Exploring Leonardo Da Vinci's Mona Lisa by Visual Computing: a Review

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Abstract. This paper surveys on relevant aspects of Leonardo Da Vinci's Mona Lisa, one of the most important pieces of art worldwide, from a visual computing perspective. This is accomplished by describing state-of-the-art works in the areas of image analysis and human computer interaction advancing hypotheses about the identity, ambiguity and hidden features of Mona Lisa's portrait. The second part of the paper is dedicated to describing computer graphics models in 2D and 3D for capturing the visual details of the portrait, in order to discover new features and advancing new hypotheses about the painting. Finally, the different works are discussed and a suggestion for future work is proposed. This paper can be particularly useful to computer vision, applied mathematics and statistics as well as art and history research communities, in order to understand the current literature methods, their limitations, and explore new directions for shedding light on a mystery still partially unsolved in the art history.

Keywords: Pattern recognition · Visual computing · Mona Lisa.

1 Introduction

Visual Computing (VC) denotes the methods for acquisition, processing, and elaboration of visual data [7]. In particular, it concerns the techniques of pattern extraction and analysis whose aim is capturing visual characteristics of data. The approaches of VC include: (i) methods of image and video analysis, (ii) computer vision, (iii) visualisation and visual analytics, (iv) augmented reality, (v) human computer interaction, and (vi) computer graphics. The methods of image and video analysis aim to capture patterns and content information from images and video frames. A further step is computer vision, which is oriented to recognition and interpretation of visual structures. Visualisation and visual analytics is referred to production of images and interactive interfaces which communicate using messages. By contrast, augmented reality includes methods for augmenting real-world objects with computer-generated features. It can generate virtual elements which are visualised by the users as embedded inside the real-world environment. Human computer interaction concerns the design, processing and evaluation of interfaces between users and machines. Finally, computer graphics is the set of methods aiming to produce images or 3D objects.

One of the most relevant application areas of VC is cultural heritage preservation and understanding, where VC plays a key role in capturing, modelling and exploring visual features and representations of findings of historical interest worldwide. Especially in art and painting, the different methods of VC are invaluable in extracting meaningful patterns and models for advancing important hypotheses and revealing useful information. The motivations for exploring VC methods in cultural heritage understanding are manifold. Cultural heritage is included in multiple aspects of everyday life. Also, it is everywhere, spread in little towns and big cities, in natural scenes and archeological sites. Cultural heritage involves the literature, art, knowledge inherited from ancestors, culinary traditions, films and cinema. Nowadays, it is considered as a world shared wealth which is composed of traditions and history of different countries, that should be preserved, understood and celebrated. Also, the cultural heritage is essential for tracking the horizon and planning the future [6].

In the context of cultural heritage, an invaluable piece of art and masterpiece of the art history worldwide is the *Mona Lisa*, a well-known portrait painted by Leonardo Da Vinci, an Italian Renaissance artist. However, the identity of the portrait's subject, its painting date, who commissioned the portrait, how long Leonardo Da Vinci worked on it, and how long he kept the portrait, still remain a mystery and different hypotheses were advanced on this [12]. In particular, the portrait could be painted between 1503 and 1506, and continued till late 1517. Also, some recent works advanced the hypothesis that the portrait could not be started before 1513 [11]. The portrait could be of Lisa Gherardini, who was the wife of Francesco del Giocondo, a Florentine cloth merchant, from which the portrait was named as *La Gioconda* (in Italian language). The portrait could be painted for celebrating the new house of Francesco del Giocondo and his wife in 1503, or the born of their second son Andrea in 1502, after the death of their daughter in 1499 [12]. However, it is likely that Leonardo Da Vinci brought the portrait with him in France instead of leaving it to the person who commissioned it. Currently, the Mona Lisa is hosted in Louvre Museum in Paris, France. Figure 1 shows the portrait of Mona Lisa in all its sheen.

In this paper, different relevant works of VC are reported and described for studying, exploring and modelling the portrait of Mona Lisa. In particular, the first part of the paper analyses different hypotheses about the identity of Mona Lisa's subject, ambiguity of the portrait and other hidden features related to the painting using image analysis and human computer interaction. In order to advance new hypotheses, the second part of the paper aims to present different graphics models in 2D or methods for 3D rendering of Mona Lisa's portrait. Finally, a discussion about the different methods is performed and a suggestion for future work directions is presented. The proposed analysis is useful for understanding the current literature techniques, their limitations and explore new directions which shed light on a mystery still partially unsolved in the art history. To the very best of knowledge, this is the first paper surveying about the topic of Mona Lisa's portrait in the state-of-the-art.

Fig. 1. Portrait of Leonardo Da Vinci's Mona Lisa from Louvre Museum in Paris, France [12]

The paper is organised as follows. Section 2 describes image analysis and human computer interaction works about identity of Mona Lisa's subject, ambiguity and hidden features of the portrait. Section 3 presents computer graphics works of the portrait's 2D and 3D modelling. Section 4 makes a discussion about the described works. Finally, Section 5 draws conclusions about the proposed analysis.

2 Identity, Perception and Hidden Characteristics

In the following, relevant visual computing works describing hypotheses about the identity of Mona Lisa's subject, ambiguity and hidden features are presented. The different works are categorised as: (i) approaches based on image analysis, and (ii) approaches based on human computer interaction.

2.1 Image Analysis Approaches

Multiple theories have been advanced about the identity of Mona Lisa's subject. In [14], Schwartz proved that Leonardo Da Vinci used himself as a model for realising the Mona Lisa. This was validated by both historical as well as visual characteristics. First, there was no clear information about Leonardo's commission of the Mona Lisa or the identity of the model. Second, at the time when Mona Lisa was realised, Leonardo moved in different places and lived in families with no women. Also, the painting did not have female features, and the difference in the left and right landscape suggested an ambiguity in the subject.

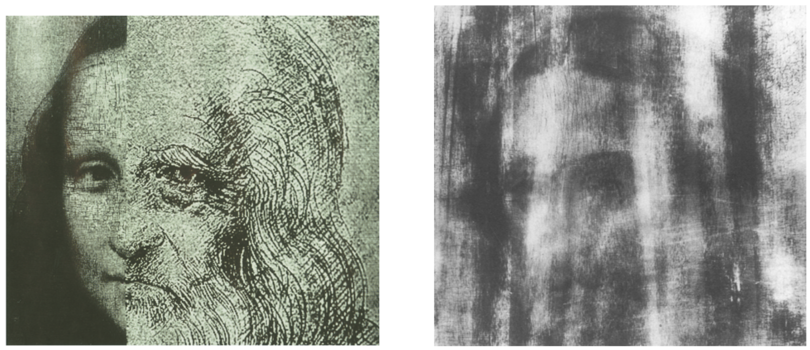

Fig. 2. Composite image of Mona Lisa and Leonardo's Self Portrait (left - a), and x-ray image of Mona Lisa (right - b) [14]

The last feature was a supraorbital ridge which could be observed on the Mona Lisa's face and that was also present on Leonardo's face, which is typical in male subjects. From a visual perspective, an experiment was performed which juxtaposed the Mona Lisa's and Leonardo's images in order to show their common characteristics. In particular, the two images were obtained by scanning and digitising the Mona Lisa and Leonardo's Self-Portrait. The grey levels of the images were enhanced. The image of Leonardo's Self Portrait was flipped along the vertical axis. Both images were scaled and aligned, vertically bisected and the two halves juxtaposed (see Fig. 2 (a)). The author observed as the position of nose, mouth, eyes, chin and forehead matched in the two images. About the landscape of Mona Lisa's portrait, it was observed that it has differences in the left and right part. In particular, the left part is lower, less logical and different in time and place than the right part. It could indicate a sort of dichotomy in Leonardo, where features of two sexes are mixed together. Another analysis was related to an x-ray of the Mona Lisa which revealed a second portrait below the surface portrait (see Fig. 2 (b)). In the past, the common opinion was that the two portraits represented the same subject. In this work, the author juxtaposed the two portraits for alignment and demonstrated, from the analysis of the x-ray's features, that they do not represent the same subject. In particular, the face's features, i.e. eyes, mouth, or chins, did not match in the two portraits. By contrast, the x-ray appeared as very similar to a Cartoon depicting Isabelle, Duchess of Aragon, that Leonardo painted with the same pictorial technique before the Mona Lisa. The final hypothesis was that the real subject of the portrait was Isabelle, that was overpainted with Mona Lisa, using Leonardo Da Vinci as the model.

The results of this analysis were contradicted by Lin et al. [10] who compared the subject of the portrait with Leonardo Da Vinci's subject. It was accomplished by extracting shape features using active shape models. The experiment was performed using a database of 488 frontal faces of various ethnicities, of which 151 were female faces, and 337 were male faces. Each face was manually labeled with

87 landmarks. Also, the face from Mona Lisa's portrait and a renowned portrait of Leonardo were labeled with the landmarks. They corresponded to significant face points, such as eye and lip corners, points along the bottom of nose and face edge. A preprocessing step to the landmarks was performed for increasing symmetry and equal spacing among the points. After that, Principal Component Analysis (PCA) was applied on the landmark representation of the faces, which determined a 12-dimensional feature vector for each face. It represented the way the face could differ from the average face along the k most relevant variation modes in the data. The Mahalanobis distance was used for comparison between the feature representations. Finally, a K-nearest neighbour classifier for categorisation of gender was employed on the obtained feature vectors. Results from classification showed that Mona Lisa's face is classified as female, while Leonardo's face is classified as male. Also, the computed Mahalanobis distance between the two faces is over 3.6 standard deviations from the average, demonstrating that Leonardo and Mona Lisa are two different subjects.

Finally, analysis of Mona Lisa's ambiguity was performed by Asmus [1], after the damages occurred on the portrait over time, e.g. discoloured, crackled and soiled varnish and cleavage inside the paint layer. First, a high-quality picture of the painting was acquired from the Louvre Museum at a resolution of 6-million pixels. Then, digital data was collected from the central part of the picture in order to create three files, one for each primary colour, i.e. green, blue and red (RGB). Second, a gain-bias modulation was applied on the RGB image files, which compensated for the filtering of the discoloured varnish, in order to recover the original and natural colours which are varnish-free. Also, removal of the craquelure was performed using sequential application of bi-dimensional Fast Fourier Transform (FFT) filtering approaches and blue/green bi-scatter filters. Since effects of craquelure-induced glints are naturally periodical, a two-dimensional matrix with phase and amplitude of different spatial waves related to the picture was created. Then, filtering was applied on that matrix in order to reduce the waves which caused those effects. Finally, the Inverse Fourier Transform, applied on the product of the filtered image with the filter, determined a picture with reduced glints. After that, selected pixels of unwanted colour were repainted to a wanted colour by modification of their three-channel values. It was accomplished by generating a bi-scatter plot counting the pixels at different combinations of blue and green with the highest alteration. A mask was generated from information extracted from the plot, which was applied on the picture for further reduction of the craquelure effects. Figure 3 shows the output of the described procedure.

Regional contrast stretch was then performed on the restored picture. In particular, a region of interest was selected, on which statistics on the three channels were computed in order to perform a histogram equalisation on the image. This operation obtained a higher level of detail on that region for its analysis. Also, local intensity enhancement was performed, which computed a new value for pixels according to the statistics computed in a square of their neighbourhood. Finally, a pseudo-colour mapping was performed, where small ranges of pixel

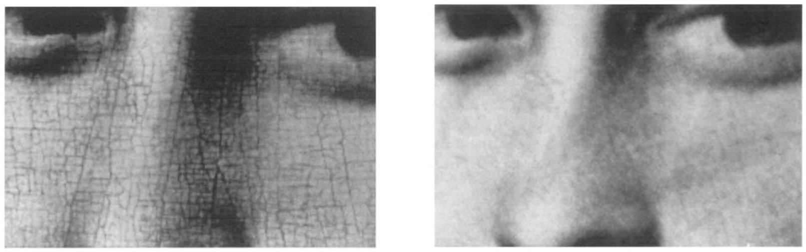

Fig. 3. Original facial detail with craquelure effects (left), and reduction of the craquelure effects after application of the procedure (right) [1]

Fig. 4. Upper torso of Mona Lisa depicting pentimenti in the neck area [1]

levels were clustered and arbitrarily re-coloured. It revealed pentimenti and portions where the painting was changed, specifically the presence of necklace and additional mountains. Figure 4 shows the result of this procedure in the neck area of Mona Lisa.

The author observed that these features revealed the ambiguous aspect of Mona Lisa's painting, with the left part representing order and conformity of the appearance of the subject, and the right part depicting disorder and chaos, which represents the interiority of Mona Lisa's subject.

2.2 Human Computer Interaction Approaches

Though analysis of the painting composition effect on youthfulness, facial femininity, and attractiveness, Pausch and Kuhnt [13] provided an estimate of Mona Lisa's age. The experiment involved a population of 107 subjects (76 females and 31 males). They were a random sample of fifth-year German dental students from University of Leipzig. Each subject was equipped with a questionnaire and was asked to observe five portraits. Each image was separately shown to each subject on a monitor screen inside a dark silent room. In the first portrait, the Mona Lisa's face was substituted with the face of a male, which was Christian IV, Duke of Zweibrücken. In the second portrait, the Duke of Zweibrücken was correctly reported with his original face. In the third portrait, the Mona Lisa's face was

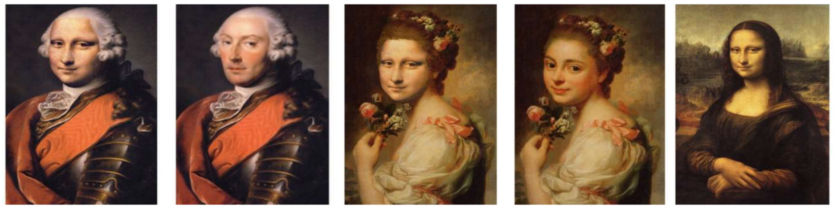

Fig. 5. The five portraits: (from left to right) male portrait with the Mona Lisa's face, Christian IV–Duke of Zweibrücken, female portrait with the Mona Lisa's face, Marie-Suzanne Giroust-Roslin, original Mona Lisa [13]

substituted with the face of Marie-Suzanne Giroust-Roslin. In the fourth portrait, Marie-Suzanne Giroust-Roslin was painted with her original face. Finally, in the fifth portrait, the original version of Mona Lisa was depicted. Figure 5 shows the five described portraits.

The two alternative paintings were randomly selected, were painted after the Renaissance and had different background. All collected data was statistically processed with a significance threshold of 0.05. The null hypothesis was that the painting composition had no influence on the Mona Lisa's youthfulness, facial femininity, and attractiveness. Another hypothesis was that in the original painting composition Mona Lisa's face appeared younger, more attractive and more feminine than the same face in a male painting composition. The last hypothesis was that Mona Lisa's face was more attractive in the original painting composition than in the female composition. The second aim of the analysis was to investigate about the perception of Mona Lisa's age. Hence, the hypothesis was that age was in the third decade of life. The independent variable was the portrait composition. The dependent variables were estimated age (years), facial femininity, youthfulness, and attractiveness of the subject in each portrait. Results from the analysis showed that the portrait composition has an influence on facial femininity, youthfulness, and attractiveness. Also, the estimated age of the Mona Lisa's face was 32.3 ± 5.6 years. In particular, the male portrait with Mona Lisa's face was ranked as younger and more feminine but less attractive than the original painting. By contrast, the female portrait with Mona Lisa's face was ranked as older but more attractive than the original painting.

Also, the emotional ambiguity of Mona Lisa was analysed in [9] using a variant of the constant stimuli psychophysical approach, well-known for detecting perceptual thresholds. In this way, the effective degree of ambiguity was measured through the happy-sad axis of emotional expressions. It was experimented on a population of twelve subjects, of which 5 were male, and 7 were female, of age between 20 and 33 years. A grey-scale version of Mona Lisa was used for generating 12 variants each corresponding to a different curvature of the mouth, which is the most relevant aspect of ambiguity. Each variant represented an emotional state from sad to happy. The experiment was characterised by two conditions. In the first one, each of nine variants equally spaced in mouth-manipulation degree (from the happiest to the saddest) was presented in random order to each subject for a maximum of 6 seconds. The perceived emotional expression and a rating of the given response were asked to each subject within the established time range. The variants' block was presented 30 times to the subjects in random order of the variants. In the second condition, the resolution of ambiguity was increased by decreasing the range of variants in the emotional scale. Also, nine variants were presented to each subject. In both conditions, the perceived happiness was modelled as sigmoid functions of Mona Lisa variants. The sigmoid functions, confidence rating per subject and variant, and reaction times to the variant presented meaningful differences between the two conditions. From their analysis, it was observed that Mona Lisa was almost always considered as unambiguously happy. However, the emotional perception and reaction to the variants was strongly dependent on the adopted emotional range.

In addition to the painting's ambiguity, an enigma is represented by the multiple copies of Mona Lisa painted over the years, specifically a restored one presented in 2012 in the Museo del Prado in Madrid. In order to compare the original Mona Lisa with the Prado copy, Carbon and Hesslinger [4] conducted an experiment involving a population of thirty-two participants, of which twenty-six were female, of mean age 21.3. Each participant was required to carefully observe the two paintings and estimate the position of the painter for both paintings (original Mona Lisa and Prado copy) in terms of distance and direction. The average perception of the original Mona Lisa was compared with the Prado version. Such comparison revealed a significant difference of the painter position in the two paintings. The difference in perspective was analysed using landmarks which were set in the original and Prado version of Mona Lisa. Landmarks were categorised in nine different types: (i) face, (ii) hair, (iii) body left, (iv) body right, (v) left arm, (vi) right arm, (vii) left hand, (viii) right hand, and (ix) chair. Analysis discovered that this change in perspective is not random but systematic. In particular, the lower part of the paintings shows a visual pattern of horizontal offset, which corresponds to a stereoscopic image composed of two parts with the same scene horizontally shifted. Consequently, the original and Prado version of Mona Lisa might be composed simultaneously with the aim of simulating the depth perception like in a stereoscopic image. It was accomplished by creating perspective difference between the two paintings for simulating the human binocular vision. If it is so, the Mona Lisa would be the first stereoscopic image in the history.

2.3 Other Approaches

Another fascinating characteristic of Mona Lisa's painting is the geometry and mathematics-based visual aspect underlying the portrait. One direction in this context is represented by the Traveling Salesman Problem (TSP) Mona Lisa. This is a 100,000-city instance of the Symmetric TSP whose solution provided a mathematical representation of Mona Lisa as a continuous-line drawing. Cities

Fig. 6. Representation of Mona Lisa as a continuous-line drawing by TSP [3]

are random points found on a grayscale version of Mona Lisa's image. The solution is a (near) optimal path of the points (see Fig. 6).

Accordingly, Carbajal et al. [3] proposed a solution based on Genetic Algorithms and Ant Colony Optimisation for the solution of TSP Mona Lisa problem. The project included different data structures which supported in finding the solution. In particular, the matrix of paths had one row for each node of the TSP graph in the TSP problem. The i-th row included the best possible successors of node i in the path. The current solution was a vector which contained the set of nodes with order corresponding to the current state of the path. Solutions were generated using a greedy strategy. It started from some node of the graph and selected its best successor from the matrix of paths until an Hamiltonian Path of the TSP graph was obtained. A selection mechanism was provided for having more attractive nodes at the end of each row in the matrix of paths. Finally, an update mechanism of matrix of paths was performed using an index derived from theoretical and current solution best length and number of candidates.

3 Computer Graphics

In order to capture the visual details of Mona Lisa and advance new hypotheses about the painting, different works of 2D and 3D modelling have been introduced in recent times. They can be classified as: (i) 2D models, and (ii) 3D models.

3.1 2D Models

From October 2004, Cotte and Dupraz [5] used a high-definition multispectral system developed by the Lumiere Technology inside the scope of the European Crisatel project. The research team took two photos of the Mona Lisa using the system from ultraviolet to infrared, which contributed to collect data and visual details about the painting. The high-definition spectral imaging system was characterised by 13 channels with an optimal definition of 360 Mega-pixels for each channel. Mona Lisa's painting was installed on a power-driven easel. It was parallel to the multispectral camera, while the painting was subjected to less direct lighting on the left and right with an angle varying between 57.5 and 66.5

degrees. First, the control software was used for setting the camera, in order to obtain the maximum quality of acquisition in a limited time. Then, a calibration step was performed for storing the levels of dark noise, compensating inter-pixel differences and lack of homogeneity of the lighting and lens for obtaining a calibrated image. Finally, the Mona Lisa was positioned on the easel for starting the process of image acquisition. It was performed in two phases: global frames of the all painting, then macro frames of the face. For each channel, the camera acquired a digital value, for a total of 13 values per pixel. The missing reflectance according to the sampling interval was interpolated in order to reconstruct the Mona Lisa's image. The final result was a high-definition colour image of the painting, by which a simulation of the lighting under different illuminants could be provided. It allowed to examine each part of the painting, study the pictorial approach, make suggestions about virtual restorations and make analysis of cracks of the painting.

3.2 3D Models

The exploration of the portrait was extended with 3D modelling by Gril et al. [8] through the study of an international research group of wood technologists. The study started in 2004 and was supervised by the Louvre Museum. The Mona Lisa is painted on a poplar panel that is surrounded with an oak frame named *châssis-cadre*. The panel is fixed to the frame using four crossbars. Also, the oak frame is put inside a wooden gilded frame. The aim of the study was to explore the effects of environmental fluctuations when the painting is located in the showcase or is moved outside and subjected to occasional checks. It was first accomplished by measuring different parameters associated to the painting. They included measurement of the panel shape, relief and out of plane deformation field on both front and rear face, 3D surface displacements, forces between panel and crossbars, deflection variations along time (transversal deflection at the center of the panel versus lateral borders, longitudinal deflection versus the *châssis-cadre*), and contact forces between panel and *châssis-cadre*. Then, all measurement results were used as input to a 3D numerical finite elements model which was able to simulate the effects of environmental fluctuations on the panel, and consequently, predict and validate in which scenarios the Mona Lisa's painting would be safer.

Also, Borgeat et al. [2] proposed a graphical 3D rendering framework with the aim to better characterise the Mona Lisa's painting methodology and details. The proposed framework was able to create an interactive environment where data was analysed under different modes and scales on a commodity hardware. First, a NRC's high-resolution polychromatic laser scanner was adopted for obtaining a digitisation of Mona Lisa. The goal was the acquisition of a high-resolution 3D version of Mona Lisa under different poses and sides for detecting a model of the portrait. Such color-per-vertex model, characterised by 333-million polygons representing the complete poplar panel of the painting, brought higher resolution in correspondence of the frontal side of the painting. The adopted method for interactive visualisation of large amount of retrieved surface data extended the technique of view-dependent hierarchical Levels of Detail (LODs), where temporal and spatial continuity between the various LODs and across the model was accomplished by using geomorphing on GPU. The full-resolution model was able to capture the finest level of detail. A preprocessing phase was performed for constructing the multiresolution data structure. The model was also equipped with different analytical tools to be directly executed on GPU, such as representing transformations, rendering depth information, multi-step filtering and image-composition methods. The framework also showed other interesting aspects related to Mona Lisa, i.e. measuring the shape of the poplar panel on which it was painted, and analysing some patterns of the paint layer. Finally, restorations of the painting were analysed using different lighting, since they could be associated to different pigments than the original paint with consequent different spectral response. Also, presence of the paint accumulation forming a crest along the original support frame and visible from 3D data disproved the hypothesis that thieves cut the wooden panel of Mona Lisa when they stole it.

4 Discussion

Different visual computing approaches have been explored for the analysis of Leonardo Da Vinci's Mona Lisa portrait, one masterpiece of the art history worldwide. They are characterised by image analysis and human computer interaction methods which are very useful for advancing hypotheses about identity, perception, ambiguity and hidden features of Mona Lisa.

From the literature review, it is worth noting that there is still contradiction about the identity of the painted subject, if Leonardo Da Vinci used himself or not as the model. Also, the ambiguity of Mona Lisa is revealed by differences between the left part, more ordered, and right part, more chaotic, of the portrait, analysis of the emotions when the subject is observed, and the multiple copies of Mona Lisa painted over the years. It is also unclear the age of Mona Lisa which was estimated between 32 and 37 years old. Finally, the mathematical and geometrical aspects underlying the portrait are still subjected to analysis and study. In order to advance new hypotheses about Mona Lisa, different computer graphics works of 2D and 3D modelling of the painting show their importance for capturing details of the portrait.

From this study, it is clear that still effort is needed for solving the open problems and ambiguities of Mona Lisa's portrait. Since it revealed interesting patterns of rigorous geometry, proportions and outlook, future research could be focused on exploring the painting details under a mathematical perspective.

5 Conclusion

This paper analysed the main characteristics of Leonardo Da Vinci's Mona Lisa and discussed the advanced hypotheses about the subject from relevant proposed works. Then, 2D and 3D models were introduced for capturing visual features from the subject and exploring new hypotheses about the painting. Finally, a discussion about the analysed works was performed and a suggestion for future research was proposed.

This review can be helpful for analysing the current literature about the topic and for understanding the limitations of the proposed works, so that research communities can propose new study directions. Hopefully, it will open new horizons in solving one of the biggest mysteries in the art history.

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