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Original article

Innovative approach to the digital documentation and rendering of the total appearance of fine drawings and its validation on Leonardo's Vitruvian Man

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ABSTRACT

The paper presents a new technique for detecting and rendering the total appearance of a drawing with the aim of digitally visualizing fine drawing collections with perceptive accuracy. A drawing's total appearance can be measured using equipment commonly found in a photographic studio. The system consists of four strobes and an RGB camera. The appearance is defined by its spatially varying spectral reflectance factor, surface macrostructure and surface microstructure. Using stereo-photometric principles, images of each light source taken sequentially from 45° by the normal and annularly at each 90° angle (for four lights) were used to measure the surface normal and diffuse reflectance. An OpenGL viewer was written to render images for specific geometries and for studio lighting. The pipeline from acquisition to visualization was tested on the most famous drawing in existence, Leonardo da Vinci's Vitruvian Man.

1. Research aims

This paper presents a unified solution to two distinct and complementary problems concerning collections of ancient drawings:

- the construction of drawing archives containing replicas with appearance features very close to the real objects. This is a conceptually easy problem – the replica of an object that is true to the object itself – that does not involve the use of the best or most innovative technology available but, rather, the use of the easiest and most appropriate technology for the purposes [1];
- the faithful perceptual reproduction of the three-dimensionality of tracings for the visual analysis of drawings. The underlying theme is the tracing and hatching investigation that corresponds to the possibility of reconstructing the artist's method, as well as the deposits and material components from past conservation treatments.

2. Introduction

Today, drawings are digitally analyzed and documented using various techniques, from simple images and RGB multispectral images to high dynamic range photographs, X-rays, UV fluorescence, raking light photography and infrared reflectography [2]. Most frequently used are techniques based on the acquisition of spectral images [3], which are able to render full color fidelity. Among them, the most widespread is certainly spectroscopy, which can obtain the spectrum of each part of the artwork [4]. These methods, however, have been developed for paintings and usually do not entirely match with the features of drawings, leaving unknown important properties or returning an unnecessary excess of information. For example, multispectral methods allow detailed investigations into colors, but this is unnecessary for drawings that have a limited range of colors compared to paintings. An analysis of more than 200 cases on a wide range of typologies (from ancient to modern, from pencils to inks, chalk and charcoal) revealed that a 16-bit RGB acquisition is accurate enough to faithfully capture all colors existing in the drawings [5]. Furthermore, multispectral methods still remain marginal for trace definitions. Even in the case of the acquisition of depth information, today's techniques present accuracies that correspond to the deformations of the painting supports or the relief of brush strokes or craquelure (10 μm–1 mm), while typical thicknesses left by pens and pencils rarely exceed 10 μm [6], with an average of 5 μm. To measure typical drawing

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resolutions, an accurate instrument is conoscopic holography, which allows uncertainties in depth of approximately 6 μm. However, the stability of the instrument during the measurement and the absence of vibrations are crucial and rarely available, and the paper deformation capture remains unsolved, being of another order of magnitude and requiring further analysis. Moreover, studies on drawings are usually performed as if they were paintings, due to the misunderstanding that many paintings were executed on paper (e.g., using watercolors, guache or crayons, which have thicknesses very different from those of oil paintings).

Lastly, it is known that drawings present specular reflective components (i.e., when using graphite on paper or gold ink), and modeling the bidirectional reflectance distribution function (BRDF), which describes how the light incident on a surface is reflected in a continuum of directions, is essential to faithfully digitally visualize the original artifact [7].

Various solutions to this problem have been proposed. One of the most efficient is described in [8]. It allows the estimation of per-pixel spatially variable reflectance properties of a surface (including translucency) and shape data, but it is expensive, unskilled staff cannot use it and the lighting system used may damage the drawings. Another solution is polynomial texture maps (PTM), an extension of the conventional texture map [9]. PTMs, however, allow observation only from a single predefined viewpoint, are efficient only in representing the mesostructure level and present difficulties for color management. Other solutions, such as the web-based viewer developed by the Centre de Recherche et de Restauration des Musées de France based on the open source software IIPImage [10], aim to offer high-resolution images (greater than the maximum resolution allowed by human vision) and tonal control in wide gamut spaces, such as CIELab. However, the absence of the third dimension limits the visualization of the mesostructure; large files are generated, hard to manage on consumer devices and by unskilled operators, and a problematic image stitching is required.

To overcome these problems, a new optimized solution, specifically designed for drawings, has been developed for acquiring the artifact using an RGB camera and a light source and then carrying out its visualization, rendering it like a computer graphics image under all illumination and observation conditions (Fig. 1). This involves:

- the acquisition of a digital signal, which is as free of artifacts as possible, from devices and its post-processing;
- a controlled pipeline from acquisition to visualization in order to avoid data quality loss (Fig. 2);
- a faithful perceived reproduction of color and reflectance properties [11].

It is a solution that is easier to use and with limited cost compared to the sophisticated techniques illustrated above, achieved by:

- the development of new shaders;
- the improvement of the quality of real-time rendering (RTR) and of the color reproduction fidelity within an OpenGL viewer [12];
- the evaluation of the drawing degradation due to the light source during shooting (exposure time to the light);
- the introduction of a systematic analysis of the quality of the images.

The developed workflow and techniques were tested on Leonardo da Vinci's most famous drawing, titled *Study of the proportions of the human body* (metal styli, silver or lead tip, pen and ink, watercolor touches, white paper, mm. 345 × 246, Venice, Gallerie dell'Accademia, Department of Drawings and Prints, cat. No. 228), also known as the *Vitruvian Man*.

This case study well illustrates the problems tackled by the developed system.

Visitors who benefit from direct observation – e.g., in the recent exhibitions in 2009 and 2013 at the Gallerie dell'Accademia in Venice – would be surprised to be placed in front of a small drawing that is little more than an A4, is hardly analyzable and has to be observed at a distance of more than 1 meter [13,14]. The sheet presents a back, which, of course, cannot be exposed because the drawing is lying on a support. Therefore, it is not possible to observe the recopying work of Giuseppe Bossi, nor is it easy to understand the amazing execution technology used by Leonardo, with its typical and extraordinary precision emphasized by the use of a silver tip [15]. For example, consider the technique used to draw the circle, certainly one of the signs that most attract our attention: it is not a single plot using the forearm or obtained by rotating a compass. The latter was used just to make a groove where Leonardo could place the metal tip dipped in ink; the circle is thus realized with signs no longer than an arc subtended at 30 degrees by drawing freehand on this groove, as shown by the various stages, which is invisible as a whole, but clearly distinguishable in the enlarged detail.

These problems of facing an analytic observation remain even for the scholar authorized to observe the drawing privately. The front and back remain permanently separated, creating the impossibility of achieving the typical handling of those who want to observe a detail on the front and then see what it corresponds to on the back, i.e., a fast rotation of the paper support, possibly repeated in both directions.

3. Methodological premise

The key issue to solve to put in practice our solution is the finding of the BRDF function and its per-pixel solution at each point of the drawing surfaces. The use of the correct BRDF allows for modeling of both the specular and diffuse reflectance components as well as the paper depressions and bumps [11]. Current research on drawing visualization aims to provide only the highest quality possible of the diffuse reflectance component, omitting the specular one, which is always present (e.g., graphite or ink).

To correctly model the BRDF, [16] suggest an organization of light interactions into three types roughly grouped by the size of the geometric structures by which they are influenced:

- macroscopic scale: features on this scale can be regarded to define the shape and geometry of a model;
- mesoscopic scale: features on this scale are still just visible with the naked eye but are usually not considered to be part of the defining shape of an object (e.g., small bumps);
- microscopic scale: on this level, the light is thought to interact with microscopically small facets on the surface of a material, orders of magnitudes below the resolution of the human eye.

The solution to the characterization of these three levels in the case of an ancient drawing was found as follows:

- macroscopic scale: the shape of the surface of a drawing has been considered as a rough plane; therefore, the macrostructure was assimilated with good approximation to a polygonal plane (512 triangles);
- mesoscopic scale: today's state of the art method for modeling the mesostructure is certainly the bidirectional texture function (BTF), a 7-dimensional texture representation that extends the