Scalable Computing: Practice and Experience, ISSN 1895-1767, http://www.scpe.org
© 2025 SCPE. Volume 26, Issues 3, pp. 1466–1473, DOI 10.12694/scpe.v26i3.4269

DESIGN OF VIRTUAL ROAMING SYSTEM OF ART MUSEUM BASED ON VR TECHNOLOGY

JIA YANG* AND XIAYING WU†

Abstract. This paper aims to explore a panoramic Mosaic algorithm combining particle swarm optimization (PSO) and mutual information (MI) to improve the immersion and interactive performance of the virtual tour system of art museums. First, this paper introduces the application background of VR technology in the virtual art museum tour and emphasizes its importance in breaking the limitation of time and space and enhancing the audience's participation. Then, the application of the particle swarm optimization algorithm in image registration is described in detail. By simulating the foraging behavior of birds, the algorithm effectively solves the matching problem in the process of panoramic Mosaic. At the same time, mutual information is introduced as an index to evaluate image similarity, which further improves the accuracy and efficiency of stitching. Then, this paper proposes a virtual roaming framework based on the panoramic Mosaic algorithm, which can seamlessly integrate high-resolution artwork images and realize free navigation in 3D space through VR headsets. In addition, the system also supports various interaction modes, such as gesture control, speech recognition, etc., to meet the needs of different users. Finally, through a model simulation test, this paper shows the significant advantages of the designed virtual roaming system regarding visual effects and user experience. The experimental results show that the system can provide a highly realistic exhibition environment and enhance the audience's immersion through intelligent interaction. The system provides new ideas and technical support for the digital transformation of art museums.

Key words: VR technology, Art Museum virtual tour system, Particle swarm optimization algorithm, Mutual information, Panorama mosaic algorithm, Model simulation

1. Introduction. Under the tide of the digital age, virtual reality (VR) technology is gradually penetrating the temple of culture and art - art museums with its unique immersive experience and interactivity. The development of VR technology has brought revolutionary changes to the display methods of art museums, enabling the audience to enjoy the art feast across time and space without being restricted by physical space.

In recent years, the application of VR technology in the virtual tour system of art museums has become a research hotspot. Literature [1] puts forward the concept of creating a virtual art museum using VR technology, which solves the problem that traditional art museum visits are limited by geographical location and opening hours. However, improving the realism and interactivity of virtual roaming has become an urgent problem for researchers. The particle swarm optimization algorithm (PSO) was introduced in the literature [2], which optimized the image registration process by simulating the swarm intelligence behavior, thus improving the quality of the panoramic Mosaic. However, the PSO algorithm still has some limitations when dealing with complex scenes. Literature [3] proposed a method combining mutual information (MI) to evaluate the similarity by calculating the mutual information between images, further improving image stitching accuracy. However, how to achieve an efficient panoramic Mosaic while ensuring image quality is still the focus of current research.

In addition, the selection of the panorama Mosaic algorithm directly impacts the performance of the virtual roaming system. Literature [4] compared several mainstream panorama Mosaic algorithms and pointed out that the algorithm based on feature point matching has advantages in speed and accuracy. However, these algorithms often face the problem of large consumption of computing resources when processing large-scale image data. Therefore, literature [5] proposed a GPU-based panorama Mosaic algorithm, which effectively improved the processing speed, but the compatibility and stability of this method on mobile devices still need to be improved.

*Guangdong Vocational Institute of Public Administration, Guangzhou 510800, China (Corresponding author, hajimeyoung@163.com)
†Guangdong Agriculture Industry Business Polytechnic, Guangzhou 511365, China

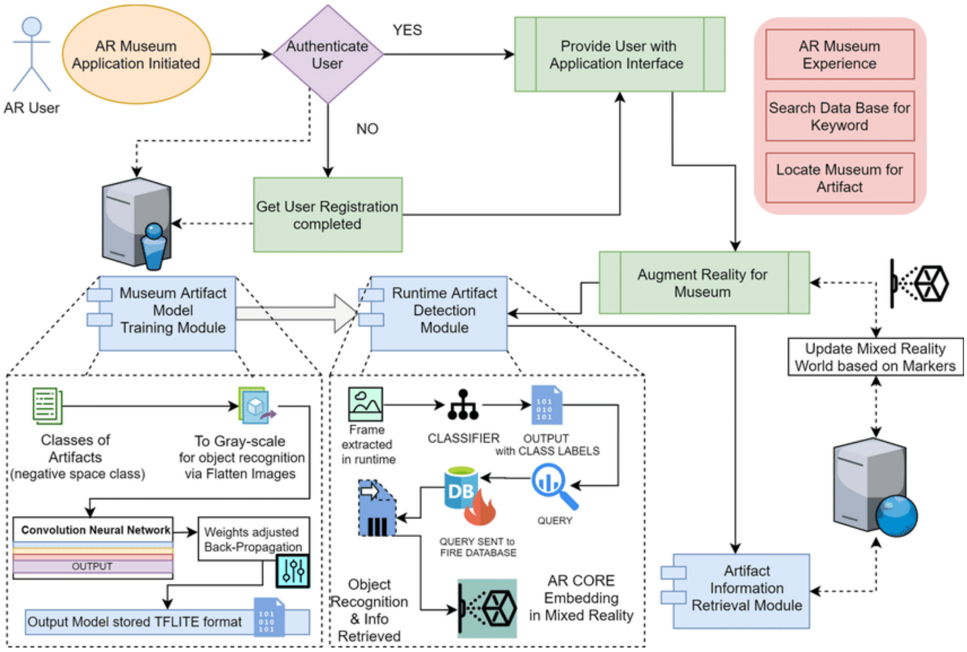

Fig. 2.1: Architecture diagram of virtual Art Museum system.

This paper will synthesize the research results of the above literature to design a new type of museum virtual roaming system [6]. Firstly, this paper will use particle swarm optimization algorithm and mutual information to optimize the panoramic Mosaic process to achieve higher image quality and faster processing speed. Secondly, this paper will explore a splicing algorithm based on GPU acceleration to adapt to the performance requirements of different devices. This paper will then examine how to enhance user immersion and engagement through intelligent interaction technologies such as gesture recognition and voice control [7]. Finally, this paper will evaluate the performance of the designed system through model simulation and user experiments and put forward suggestions for improvement.

2. System architecture design of virtual art museum.

2.1. System Architecture. The virtual art museum contains a three-layer structure: data storage, core business, and display layers (Figure 2.1 is quoted in Using Augmented Reality and Deep Learning to Enhance Taxila Museum experience). The data storage layer manages and stores system model data, attribute data and spatial data in a unified manner to achieve the purpose of data integration management. The system includes the main commercial functions, such as map service, permission management, information query, 3D model display, map annotation, browser adjustment, etc. Some modules can be built separately with software such as 3DS MAX. The function of the presentation layer is to display the user's interactive interface and 3D virtual environment online. Using VRML technology, the 3D virtual environment model can be displayed in the network. VRML is also inserted into a web page to view a 3D virtual environment.

2.2. System function design of virtual art museum. The function of the virtual art museum is to present the art museum to the public in the form of pictures through the introduction of the art museum, the operation of the two-dimensional map of the art museum, the query of works information, and the visit of the virtual three-dimensional art museum [8]. This is of great help to enhance the visibility of the museum. The specific functional structure of the system is divided into the following parts: (1) Art Museum introduction. Its content is a simple description of the general situation of the gallery through the way of text, including the origin of the gallery, the purpose of the museum, the collection of information, business hours, etc., so that more people have a better understanding of the gallery and even the museum. (2) Mapping operation. The content of map operation is the essential operation of a geographic information system, which includes processing 2D plan enlargement, reduction, translation, selection map annotation, etc. Its role is to display the layout of an art museum and the layout of works. (3) Information inquiry. The "information query" function focuses on retrieving paintings, while in the graphic gallery design, the paintings are represented by a dot or a rectangular frame. When you use the Information Query function, a window to draw the image appears. (4)3D roaming. The most important feature of this system is the "three-dimensional browsing" function. In the "3D Browse", a page will appear, reminding users to download the VRML plug-in and then complete the 3D tour of the museum on this page. This gives the user a feeling of being there. (5) Authority management. The "Rights management" module ensures the system's security. You can manage groups of users that have logged in to the system and assign login and management rights to different groups. (6) Tourist information bar. People can visit the gallery after the experience and target to give their views and suggestions so that other visitors in the tour process to play a specific role in the reference, but also can give museum managers some service suggestions to make the museum service more perfect.

2.3. Specific modeling of virtual art museum. The virtual gallery is divided into 5 modules: wall model, top component model, top lighting model, ceiling model and individual painting model. After accurately measuring the walls and door frames of the museum, different rectangular models are made according to the predetermined space dimensions [9]. The top and wall elements constitute the overall shape of the entire gallery perimeter, and the coding is roughly the same as that of the wall. A series of miniature lighting fixtures are made up of tin cylinders and spherical balls arranged on the ceiling. The ceiling model consists of the top and the floor where the lamps are arranged. The Indexed Face constructs the top, and the floor where the lamps are laid is extended by an Extrusion pattern. The pre-made lighting model is regularly displayed on the floor in fixed coordinates, and the spacing of the coordinates is balanced according to the spacing of the X, Y, and Z axes. Keep them as evenly spaced as possible. The individual painting models are the main exhibits in a virtual gallery, and they need to be photographed and imported into a pre-made rectangular frame and drawing board. Using glass materials to make the paintings appear.

2.4. Model data storage and presentation. First, each module in the completed art gallery is formed into an independent solid model. The space layout scheme of the 3D gallery is designed, and the saved 3D stereo models are added to the 3D space one by one and integrated with VRML documents [10]. This results in a complete three-dimensional art museum (Figure 2.2). After the VRML document is generated, the various virtual environments are integrated using Inline nodes to speed up web browsing and download rates.

3. Use mutual information combined with the PSO algorithm to achieve a panoramic image Mosaic.

3.1. Mosaic of panoramic images. The image is preprocessed by a smoothing method to reduce the interference of noise [11]. The PSO algorithm is used to find the features in as many images as possible, and the image matching is found by using the mutual information degree to complete the Mosaic. Here are the specific steps:

3.1.1. Image smoothing. Some random noise is often generated during imaging because the appearance of these noises will cause the details of the adjacent image to be not wholly consistent, which will have a more significant impact on the later processing. Therefore, this article should smooth the image first. The image is smoothed according to the following equation.

$$P(i,j)=\sum_{m=0}^{T-1}\sum_{n=0}^{N-1}L(m,n)W(i-m,j-n) \tag{3.1}$$

W is the input image. P represents the output image. L is a smooth convolution filtering algorithm. Gaussian smooth filtering is used here.

3.1.2. PSO Algorithm. The traditional image registration is mainly used to find the exact overlap between two images. In general, search for A template lm f_T in picture N. Use this template to match the image S. Finally, the two images were matched to achieve registration (Figure 3.1 cited in Comparison of

Fig. 2.2: Example of the final integration model of the museum.

Population Based Intelligent Techniques to Solve Load Dispatch Problem). Search for $\operatorname{lm} f_T$ using PSO. The most significant advantage of PSO is its rapid convergence. A multi-target detection method based on wavelet transform is proposed in this paper. Match other images S to achieve alignment. First, the particles are initialized. Both positioning and speed are included [12]. Then, the fitness of each particle is calculated. The method of iterative optimization is adopted. Each particle moves on its own. One is the personal limit q_{best}. The other is the overall maximum f_{best} . The performance ends when sufficient good fit or maximum number of iterations is reached. The particle self-renews its rate and orientation according to the following formula:

$$\begin{aligned} &U(\tau+1)=U(\tau)+\operatorname{rand}() \times z_1 \times\left(q_{b \text{ bes }}(\tau)-\operatorname{present}(\tau)\right) \\ &+\operatorname{rand}() \times z_2 \times\left(f_{\text{best }}(\tau)-\operatorname{present}(\tau)\right) \end{aligned} \tag{3.2}$$

$$\operatorname{present}(\tau+1)=\operatorname{present}(\tau)+U(\tau+1) \tag{3.3}$$

Here $U(\tau)$ is the particle rate of time $\tau \cdot \operatorname{present}(\tau)$ is the location of the current particle on time b. rand() is any number chosen in E. F is the learning coefficient, and in general, $z_1=z_2=2$. Ten particles are randomly allocated in the first picture's right half of the space using the 50% overlap principle [13]. The coordinates of several pixel points determine an initial value. Set the initial particle speed.

3.2. Mutual Information. If people continue to use the conventional N_2 distance, the calculation is complicated and easy to be interfered with by lighting, brightness, and other factors, but also, when there is a specific Angle deviation between the two frames, the algorithm will often fail. Because of the robustness of the mutual information measure, this paper uses it as a statistical correlation measure between images [14]. The mutual information of the algorithm is like that of the algorithm without rotation error when there is a slight rotation deviation between two images. The algorithm is suitable for statistical correlation analysis of two images in various cases. Cross-information is a measure used to describe the relationship between random variables [15]. Assume that the image N and S are two uncertain variables. $L(N)$ is the entropy of picture N, and $L(S)$ is the entropy of picture S. Where $L(N, S)$ is their total entropy. So, the amount of mutual information between them is:

$$Y(N, S)=L(N)+L(S)-L(N, S) \tag{3.4}$$

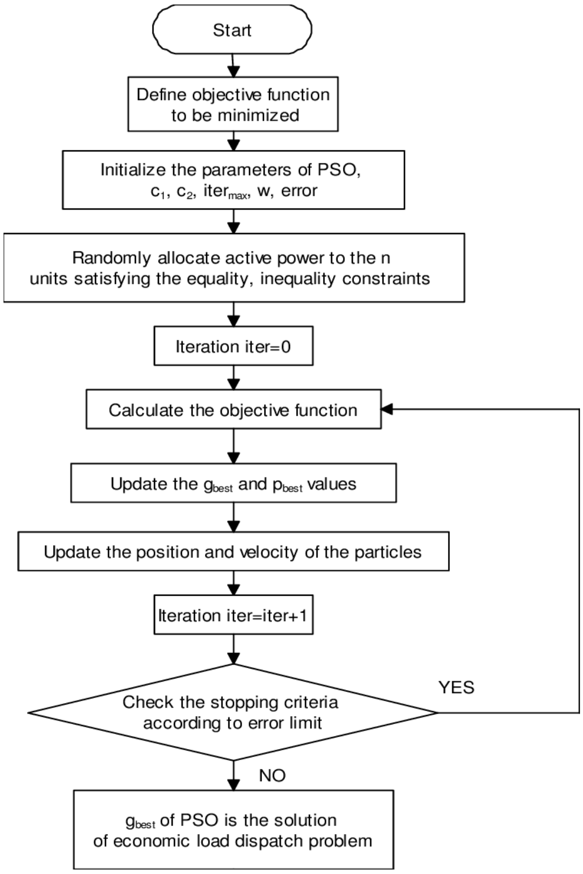

Fig. 3.1: PSO algorithm flow.

If the gray probability density distributions of images N and S are $q_N(l)$ and $q_S(s)$, respectively. The gray joint probability density distribution is $P_{NS}(l,s)$. Mutual information $Y(N,S)$ can be expressed as:

$$Y(N,S)=\sum_{a,b} q_{NS}(l,s)\log\frac{q_{NS}(l,s)}{q_N(l)q_S(s)} \tag{3.5}$$

Entropy is:

$$L(X)=\sum_{x} q_X(x)\log q_X(x) \tag{3.6}$$

The joint entropy is:

$$L(X,Y)=-\sum_{x,y} q_{MY}(x,y)\log q_{XY}(x,y) \tag{3.7}$$

In the left half of image S, find a zone $\mathrm{Local}\,\mathrm{lm}\,f_i i=1,2,\cdots,n$ of the same size as the template $\mathrm{lm}\,f_T$. Compare the mutual information between this region and $\mathrm{lm}\ f_T$ template. The most mutually informative region found in image S is used as a matching region $\mathrm{lm}\,f'_T$. Then, image S and image N can be registered according to the matching region. Thus, registration based on mutual information metrics can be expressed as:

$$w'=\arg\max_{w} Y\left(\mathrm{lm}\,f_T, w\left(\text{ Local } \ \mathrm{lm}\,f_i\right)\right) \quad i=1,2,\cdots,n \tag{3.8}$$

4. System implementation.

4.1. Model standardization processing.

4.1.1. UVW and stickers. UVW uses modeling software to express the three-dimensional space of the X, Y and Z axes. For texture, U is the component in the horizontal direction, and V is the component in the vertical direction. Before adding materials and textures, they must be UVW adjusted so that subsequent materials or textures can achieve the desired results on each component. Texture mapping can be divided into image and programming textures [16]. The image texture is adding the processed image to the model's surface. The algorithm is relatively simple. However, if it is enlarged, there are apparent arrangement tracks and partial Mosaic phenomenon. Therefore, for the accuracy and repeatability of images, maps are generally only suitable for regular brick or independent flat textures. Program mapping is a calculation method by the software, according to the set parameters to produce a material, because of its vector and disorder, so whether it is scaled or shrunk, there will be no Mosaic and no gaps [17]. But, because its structure is cumbersome and limited, its application scope is insignificant. As for the texture method used, it depends on the actual needs and the requirements for accuracy.

4.1.2. Model Optimization. Because the algorithm needs to complete the tasks of illumination information statistics and shadow calculation in the calculation process, when the number of models is too large, the memory cost will increase in the calculation process, resulting in screen delay, response speed and other problems. Therefore, polygons in the following cases can be deleted: (1) the intersection area of the grid is divided; (2) Polygons that will not exist in the image; (3) Over-detailed polygons and so on.

4.1.3. Model Export. After the modeling is completed, the model of the same material is spliced according to the commonness and difference of the material, Adding automatic smoothing features to the surface layers of all models. A painting can combine parts and remove redundant layers or patterns from the solution manager. Name a single Grid body, image, material, etc., generally M_ (material name), T_ (map name), SM_ (static Grid body name), etc. After all the above operations are done, select all the modes, select the coordinates in the right toolbar, and specify the XYZ coordinates of the mode to 0. Select Export Selection Mode from the file options in the upper left corner. Export the pattern to the working folder [18]. Select Smooth Group above the output TAB and cancel Camera, Animation, and Lights.

4.2. Available Functions. Using Steam VR and VRTK technology, people completed the Teleportation, slow walking, scene interactive jumping and display of work information in 3 scenes.

4.2.1. Teleportation. Through virtual reality technology, the player can move to the designated position instantaneously by manipulating the light on the stick. After introducing the Steam VR plug-in and VRTK plug-in into the Unity3D engine, create a blank target, rename it VRTK_Manager, load the VRTK_SDK_Manager script, and add a blank object. VRTK_Controlller Events are added, and new control point references are defined separately in the Script Aliases column of VRTK_SDK Manager, thus avoiding damage to the original Camera Rig prefab. Under Camera Rig, select a control point to use as a teleportation indicator and add VRTK_ control events to this control point [19]. This code is used to listen for input from the HTC Vive controller. Then, add the VRTK_Pointer script to the control point and check the remote selection box.

In the destination setting event, the teleport flag bit is valid, so the transport script can decide whether to move to the new destination [20]. If this option is not selected, the lever emits a beam of light but does not trigger displacement. When the object tag is set to VRTK_Policy List, it cannot be transferred to the object.

4.2.2. The jump of the world in the painting. In the main stadium, there is a jumping area. Visitors step into the area, will be activated, and then teleported to a specific screen. After visiting the "World in Picture," press the "back" button to return to the game site. This function is done by jumping around C# scripts.

4.2.3. Display of work information. When you visit the main museum, you can touch the light of your hand to the oil painting on the wall, and information about a work will appear [21]. Add a Canvas widget under each image, load the VRTK_UI Canvas script, and adjust the button size under the Canvas to cover the entire screen.

4.2.4. Scenario Optimization. Using particle effects, constructing terrain, and other means to render landscape and artistic atmospheres. Since the gallery is an indoor environment, its effect is achieved by lighting some details around the artwork and lighting from the top of the gymnasium. For roof lighting, add a Spot Light to the scene, adjust the brightness and direction of the lighting, and let the light fall on the place or artwork to be lit. For the detailed lighting in the works of art, this paper can combine the point light source so that every Angle of the work can get light exposure. It also prevents the light from getting too dark. In addition, to save calculation, the mode of part of the Light source can be converted to Baked, and then the Light Mapping technology is used to "bake" the color and intensity information of the light source into the light mapping.

5. Conclusion. First, VR technology provides an unprecedented immersive experience for the museum's virtual roaming system, enabling the audience to cross geographical boundaries and enjoy the art journey anytime and anywhere. By integrating particle swarm optimization (PSO) and mutual information (MI) algorithms, this paper significantly improves the accuracy and efficiency of image processing and lays a solid foundation for constructing a virtual environment. Secondly, the system design scheme proposed in this paper shows excellent performance in the model simulation, which is close to the real art museum in terms of visual effect and realizes a qualitative leap in interactive experience. By integrating intelligent interactive technologies, such as gesture control and voice recognition, users can interact with virtual artworks more naturally, enhancing the fun and educational value of visits. However, despite these achievements, this study also reveals the challenges of existing technologies in handling complex scenes, improving rendering speed, and optimizing user experience. Future research should focus on further improving the robustness and adaptability of the algorithm and exploring more efficient image processing and rendering techniques to meet the growing visual and interactive needs.

REFERENCES

[1] Resta, G., Dicuonzo, F., Karacan, E., & Pastore, D. (2021). The impact of virtual tours on museum exhibitions after the onset of covid-19 restrictions: visitor engagement and long-term perspectives. SCIRES-IT-SCIentific RESearch and Information Technology, 11(1), 151-166.

[2] Mu, M., Dohan, M., Goodyear, A., Hill, G., Johns, C., & Mauthe, A. (2024). User attention and behaviour in virtual reality art encounter. Multimedia Tools and Applications, 83(15), 46595-46624.

[3] Othman, M. K., Nogoibaeva, A., Leong, L. S., & Barawi, M. H. (2022). Usability evaluation of a virtual reality smartphone app for a living museum. Universal Access in the Information Society, 21(4), 995-1012.

[4] Durmuş, U., & Günaydın, M. (2024). Virtual Reality Based Decision Support Model for Production Process of Museum Exhibition Projects. International Journal of Human–Computer Interaction, 40(11), 2887-2904.

[5] El-Said, O., & Aziz, H. (2022). Virtual tours a means to an end: An analysis of virtual tours' role in tourism recovery post COVID-19. Journal of Travel Research, 61(3), 528-548.

[6] Trunfio, M., Lucia, M. D., Campana, S., & Magnelli, A. (2022). Innovating the cultural heritage museum service model through virtual reality and augmented reality: The effects on the overall visitor experience and satisfaction. Journal of Heritage Tourism, 17(1), 1-19.

[7] Giannini, T., & Bowen, J. P. (2022). Museums and Digital Culture: From reality to digitality in the age of COVID-19. Heritage, 5(1), 192-214.

[8] Kim, Y., & Lee, H. (2022). Falling in love with virtual reality art: A new perspective on 3D immersive virtual reality for future sustaining art consumption. International Journal of Human–Computer Interaction, 38(4), 371-382.

[9] González-Rodríguez, M. R., Díaz-Fernández, M. C., & Pino-Mejías, M. Á. (2020). The impact of virtual reality technology on tourists' experience: a textual data analysis. Soft Computing, 24(18), 13879-13892.

[10] Casadio, F. (2021). Sharing power: Leadership lessons from interdisciplinary practices in an art museum. Curator: The Museum Journal, 64(3), 505-527.

[11] Raimo, N., De Turi, I., Ricciardelli, A., & Vitolla, F. (2022). Digitalization in the cultural industry: evidence from Italian museums. International Journal of Entrepreneurial Behavior & Research, 28(8), 1962-1974.

[12] Go, H., & Kang, M. (2023). Metaverse tourism for sustainable tourism development: Tourism agenda 2030. Tourism Review, 78(2), 381-394.

[13] Wu, W. L., Hsu, Y., Yang, Q. F., Chen, J. J., & Jong, M. S. Y. (2023). Effects of the self-regulated strategy within the context of spherical video-based virtual reality on students' learning performances in an art history class. Interactive Learning Environments, 31(4), 2244-2267.

[14] Trunfio, M., Campana, S., & Magnelli, A. (2020). Measuring the impact of functional and experiential mixed reality elements on a museum visit. Current Issues in Tourism, 23(16), 1990-2008.

[15] Guo, K., Fan, A., Lehto, X., & Day, J. (2023). Immersive digital tourism: the role of multisensory cues in digital museum experiences. Journal of Hospitality & Tourism Research, 47(6), 1017-1039.

[16] Wu, X., Chen, X., Zhao, J., & Xie, Y. (2024). Influences of design and knowledge type of interactive virtual museums on learning outcomes: An eye-tracking evidence-based study. Education and Information Technologies, 29(6), 7223-7258.

[17] Agostino, D., Arnaboldi, M., & Lampis, A. (2020). Italian state museums during the COVID-19 crisis: from onsite closure to online openness. Museum Management and Curatorship, 35(4), 362-372.

[18] Spachos, P., & Plataniotis, K. N. (2020). BLE beacons for indoor positioning at an interactive IoT-based smart museum. IEEE Systems Journal, 14(3), 3483-3493.

[19] Garbutt, M., East, S., Spehar, B., Estrada-Gonzalez, V., Carson-Ewart, B., & Touma, J. (2020). The embodied gaze: Exploring applications for mobile eye tracking in the art museum. Visitor Studies, 23(1), 82-100.

[20] Walsh, D., Hall, M. M., Clough, P., & Foster, J. (2020). Characterising online museum users: a study of the National Museums Liverpool museum website. International Journal on Digital Libraries, 21(1), 75-87.

[21] Kirova, V. (2021). Value co-creation and value co-destruction through interactive technology in tourism: The case of 'La Cité du Vin'wine museum, Bordeaux, France. Current Issues in Tourism, 24(5), 637-650.

Edited by: Hailong Li
Special issue on: Deep Learning in Healthcare
Received: Jul 9, 2024
Accepted: Aug 17, 2024