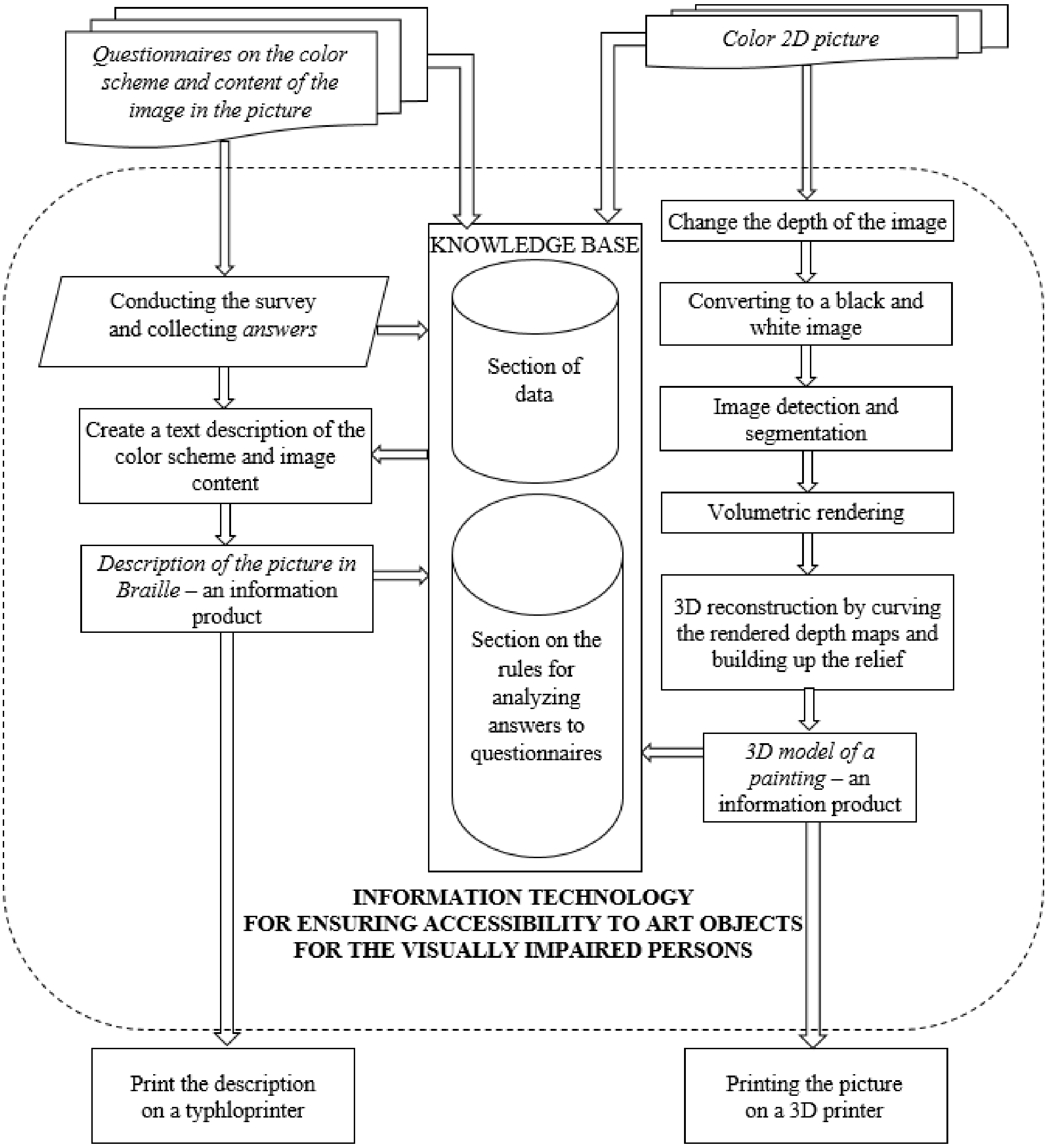

Figure 3: Concept structure of information technology for ensuring accessibility to art objects for the visually impaired persons.

5. Results & Discussion

Let's consider the work of the currently implemented branch of information technology, which is responsible for converting a color 2D picture into a 3D model, on the example of two paintings - "Mona Lisa" by Leonardo da Vinci and "Girl with a Pearl Earring" by Jan Vermeer.

The resulting 2D color images (Figs. 4, 5) are processed by changing the depth (Figs. 6, 7), converting them to black and white (Figs. 8, 9), detecting and segmenting the image, volumetric rendering, and 3D reconstruction by curving the rendered depth maps and building up the relief, resulting in an information product – 3D models of paintings (Figs. 10, 11) in *.glb, *.stl formats, ready for printing on a 3D printer.

Obviously, it is clear that currently, the obtained 3D models are not yet of high quality and accuracy, so the task of the authors' next research is to improve the quality and accuracy of the obtained 3D models of paintings, as well as to develop a branch of information technology responsible for generating descriptions of the painting in Braille.

Figure 4: "Mona Lisa" by Leonardo Da Vinci.

Figure 6: "Mona Lisa" after changing the image depth

Figure 8: "Mona Lisa" after conversion to black and white image.

Figure 10: 3D model of the painting “Mona Lisa”, ready to be printing on a 3D printer.

Figure 5: "Girl with a Pearl Earring" by Jan Vermeer.

Figure 7: "Girl with a Pearl Earring" after changing the image depth.

Figure 9: "Girl with a Pearl Earring" after conversion to black and white image.

Figure 11: 3D model of the painting "Girl with a Pearl Earring", ready for printing on a 3D printer.

6. Conclusions

Nowadays, the current challenge is to ensure accessibility to art objects for the visually impaired persons by developing information technology, that provides converting 2D images into 3D models and generating descriptions for them in Braille (for example, a description of the color scheme, a brief description of what is depicted in the picture, etc.).

The brain of a blind person is able to convert tactile information into visual images, so tactile paintings created using 3D modeling and 3D printing technologies will allow blind people to "see" artistic masterpieces with their fingertips.

The variable height of volumetric elements when creating tactile graphics for blind people can effectively and intuitively transmit various types of information, so when developing information technology for ensuring accessibility to art objects for the visually impaired persons, an important and urgent task is to recognize a 2D image and its 3D modeling (building up the relief to obtain an image of a three-dimensional object, as well as a mathematical model that describes the structure of the object, the location of its points in space, and a mathematical description of the object's surfaces).

The conducted analysis of the known methods and tools for 2D image recognition and their 3D modeling has shown that the methods and tools for rendering art objects (paintings) in 3D models are currently underdeveloped.

The proposed information technology for ensuring accessibility to art objects for the visually impaired persons automates (in order to simplify the implementation) the transformation of a 2D picture into its 3D model, ready for printing on a 3D printer, and also generates a description of the picture in Braille, ready for printing on a typhloprinter.

Currently, the obtained 3D models are not yet of high quality and accuracy, so the task of the authors' next research is to improve the quality and accuracy of the obtained 3D models of paintings, as well as to develop a branch of information technology responsible for generating descriptions of the painting in Braille.

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