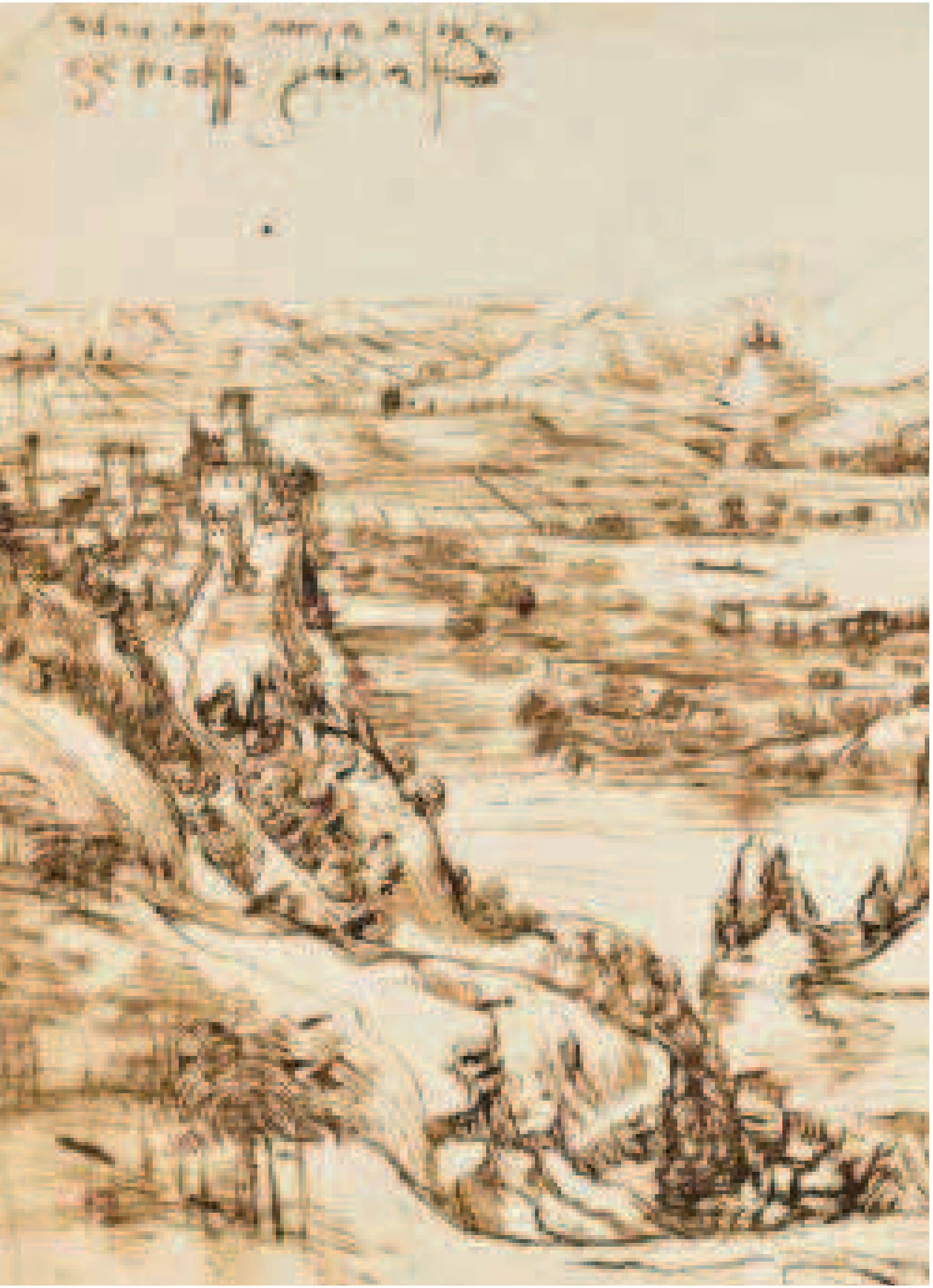

Leonardo in Vinci. At the origins of the genius

edited by
Roberta Barsanti

GIUNTI

Leonardo a Vinci. At the origins of the genius

Vinci, Museo Leonardiano
15 April
15 October 2019

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Il Paesaggio 8P tra tradizione e innovazione
Il paesaggio di Leonardo

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Thanks
Gallerie degli Uffizi, Firenze: Maurizio Catolfi, Antonio Godoli

Soprintendenza Archeologia, Belle Arti e Paesaggio per la Città metropolitana di Firenze e le province di Pistoia e Prato: Superintendent Andrea Pessina; Local area officers Vanessa Gavioli, Gabriele Nannetti

Catalogue

Giunti Editore

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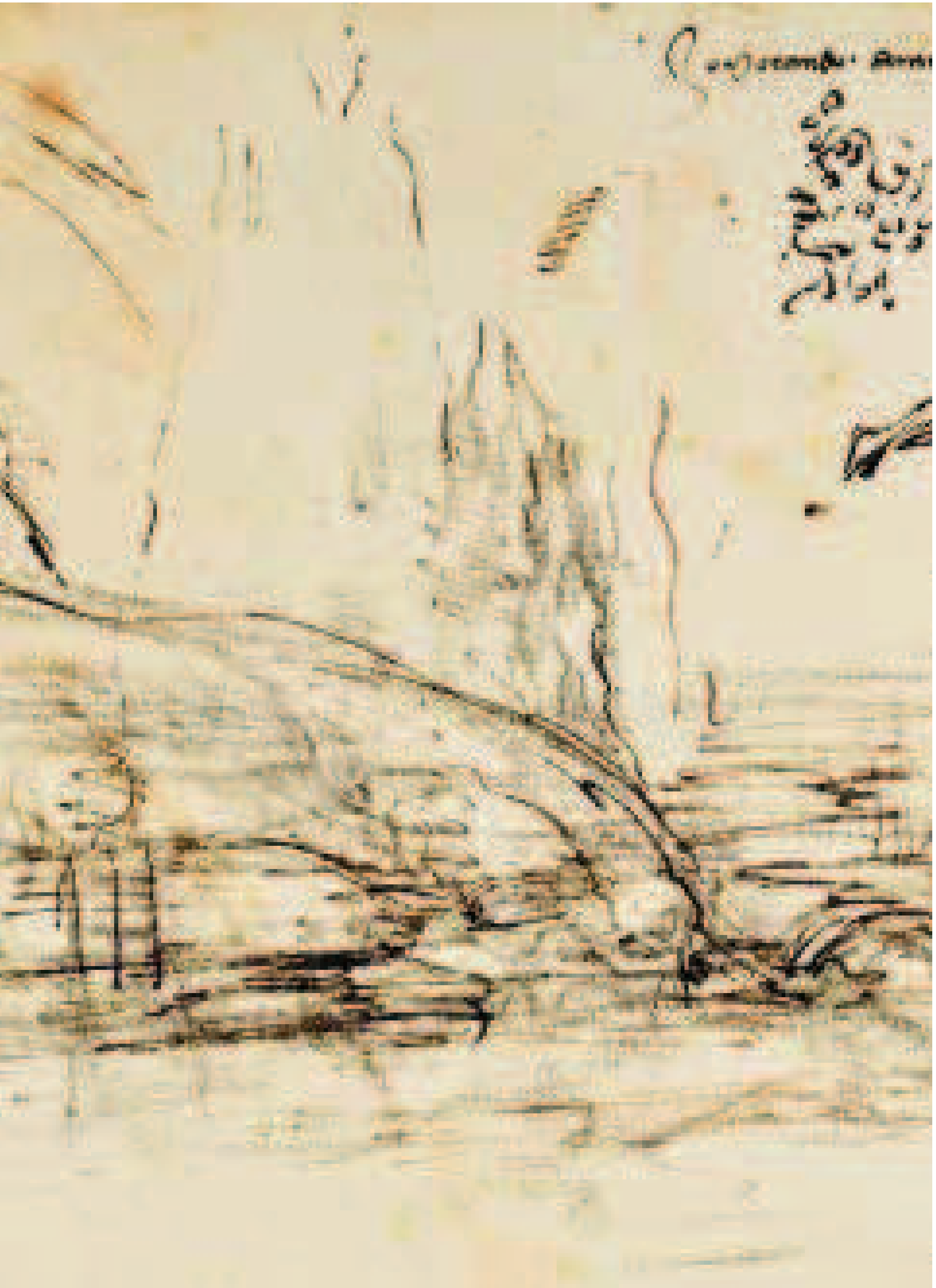


Seeing inside drawings: a system for analysing, conserving, understanding and communicating Leonardo's drawings

Marco Gaiani, Fabrizio Ivan Apollonio, Giovanni Bacci, Andrea Ballabeni, Marco Bozzola, Riccardo Foschi, Simone Garagnani, Roberto Palermo

Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P, detail of the verso (fig. 29 enlargement), geometric figures drawn in black chalk (?).

INTRODUCTION

This work describes a digital communicative artefact that is designed as a means of surrogating, investigating, describing and communicating drawings, including their content and methods, accurately reproducing their form, features and appearance in order to provide a unitary response to two distinct and complementary issues: the first is to create archives of drawings that faithfully describe the information contained in the original analogical, physical system; the second regards the methods for capturing the drawings and rendering them three-dimensionally, that is, those systems and techniques that make it possible to reproduce and display analytically the three-dimensionality of the graphic sign in a perceptual form. The aim of this is to conduct a visual appraisal of the state of conservation of the drawing, the overlying deposits and the interventions to which it has been subjected over time (Fig. 1).

The name of the application is *ISLe – InSight Leonardo,* and it uses five photographs of the original document to reconstruct and digitally render the three-dimensionality of analogic drawings, reproducing the complete formal quality and surface reflectance of the original, rendering the colour with a difference imperceptible to the expert eye and the whole weft of the work at 50 µm resolution.

The goal of the solution is to three-dimensionally reconstruct the whole spatial reflectance in order to gain an appreciation not just of the graphic features of the work, but also of the deformations in the paper and areas where there may be conservation issues arising from corrosion of the paper due to the acidity of the ink.

ISLe needs to be seen, touched and visualized. It sets out to recreate the drawing in digital form, in so far as it is a three-dimensional photorealistic replica that employs two paradigms: firstly to give the sense of having the drawing in one's hands, and, secondly, that of showing what is not visible to the naked eye. It can be used both by the conservator on a desktop PC or tablet, or by visitors to an exhibition on high-definition touch screens based on the same principles of smartphone usability.

The system enables conservators, scholars and restorers to observe what it is hard to see with the naked eye, and to quickly crosscheck information that would otherwise require multiple tests, often instrumental and non-synchronic, and often hard to superimpose.

During an exhibition, a solution like this could be set alongside the original work to allow it to be "read", or could stand in for it. At the same time, besides permitting predefined paths (the customary narrative style of multimedia found in museums and exhibitions), the software also supports individual exploratory pathways, stimulating the attention and interest of visitors.

Users can zoom in on high-resolution images, measure the characteristics of an image, modify the visible dynamic range, compare and juxtapose *recto* and *verso* or various parts of the drawing with different shaders or lighting techniques in order to emphasize details, colours, materials and procedures. Finally, the system integrates semantic and critical-historical annotations to the 3D model due to the multimedia environment, so ordinary members of the public but also scholars can not just see the many extraordinary details of the drawing appearing before them, but can also link them to earlier studies and discover previously unobserved features.

ISLe was engendered and inspired by humanists, who over time have supported and encouraged its development: Paola Barocchi, who did a lot of the groundwork with a view to a careful and wide-scale digitalization of the collections of ancient prints; Marzia Faietti, who, engaged as she was in studying the line, a key element in European art, asked us for around ten years to devise instruments capable of perceptually showing the graphic process underlying a drawing; and finally, Salvatore Settis and Carlo Pedretti, who, by enthusiastically checking its use, enabled us to understand that our approach was right and that we had not just built a "beautiful toy" but a tool that was useful for seeing, analysing, understanding and for genuinely stirring feelings.

A big role in the development of the application, a decade in the making, was played by Leonardo da Vinci, whose drawings, not by chance, have defined the milestones of *ISLe.*

One of Leonardo's best-known drawings, the *Studio di volto femminile* (*Study of a Female Face*),[1] permitted the definition of the problems and prerequisites associated with two-dimensional digital capture.[2] Later, when the first visualizer prototype seemed to have the characteristics of the mature system, it was his most famous and widely studied drawing, *Studio di proporzioni del corpo umano* (*Study of the Proportions of the Human Body*), better known as *Uomo Vitruviano* (*Vitruvian Man*),[3] that made it possible to realize the final configuration, both with regard to capture techniques and instruments and in relation to the system of visualization. The success of this union was crowned by a monographic but wholly digital exhibition in Fano in 2014,[4] which attracted over twenty thousand visitors in little more than two months, before then being replicated in Vinci.

Finally, the basic assumption and hypothesis of all our work came from a passage written by Leonardo himself. The way in which it is rendered by Paola Salvi in a fine work about Leonardo's anatomy is so closely interwoven with the aims and methods of our project that simply citing it here,[5] with apologies to the author, seemed to us to be the best way to define it. The passage from Leonardo, which draws on Aristotelean thinking, especially the *Metaphysics,* can be found in a note on folio K/P 144 v, now in Windsor Castle (London): "Adunque [per conoscere] è necessario figurare e descrivere." ("So [to understand] it is necessary to represent and describe").[6] This principle brings together experience and theoretical elaboration, conferring an operative dimension on Aristotelean doctrine, and is formalized by Leonardo through a conceptual circuit that can be schematized as follows:

REALITY
EYE
MIND
ELABORATION THROUGH THE
SCIENCE OF PAINTING
EYE
MIND
REALITY

The procedure is referred to by Leonardo as "experience" of the world around him, "acquired through the senses", and it was his point of departure for new understanding.

ISLe provides knowledge, reproducing and analytically showing in perceptual form the three-dimensionality and features of the graphic sign of an original in analogic form on a paper or at least a flat support for the purposes of visual analysis.

The basic procedure can be divided into three phases: capture, reconstruction and rendering. The aim of the first phase is to learn about the surface properties of the drawings: their form, reflective properties and the parameters of the reflection model. The purpose of the second one is to modelize them *mathematically,* while that of the third is to reproduce them visually in an accurate way. With respect to this workflow, the existing methods presented three problems:

– the estimate of the surface spectral reflectivity usually does not permit an accurate reproduction of the colour;

– the reconstruction of the 3D surface is not precise;

– realistic images can not be rendered by using a reflection model with fixed, i.e., reproducible, parameters.

The method that was developed enabled us to precisely estimate the surface properties of the drawings so as to overcome the three above-mentioned limitations, especially in the definition of the colour – which, in the case of drawings, has very different characteristics to those of paintings (just a few colours, and usually close to neutral), of the reflectance of the surface, which plays a fundamental role in the perception of the figuration (the surface of a drawing is not smooth, but rough, and as it consists of ink, red or black chalk, pencil and stylus marks, furrows and highlights appear on the surface), in the type of depth-related information (while the brushstrokes and cracks of a painting measure between 10 µm and 2-3 mm, the typical depths left by pens and pencils rarely exceed 10 µm, with an average of 5 µm; the micrograin of the paper itself has lumps no greater than 100 µm), in the possibility of producing images from different angles (in order to analyse the state of conservation of the drawing, overlying sediments and interventions to which it has been subject over time, issues that have seen raking light photography become the best-known solution[7]) and condensing the front and rear of the drawing, a typical characteristic of this graphic system. In particular, the need to render this final characteristic means that techniques that deliver excellent digital visualizations, such as Reflectance Transformation Imaging (RTI), are not entirely appropriate. Proposed by Tom Malzbender in 2001[8] and then developed by Cultural Heritage Imaging,[9] it is basically an extension of the texture map, which, by using Photometric Stereo techniques,[10] permits greater control over the rendered appearance. However, results can only be obtained for a single pre-established point of view, leaving the *recto* and *verso* of the sheet permanently separate. The same problem is inherent to other systems as well, such as the web-based visualizer developed by the Centre de Recherche et de Restauration des Musées de France on the basis of open-source IIPImage software,[11] or the one proposed by Google Arts & Culture,[12] which produces single high-resolution images (Gigapixel images) with a wide colour range (up to 32 bits per channel) or multispectral images.

While current research aims to obtain the highest possible colour fidelity just in the diffuse reflectance component, with drawings it is also necessary to evaluate the specular reflectance component, which completely alters the perception of the graphic work, above all with regard to materials that contain metals, such as inks.[13]

ISLe sets out to overcome these problems with a completely 3D solution, where the reproduction of the graphic properties of the surface of the sheet stems from the total appearance concept.[14] This basically consists of a faithful transposition of the reflectance properties of the drawing through a process that covers three main areas:[15] goniometric (validation of the properties of the surface, that is, of their Bidirectional Reflectance Distribution Function (BRDF),[16] radiometric (accurate simulation of light movement) and perceptual (final image corrected for the human eye). The appraised BRDF is then rendered as a graphic computer image at a frame rate of 60 Gz under every condition of lighting and observation.

Globally the solution starts from the assumption of guaranteeing perceived fidelity rather than the metric accuracy of the artefacts, and uses a capture method that is much simpler and less damaging for the drawing than other workflows with excellent results, such as the one described by Gardner *et al.*,[17] then developed by the same group and by other researchers.[18]

The *ISLe* workflow consists of five subsystems:

– capture with a three-sensor camera that produces high-performance colour images;

– an ad-hoc LED-based lighting system;

– a solution developed to reproduce the surface with micro and macroscopic fidelity;

– a solution to visualize the high-fidelity communicative artefact, making use of a low-cost, portable rendering engine on multiple devices (wall, PC monitor, touch tables, tablets, smartphones);

– a visualization interface for museum and exhibition visitors based on touches and gestures that are familiar because they are adapted from the ones used on smartphones.

Overall, the system basically mirrors the one used for *Uomo Vitruviano,* described in the publication that was brought out at the time.[19] Though we started with the same basic scheme, numerous innovations were made for the *Paesaggio,*[20] to the extent that the application can be considered to be completely new (fFg. 2). The reason for this was both the desire to improve some features that by the end of the previous experience we had already identified as being susceptible to further progress, and the fact that the morphological configuration of the drawing is very different to the previous case. While the paper support of *Uomo Vitruviano* is effectively flat, following the restoration that reduced the deformations perpendicular to the plane of the sheet to the order of its thickness, measured as 0.2 mm, in the case of the *Paesaggio* the surface has deformations of a greater magnitude. This made it necessary to devise a more accurate solution for reproducing the mesostructure of the artefact (Fig. 3).

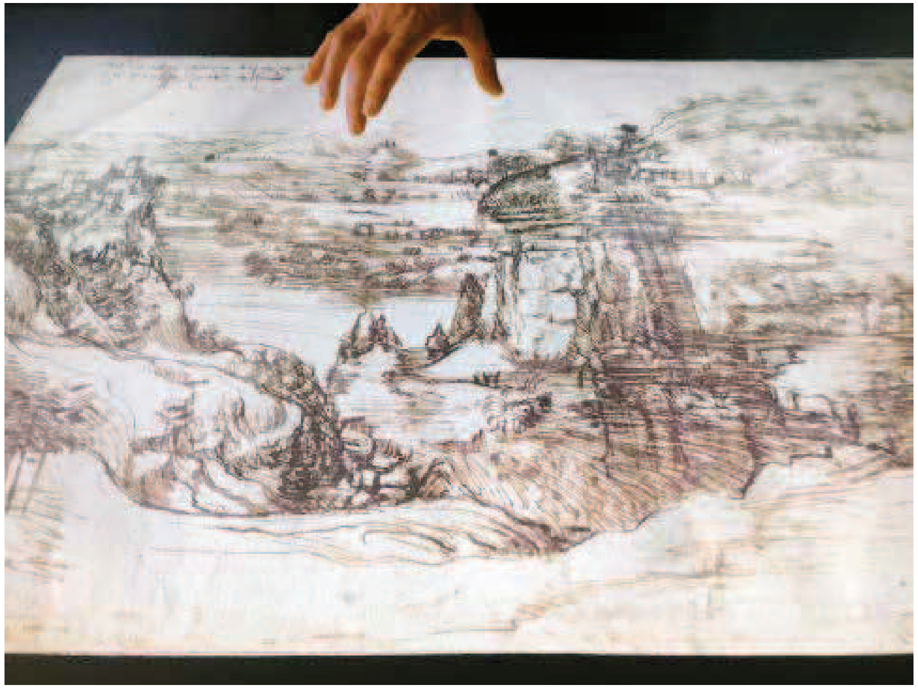


Fig. 1. The ISLe application – *Landscape.*

Fig. 2. Grey-scale representation of the map of the heights of the sheet on which the *Landscape* is drawn.

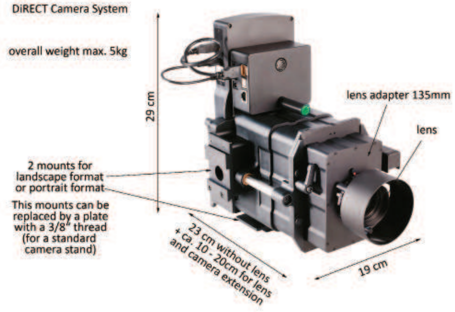


Fig. 3. Rencay DiRECT digital scan back and camera system.

In the notes that follow we will therefore describe the main innovations that were introduced and the specifications of the system. Though, as usual, these change each time, consolidated measurement and evaluation procedures were followed.

CAPTURE TOOLS AND INSTRUMENTS

The capture involved the use of three new instruments:

– an updated version of the scanner camera already used in the previous experiences;

– a repro copy stand;

– a lighting system based on LED lights instead of the previous fluorescent lights.

The capture device

The capture device chosen for the earlier works was a digital scanning back (*Rencay Superfineart*) equipped with an RGB trilinear CCD sensor, 8000 pixels per sensor (*Kodak KLI-8023*).

For the capture of the *Paesaggio* an integrated scan back and camera system, the *Rencay DiRECT Camera Systems* 24k^3 (Figs. 4-5), was used;[21] based on the same sensor, it has a pixel pitch of 9 µm, which permits a limit resolution of 55 lp/mm with 60% contrast on an area covered by the sensor equal to 72 x 118 mm[22] and a 48-bit resolution with a native colour depth of 13000 x 8000 pixels and a maximum of 39000 x 24000 pixels. In our case the native resolution was used, which corresponds, on the sampled area of 350 x 250 mm, to a nominal resolution of around 950 pixels/inch and an exposure time of 8 milliseconds per line, the overall time for each capture being around 1 minute and 30 seconds.

The adopted solution has various advantages over a reflex camera, as the image of the trilinear sensor contains RGB data in every spatial position of the image, permitting the interception of a lot more data in the visible spectrum, eliminating the typical demosaicing problems of the Bayern patterns:

– a limited response of the colour in regions where fine details are present to try to eliminate unnatural elements, which lead to an imprecise colour response in those regions;

– difficulty in precisely aligning the pattern of the colour filters on the photodiodes of the sensor, creating misalignments.

Furthermore, the large imaging area of the trilinear system makes it possible to have large pixels, less onerous than small pixels for the camera lens, thereby yielding more information (more pixels) but also greater clarity and contrast.

Finally, the capture involved a limited number of scans (just 4, compared, for example, to the minimum of 36 photographs required for the RTI system).

The chosen lens was a Rodenstock Apo-Macro-Sironar-Digital 120mm. f/5.6 72×96 mm, which, for the area that needed to be covered, allowed the camera to be kept at a limited height (around 75 cm), while retaining excellent resolution even at the corners, with limited distortions and an excellent uniformity of illumination. These lenses are practically distortion-free and have excellent clarity and high contrast thanks to the large image format, the high resolution of the line pairs (up to 90–200 line pairs per mm, as opposed to the 40–60 line pairs per mm of an average format).

The Rencay DiRECT Camera Systems $24k^3$ easily solves crucial problems associated with the capture of a drawing, without requiring any further software or hardware:

– flatness between the sensor plane and the drawing plane to ensure sharpness from corner to corner;

– control of light uniformity, avoiding variations caused by the positioning of the light or the decay of the lens, thanks to the implementation of flat fielding algorithms,[23] which permit the homogenization of the average luminosity of the image;

– focussing by means of two instruments: the first one is manual, and uses a projection system consisting of four flashing lights incorporated within the cover of the shutter; the second is a software tool that helps to find the optimal level of sharpness, even if the original is not completely flat, by comparing different focussing levels.

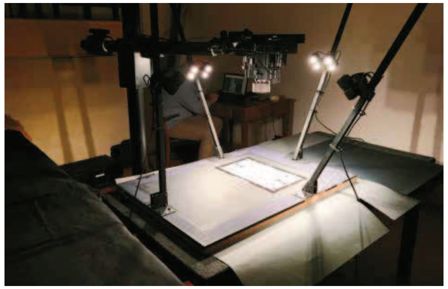


Fig. 4. The solution for the structure to support the lighting system and hold the drawing, with the column holding the Rencay DiRECT Camera Systems $24k^3$ (digital scan back and camera) in position at the Gabinetto Disegni e Stampe, Uffizi Gallery.

Fig. 5. The light supports printed in matt black ABS filament: the printed support.

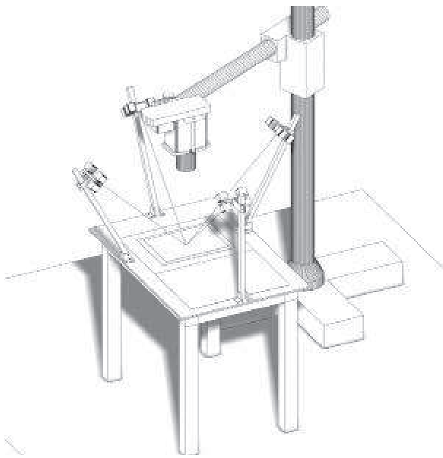


Fig. 6. Three-dimensional view of the planned structure for housing the lights and drawings, with the profile for positioning the drawings.

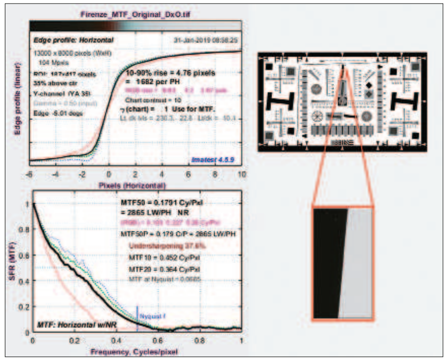


Fig. 7. Measurement of the Modulation Transfer Function (MTF): Diagrams of the Edge/SFR results for the image of the ISO 12233 target on the left, with the relative area of interest on the right.

The copystand

In order to minimize the time required and operational uncertainties, and to optimize the quality of the results, it was decided to produce a copystand able to satisfy the specific requirements of the chosen camera/lights solution and the type of artefact being captured:

– a structure that is both stable (to minimize fuzziness caused by oscillations, a particularly acute problem with scan capture systems) and easy to transport;

– standard reproduction area able to contain the drawing and the passe-partout in which it is contained in an open position;

– illumination system with lights mounted on all four sides, inclined at an angle of 45° with respect to the horizontal, and equidistant from the centre of the drawing;

– no interference between the light sources and the camera;

– limited costs;

– adaptable to different contexts.

The solution was found by separating the structure that supports the lighting system and houses the drawing from the stand holding the camera (Fig. 6). A commercial solution was chosen for the latter, a Manfrotto 816 Salon Camera Stand, with a column reaching up to 280 cm from the ground and mounting a Manfrotto 410 tripod head (Fig. 7). The specially made structure for the lights and the drawing consists of a base measuring 90 x 65 x 1.6 cm, made from two superimposed medium density panels weighing 14 kg in total, and capable of holding the drawing and the passe-partout in an open-book position.

To support, on each side of the copystand, the four LED lights mounted at a 45° angle to the ground and consisting of a cuboid with a side measuring 35 mm, four removable extruded aluminium square bar arms with a section of 20 x 20 x 1 mm and a length of 1000 mm were produced. These were attached to the copystand with two angle brackets held in place by bolts. The positioning of the arms was asymmetrical so the passe-partout could be open (Fig. 8): three arms were placed at a 63° angle to the vertical, while the fourth was mounted vertically.

Housed on the square bars, and produced with a 3D *XYZprinting da Vinci pro1.0* printer,[24] were the sliding supports, made from matt black ABS (Acylonitrile Butadiene Styrene) filament with a diameter of 1.75 mm and resistant to the heat emitted by the light sources (Figs. 9, 10).

A number of further devices were added in order to: centre the drawing more precisely with respect to the vertical of the camera (two outlines with the same measurements as the drawing and the open *unnatural elements*) (Fig. 11); to permit ease of transport (two handles on each side); and to ensure the absence of diffuse and specular reflection (matt-black water-based paint and black card). Some templates were also made to check the perfect inclination of the arms and the height of the lights during assembly (Fig. 12).

The adoption of this solution for the copystand and the new camera enhanced the effective capture resolution measured as limit of resolution[25] and sampling resolution.[26] In the specific case, as had already emerged during previous experiences,[27] the line in Leonardo's drawings is particularly challenging with regard to this parameter. The reference data indicate, in fact, sign values at a minimum of 90 µm thickness, a measure completely in line with the limit of sensitivity to visual contrast (Contrast Sensitivity Function or CSF), that is, the ability of the eye to distinguish minimal details, which for a draughtsman working with an interior light or torch has a maximum value of 100 µm. On the basis of the Shannon-Nyquist theorem, whereby the resolution necessary for correct sampling must be at least equal to at least double the inverse of the amplitude of the finest detail, Leonardo's line requires a resolution of at least 24 pixels/mm, that is, at least 610 effective ppi. The measurement of the conservation of the detail can be carried out at different spatial frequencies through measurement of the Modulation Transfer Function (MTF). This is a measure of the degree to which an imaging device or system can accurately reproduce a scene,[28] codified by regulation ISO 12233. To maintain congruity with the measurements taken in 2014, here we used the version dating to 2000.[29]

The response of our system towards an inclined edge in terms of climb distance (climb 10–90%), the MTF curve as a function of spatial frequency expressed in units of cycles per pixels, measured by the values of MTF50 and MTF10 (Fig. 13),[30] is illustrated in Tables 1–2, and it corresponds to an effective resolution of 740 ppi, capable of resolving details of 60 µm.

The lighting system

There are two main aspects to consider when planning the lighting system for the image capture of a drawing.[31] On the one hand, it is necessary to achieve high quality in terms of luminance, uniformity, contrast and colour reproduction. On the other, to adequately conserve drawings and cause the absolute minimum of damage, the interaction of the artistic artefact with electromagnetic radiation must be minimized.[32]

In 1990, the Commission Internationale de L'Eclairage (CIE) CIE 89/3-1991 drew up recommendations for a vast range of light-sensitive materials, including paper, oil on canvas, fabrics and watercolours on paper, pointing out that the damage per radiant unit of exposure to light increased as the wavelength of the light diminished.[33]

In 2004 the CIE published recommendations to limit the damage caused to museum artefacts by optical radiation. These are: (1) to eliminate all optical radiation below 400 nm; (2) to keep the level of illumination below 50 lux for materials that are moderately or very sensitive to damage caused by optical radiation;[34] (3) to keep the level of illumination below 200 lux for materials with low reactivity.[35] These recommendations, which served as our main reference guide, also lay out exposure limits measured in lux-hours per year, operating according to the consolidated hypothesis of cumulative damage, as indicated by the law of Bunsen and Roscoe, which states that high-intensity exposure for a brief period is the same as low-intensity exposure for a longer period, that is to say the expression

exposure = intensity x time

remains constant,[36] and so 1000 lux for 10 seconds has the same effect as 10 lux for 1000 seconds. Various studies have confirmed this principle with regard to light-sensitive materials, in particular the one conducted by Saunders and Kirby from the National Gallery in London.[37]

For exposure at 50 lux the guidelines for exhibitions state as the maximum duration of exposure of works on paper periods of time ranging from four to twelve weeks a year. At this level of exposure, the paper artefacts would show evident signs of discolouration only after 1.2 Mlux/hour, or 100 years of four-week annual exhibitions.

The Italian UNI regulation (UNI 10829/July 1999) basically echoes the CIE directive, introducing limitations on the annual dose of light, defined as the sum of illumination multiplied by the number of hours of exposure in a year and measured in lux-hours/year. The regulation stipulates three months every three years, effectively quantizing the more restrictive indication of the CIE on a three-year basis.

The calculation method, based on Bunsen and Roscoe's law, is also excellent for evaluating exposure to light during photography, where an accurate reproduction of the appearance of a drawing requires light sources with high colour rendering.[38] The light source with the maximum colour fidelity is natural sunlight; the artificial light source that most closely resembles that spectrum composition is generated by incandescent bulbs. Both these light sources (sun and incandescent bulbs) emit light with spurious wavelengths (infrared, IR, and ultraviolent, UV), which are invisible and undesired. The presence of these spurious emissions entails a waste of energy in the form of heat, making incandescent bulbs unsuitable for uses such as photographing and observing drawings. For this reason the lights preferred for observing art works, including drawings, are low colour correlated temperature (CCT) incandescent lights, provided they have a low emission of short waves (damaging only to a limited degree) and a usual temperature of 5000* K. The studies of Scuello *et al.*,[39] moreover, in relation to reproductions of printed artworks, indicate that observers prefer a CCT of 3600° K with an illumination of 200 lux.

Regarding lighting for photography, it should be pointed out that linescan camera systems are well suited to various kinds of continuous light illuminators – tungsten, fluorescent, HMI[40] – but only the last two are usable because tungsten bulbs emit a lot of heat and are therefore highly damaging.

For the capture of *Uomo Vitruviano,* four Lunarea illuminators were used. Each one had six Osram Studioline continuous fluorescent light tubes, with no flickering, each one 55w, a CCT of 5600° K and a spectrum suited to the sensitivity of the CCDs, with a Colour Rendering Index (CRI) of > 85.[41] Spectral Power Distribution (SPD) analysis, which describes a light source in a much more complete way than the CCT, shows however that these illuminators have a slightly dominant green, determined by their particular spectral distribution and the presence of frequencies in which the response is extremely limited, which, as Fig. 14 shows, are also for the most part the ones relating to the colours of the *Paesaggio.* The nature of the tubes, moreover, entails a certain instability in the colour response, requiring frequent checks and adjustments, and very long operational times. As it is, it takes around half an hour after switching it on to reach the nominal CCT. Because of this necessary dead time, the exposure of the drawing during photography was equivalent to around 600 lux-hours/year, the equivalent of around 12 hours of public display. On the other hand, the temperature of use is only 22°C, and it damages the drawing to a very limited degree. Likewise, the damage caused by the small UV component, in our case measured at 50 milliWatt/lumen for a luminance of 2668 lux, is limited.

The data concerning the illumination risk for the capture of *Uomo Vitruviano* are summarized in Table 3.

To improve these performances in the case of the *Paesaggio,* use was made of white High Flux LED lighting technology,[42] which consists of a single one-chip luminous diode capable of supplying a very luminous source with a primary thermal dissipation device integrated in the packaging.[43]

As regards the quality of illumination, Boissard and Fontoynont's study involving visual experiments on a colour test target and a Vermeer reproduction to compare white LED, tungsten, halogen and fluorescent lamps showed that observers preferred the white LED light illumination.[44]

As for the security of capture, Ishii *et al.* compared the colour degradation due to white LED and fluorescent lamps, showing that the former generate more limited losses in saturation than fluorescent lights.[45] Piccablotto *et al.* tested the decolouration caused by white LED lamps with different CCTs compared to a traditional halogen lamp.[46] The results showed the importance of the SPD for evaluating the effective cause of colour degradation, and at the same time indicated how, in general, white LED lights are less damaging than traditional halogen lamps.

For the photographic reproduction of drawings, and with reference to the parameters already described, the LED system currently offers innumerable advantages with respect to fluorescent lights. Rendered light flow being equal, the LED lamp occupies less space, is lighter, reaches nominal CCT immediately after being switched on, has low energy consumption and, above all, does not emit UV and IR radiation, but only visible radiation, a characteristic that makes it particularly suitable for illuminating objects that suffer damage from light at these wavelengths. Finally, the low power and small size facilitate partialization, customization, geometric regulation of the light flow and colour management.

The selection of the specific LED illuminator posed a number of problems: the highly automatized nature of LED production results in very uneven performance levels, even among LEDs of the same type and series: the LED lamps available on the retail market are more geared in to energy efficiency than to spectrum continuity.

The solution was to limit the number of diodes, use high-quality LEDs that guarantee only modest variations in terms of colour rendering and, at the same time to take on board the observed preference for a CCT of 3600° K, which improves the colour appearance, increasing the perceived contrast and chrominance.[47]

To satisfy these requirements a prototype was built, consisting of sixteen Relio² (www.relio.it) LED lights (four per side) (Fig. 15), the technical specifications of which are listed in table 4 and which permitted a single light set-up. This illuminator emits light as a continuous spectrum at a CCT of 4000° K. This is a neutral white with high colour rendering. It has a luminosity of 40,000 lux at 0.25 m, and a CRI of > 95. Its SPD is in Fig. 16, and has a high colour reliability on all wavelengths, and excellent colour reproduction even in the rendering phase. Each Relio² was calibrated individually, and the emitted light was certified by a spectrophotometer, permitting mathematical rather than the empirical calculation of the balancing of the white (Fig. 17).

Overall, the illuminator inherits many of the positive properties of incandescent lamps, but avoids the excessive emission of colour and the emission of damaging UV and IR radiation. The data regarding the risk posed by the lighting for the capture of the *Paesaggio* is summarized in Table 5.

The collimation optics used by Relio² comprise five interchangeable TIR (Total Internal Reflection) lens with different apertures, which make it possible to capture and collimate all the light emitted by the LED in the 180° arc, unlike classic open parabola collimation, which is not suitable where constant colour rendering is necessary across the whole aperture of the lens (Fig. 18). Above the main TIR parabola, Relio² has a second collimation stage formed by a multitude of hexagonal lenses in a honeycomb pattern. The aim is to standardize even more the chromaticity of the emitted beam, eliminating any spurious collimation, including any eventual traces of colour aberrations.

The power electronics of Relio² avoids a typical problem associated with LEDs, that is, the flicker effect caused by the harmonic ripple generated by the traditional pilot electronics of LEDs in current control and luminosity regulation.

The illuminator therefore possesses a series of basic characteristics that make it highly suitable for photography, while others, more closely linked to specific operativity, were obtained with rapid and efficient customization by the manufacturer.

MAINTENANCE OF COLOUR CONSISTENCY

The fundamental problem in the digital capture and reproduction of art drawings concerns the colour and tonal definition of the graphic work, which, in our case, must be framed within the more general theme of the complete definition of the properties of the material, that is, of the BRDF. It can therefore be identified in the capture and reproduction of an albedo map.

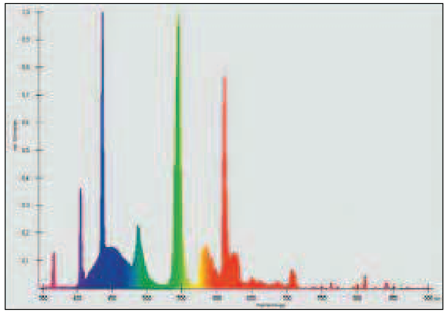


Fig. 8. Spectral power distribution of the Osram Studioline 55W/5600K continuous fluorescent light tubes (Source: OSRAM GmbH).

Fig. 9. The Relio² light.

As the digital reproduction of the reflection of a surface requires powerful simplifications of the physical behaviour of light and its interactions with the surface in order to be calculable within an acceptable period of time, one of the most critical issues in capturing and reproducing an albedo is therefore associated with the impossibility of obtaining the metric fidelity of the colour properties. An acceptable objective is to achieve perceptual fidelity at least. This is the key aim of *ISLe,* which seeks to maintain perceived colour fidelity, making use of an accurate workflow from capture to visualization on the display. A crucial phase in this workflow concerns the colour correction (CC) of the captured images, that is, in the phase in which the colour signals detected by the sensor are transformed into the corresponding pixel values.

The need for colour correction stems from the fact that the camera sensors do not have the same spectral sensitivity as the cones in the human eye, nor does their spectral sensitivity perfectly satisfy the Luther conditions, that is, they are not a perfect linear transformation of the sensitivities of the cone.[48] As a result there may be metamerism phenomena between the camera and the eye.[49]

The goal of CC is therefore to correct the camera's colour measures towards colour spaces correlated with the human visual system. With digital cameras, the most common way of obtaining CC is to use reference charts of colour patches with known spectral reflectance, usually measured with a spectrophotometer.[50] From their colourimetric description and the corresponding values of the non-elaborated acquired pixels, it is possible to calculate the CC parameters necessary to obtain accurate colour images.

To find the transformation between values in the CIEXYZ[51] space and acquired values in the RGB space,[52] various techniques have been developed over the years: simple linear matrixes, look-up tables, polynomial least squares systems, etc. A full description of these can be found in Reinhard *et al.*[53]

In any case it is assumed that the spectral sensitivities of the digital camera are linear combinations of those independent from the device, namely that the measured tristimulus value is a linear transformation, by means of a 3 x 3 matrix called the colorimetric matrix, of the values estimated by the sensor, whereby:

$$(\hat{X}_i, \hat{Y}_i, \hat{Z}_i) = f(R_i, G_i, B_i)$$

An efficient solution for calculating this matrix is to reduce the total visual colour difference *J* to the minimum, which is a weighted sum of the colour differences *ΔE* (calculated, for example, in the CIELab perceptually uniform colour space) between the tristimulus target (X_i, Y_i, Z_i) and its estimate (R_i, G, B_i), for each patch $1 \le i \le n$:

$$J = \sum_{i=1}^{n} w_i \, \Delta E(X_i, Y_i, Z_i, R_i, G, B_i)$$

where wi are the weights for the different patches. Usually the minimization is that of the squares.[54]

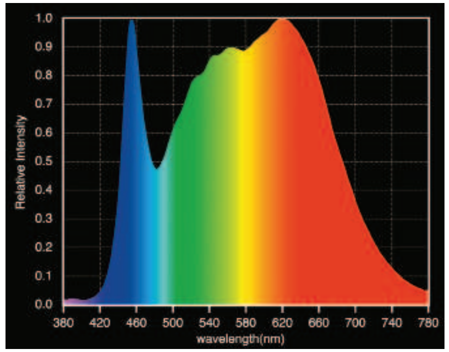


Fig. 10. Spectral power distribution of the 4000KRelio² light. There is a broad band in the 620–640nm area, one of the factors that determines high colour rendering.

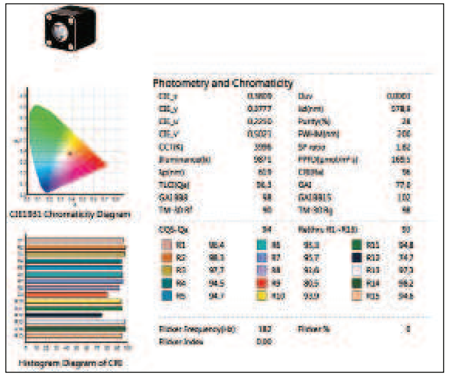


Fig. 11. Photometric and colour values of the 4000K Relio² light.

This method yields the specific results of a given illuminator,[55] and they are very sensitive to the technique used and to operator errors during the capture process. In our case, these are marginal problems because the photography is done in a studio, with controlled lighting and with just one stable set of lighting conditions, with a very simple operational process and immediate evaluation.

The CC was conducted using an automatized target-based solution previously developed by our working group and efficiently applicable to this case as well. Called SHAFT (SAT & HUE Adaptive Fine Tuning),[56] it is based on an X-Rite ColorChecker Classic target[57] This chart, measuring 21.59 x 27.94 cm, consists of 24 standardized coloured squares with known reflectance, the colours of which were chosen to represent various natural objects, colours that are problematic to reproduce, the primary colours RGBCMY and a grey scale (Fig. 19).

SHAFT, implemented in MATLAB, is basically divided into three steps (Fig. 20):

Linearization of the RAW image. Using the DCRaw decoder, the image is linearized in the CIEXYZ colour space in 16 bit in order to avoid the loss of information, requiring a 16-bit output with a fixed level of white, gamma equivalent to 1, and ignoring the specific histogram of the image. The solution was not as precise as the one proposed, for example, by Cheung *et al,*[58] but the final result was sufficiently accurate thanks to DCRaw's capacity to take account of the camera's integrated functionalities, and to the basic quality of the trilinear sensor used;

Exposure equalization and white balance. The first phase in the CC involves balancing the white through a linear transformation and correction of the exposure with respect to patch D4 of the *ColorChecker*;

Two-steps colour correction. Preliminary colour correction was achieved by using a polynomial per-channel fitting algorithm based on the *MATLAB Weighted Polyfit (x,y,n)* function. The algorithm is detailed in Gaiani *et al* (Fig. 21).[59] A second correction was then made with an algorithm established in accordance with the basic idea of the Adobe Camera Raw (ACR) calibration scripts derived from Bruce Fraser's calibration procedure by way of successive approximations,[60] which involves making selective variations and evaluating the global ΔE error for all the patches. SHAFT differs from ACR scripts in the number of tests conducted and the algorithm used to find the best amount of variation (Fig. 22). More details can be found in Gaiani and Ballabeni, 2016.[61]

One key point in the CC process is the use of appropriate colour spaces with which to apply the colour correction algorithms and render the final images.[62] The main parameters enabling this choice are: the extension of the colour range; the perceptually linear coding of the tonal scale to reduce to a minimum the bit depth required to encode an image; the dynamic range; the point of white of the illuminator; the observation conditions; the quantization and compression efficiency.

For *ISLe,* the analysis of these parameters led to the choice of the sRGB, now the predefined colour space for multimedia applications with the IEC 61966-2-1 standard.[63] The values of this colour space are defined at the temperature of 6500° K (that is, with respect to the CIE D65 illuminator). Despite some potential counter-indications (non-linearity, less amplitude of the colour space perceived by the human eye), a number of advantages proved decisive:

– it is the only colour space supported by our API (OpenGL) for 3D graphics;

– it is the only colour space that is 100% visualizable on currently existing monitors;

– the poorly represented colours are not present in the *Paesaggio.* The iron gall ink, the black and red chalk and the paper are instead representable in the sRGB colour space without any need for colour clipping or remapping, as can be seen from the colorimetric diagrams relating to the two faces of the drawing in Fig. 23.

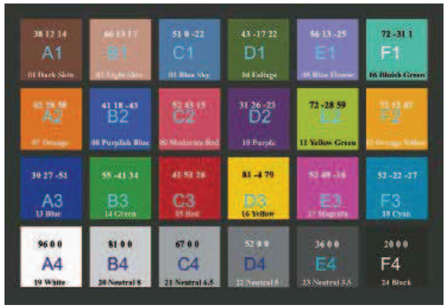
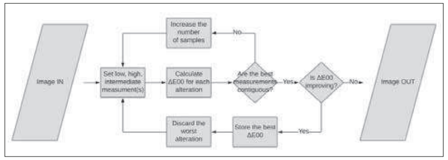


Fig. 12. The X-Rite Color Checker (CC) Classic targets with CIELab colour values and their identification.



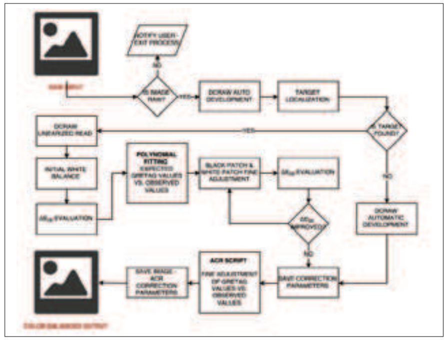


Fig. 13. Process flow of the SHAFT (SAT & HUE Adaptive Fine Tuning) colour correction algorithm.

Fig. 14. Workflow of the colour correction system.

The colour correction workflow is instead realized entirely in the CIEXYZ linear space. The reason for this lies in the observation that, by using this colour space, the errors calculated by the least-squares fitting algorithms correspond very well to the variance of the corrected images with respect to the original, whereby smaller numerical variances correspond to more visually faithful images.[64] Only at the end of the workflow are the images compressed in the sRGB colour space of visualization, employing a look-up table that minimizes the information loss.

The evaluation of the image colour capture normally requires validation. Various visual colour difference formulas now exist to achieve this aim. The most commonly used is the CIELAB, Δ*E* colour difference, calculated for each colour patch.[65] The overall colour coding performances are normally obtained by adding up the statistical measures of the Δ*E* relating to the whole set of colour samples contained in the targets. In our case, the colour metric brought out by the CIE in 2000 was used:[66]

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}$$

The formula draws on the concept of measuring the Euclidean distance between expected colour and measured colour in the CIE colour space and introduces correction factors to minimize the problem of non-percep-

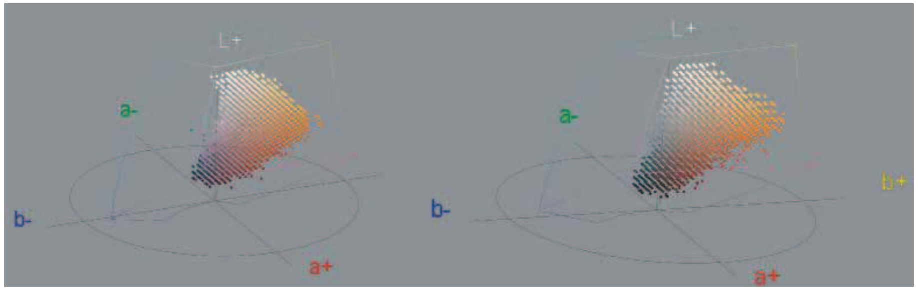


Fig. 15. Colorimetric diagrams relating to the two sides of the drawing in Lab colour obtained by means of ICC3D software. The sRGB colour space is indicated with wire. On the left is the *recto*, on the right the *verso*.

tual uniformity of colours.[67] The differences in luminosity (ΔL), chroma (ΔC) and hue (ΔH) are weighted in relation to the position of the given colour in the CIE space and its luminosity by means of "parametric factors".[68] Specifically, the $\Delta E00$ metric offers five different corrections to the CIELAB space:[69] the functions of weighting for luminosity, chrominance and hue; a modification of the a^* axis in the neutral region; a chroma-hue interaction term effective only in the saturated blue region.[70] The formula, despite some discontinuities, corresponds better to the way in which human observers perceive small colour differences and, for this reason, is recommended by the CIE for colour differences lying in the CIELAB 0-5 units interval,[71] which correspond to typical instances of drawings.

A recent work illustrates how the latest colour difference formulas can be modified by simple power functions (that is, with a single additional parameter) to obtain results considerably closer to the visually perceived colour differences.[72] However, the obtainable statistical differences, and likewise how to pose $SL = 1$,[73] are marginal.[74] For this reason the original formulation was maintained.

The CIE $\Delta E00$ measurement formula was used in SHAFT in two different phases:

– as part of the colour correction workflow, to ensure accurate capture of the colour image;

– to calculate deviation from desired values for the purposes of the colour correction process.

The expected values were obtained by measuring the patches of the ColorChecker used by means of a bidirectional spectrophotometer.

The corrected tolerance values for ΔE were the ones suggested by the best-known guidelines for the digitalization of art works: the Federal Agency Digitization Guidelines Initiative (FADGI)[75] and Metamorfoze.[76]

In relation to our field of interest both FADGI and Metamorfoze supply tolerances with respect to two maximum ΔE quantities (all the measured colour errors must be lower than this value) and mean ΔE (the mean colour error cannot exceed this value), but using different formulas: $\Delta E76$ for Metamorfoze and $\Delta E00$ for FADGI (Table 6). We therefore followed both in the method, and just the latter in the indication of quantity.

The results obtained for the drawing were a mean value of $\Delta E00 = 2.31$ and a maximum value of $\Delta E00 = 5.6$, which corresponds to indistinguishability to the naked eye from the real on a calibrated monitor, and well within the limits indicated by the FADGI guidelines (Fig. 24).

At this point direct and comparative observation of the corrected images and of the original drawing yielded an important observation with regard to the CC procedure, already made by some authors. It was found that the use of standard colour targets becomes a problem when the object that must be reproduced is distinguished by a limited and close to the neutral range of colours.[77] The most common solution found in literature is to construct customized colour targets using patches that are usually chosen empirically from within the palette of colours present in the original. The CC process is then carried out with reference to the new target.[78]

The experimental attempts we made to try to use choices of this kind showed that there is a strong risk in the selection of candidate colours. Moreover, the fact that these pertain to a narrow tonal range can lead to even greater errors than the original solution. It was therefore decided to adopt a different procedure:

A. starting with images of the drawing (*recto* and *verso*) obtained with the standard CC process, manually corrected images were created with Adobe Photoshop on two different monitors calibrated respectively at 5000°K and in the sRGB colours for visual comparison with the original drawing placed alongside the monitors and illuminated with the LED lamp used for the image captures, until perceptually marginal differences were obtained when subjected to prolonged observation by five expert users. The NEC Spectra View 2690 and the SpectraView Reference 302 were the two monitors used;[79]

B. the CC process with SHAFT was carried out on a RAW image, but different weights were given to the patches of the ColorChecker Classic, emphasizing the neutral A4-F4 ones and those with colours closest to those present in the drawing. This procedure was repeated for various weights;

C. the images of the drawing thus obtained were compared perceptually by 20 expert subjects with the images corrected manually in this way:

- with respect to the original drawing illuminated with the LED light used for the captures on the two NEC spectraview monitors, calibrated as outlined above (5 people);

- with respect to the image corrected manually (20 people, of whom 5 on the two NEC spectraview monitors, and 15 on a LaCie 526 LCD monitor calibrated with respect to the sRGB colour space).

Considering that changes in ambient light only influence the perception of absolute colour, but do not have any effect on the relative sensation of colour difference,[80] the evaluation was conducted in two differently lit environments:

– in the presence of the drawing, just with a pale diffused light (less than 10 lux) from the LED lamp illuminating the drawing;

– in the absence of the drawing, natural light from a cloudy sky, amounting to around 30 lux on the plane of the monitor.

During the prolonged examination, all the observers noted only perceptually marginal differences in the images in which A4 was given weight 2, F4 weight 3, and A1, B1, A2, F2, C3 and D3 were ascribed weight 2.

In the second place, the $\Delta E00$ was measured for these CCs, and the MacAdam ellipses analysed. With L^* (*lightness*) fixed in the colour space CIE 1931, the ellipses enable identification of the colour constancy. For the ellipses three standard deviations correspond to "just noticeable difference", that is, to $\Delta E00 = 1$. Fig. 25 illustrates the MacAdam ellipses for the CC obtained.

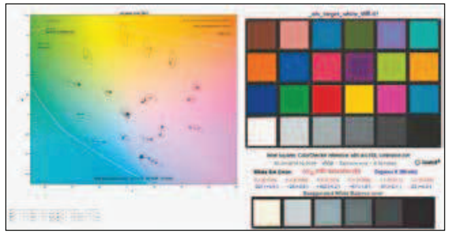


Fig. 16. Evaluation of the efficiency of the colour correction through the X-Rite Color Checker Classic target, colour correction, attributing equal weight to all the patches of the table: analysis of colour and exposure for the patches and diagram of the Mean camera chroma relative to the Mean ideal chroma in the CIE ΔE^*_{00} metric.

The final result of our process is shown by two colour maps in the sRGB format at 8 bits per channel, which effectively describe the diffused component of colour (Figs. 26a, b).

TECHNIQUES AND METHODS FROM CAPTURE TO VISUALIZATION

Visualization through the rendering of a digital 3D model in order to ensure perceived fidelity involves the need to correctly model the behaviour of light both in terms of its spectral composition and the path it traces in the scene and the reflections and inter-reflections that occur.

The decisive model of the problem developed in computer graphics, extremely simplified and formulated empirically, is known as Kajiya's rendering equation,[81] an integral equation that describes all the exchanges of light in a scene and which explains that, in relation to a particular position and direction of light, the outgoing light from any point of a surface is the sum of emitted light and reflected light. The reflected light is obtained by multiplying the light that arrives from all directions by the BRDF and by the angle between normal direction and direction of the light.

The BRDF, defined as the differential relationship between reflected radiance and irradiance, therefore quantitatively describes all the reflection phenomena on the real surface – not just colour, but also the optical properties of diffused, specular or, more generally, mixed reflection.[82]

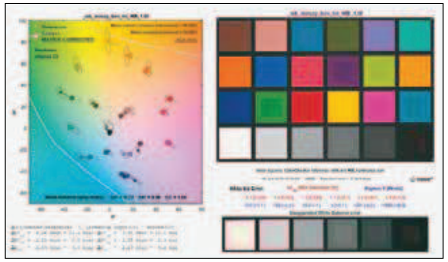


Fig. 17. Evaluation of the efficiency of the colour correction through the X-Rite Color Checker Classic target, colour correction, attributing greater weight to the patches of the table with similar colours to those in the drawing: analysis of colour and exposure for the patches and diagram of the Mean camera chroma relative to the Mean ideal chroma in the CIE ΔE^*_{00} metric.

In case of translucent materials such as alabaster, the BRDF requires greater generalization in order to include transmission and sub-superficial dispersion phenomena as well. For this reason it is necessary to evaluate the entire BSSRDF (Bidirectional Scattering Surface Reflectance Distribution Function),[83] which describes the transfer of light between any two incident rays on a surface, without requiring the hypothesis of the BRDF of opaque objects.[84] For a homogeneous material, this takes the name Bidirectional Scattering Distribution Function (BSDF), and consists of the sum of a BRDF and of a Bidirectional Transmittance Distribution Function (BTDF),[85] which models transmittance.

Finding the BRDF correctly is fundamental for the faithful reproduction of the artefact, that is Leonardo's drawing. It is important to consider that an approximate representation of the colour, which shows the roughness of the paper, appears perceptually more faithful to the eye than one that has greater colour fidelity but lacks the inter-reflections given by the micrograin of the paper.

The complete evaluation of a BRDF variable in space, as in drawings, is usually conducted by means of complex techniques: exploiting linear light sources in an analytic way,[86] or through dense angular and spatial sampling.[87] The first system is restricted by the representative power of the analytic models and can go wrong when it comes to characterizing complex anisotropic materials such as hand-made paper with precision. The second solution often requires complicated capture configurations and its accuracy is limited by the capture effort.

For this reason, image-based measurement techniques have been developed in recent years, as they accelerate the measuring of reflectance and reduce costs, given that it is simply necessary to conduct photographic image capture.[88] This is the path we followed. To model the BRDF correctly, it is necessary above all to consider the fact that the appearance of a material is a phenomenon dependent on scale.

In our case, to modelize this phenomenon we used the types of light interaction described in Westin *et al*,[89] where they are grouped according to the size of the geometric structures in three different levels:

- macrostructure: defines the form and geometry of a model;

- mesostructure: given by elements still visible to the naked eye, but which are not usually considered to be part of the overall form of an object. These superficial structures, consisting for instance of small protuberances, cause effects such as inter-reflections or self-shading;

- microstructure: considered to be formed by microscopic facets with an order of magnitude below the resolution of the human eye, but which do however contribute significantly to and determine the material appearance, because they can occlude light or project shadows or inter-reflections onto each other.

The solution that we adopted for the definition of the BRDF and its behaviour on the various scales is basically the one described in Gaiani *et al*,[90] to which reference can be made for further details. It is worth mentioning only that the mesostructure and part of the microstructure are reconstructed by means of multitexture methods with four maps:[91] albedo, normal, depht and specular maps

A number of significant innovations were introduced with respect to the basic scheme proposed in 2014. These relate to three areas:

– discovery of the normal maps;

– discovery of the depth maps to model the undulations of the paper;

– modelization of the microstructure, for which a new shader was created in order to correctly interpret the behaviour of the paper in the light.

a. Modelization of the paper

Recently Papas *et al.*[92] have effectively modelled the BRDF of paper as BSDF, starting from the experimentally verified observation that paper is highly scattering.

Having defined paper as an optically thick material that exhibits a behaviour in light given by the combination of various effects (subsurface scattering, specular reflection, retroreflection, surface sheen and transmission), this behaviour is reconstructed through a representation that exploits three components:

– a reduced version of the Donner and Jensen multistrata model;[93]

– the Hanrahan and Krueger model of the theory of single scattering;[94]

– the microfacet model of Walter *et al* for surface reflection and refraction.[95] The general form of the microfacet model for isotropic materials is:

$$f(l,v) = \frac{c_{diff}}{\pi} + \frac{F(l,h)\,G(l,v,h)\,D(h)}{4(n\cdot l)(n\cdot v)}$$

where l is the direction of the light, v the direction of view, n is normal at the current microfacet, $h = l + v$, c_{diff} diffused reflection of the albedo, $F(l,h)$ is Fresnel reflectance, $G(l,v,h)$ is the quantity of microfacets not masked or in shadow, expressed as a proportion of the total, $D(h)$ is the normal distribution function of the microfacets evaluated at the normal of the current microfacet; in other words, the concentration of microfacets with normal equal to h and which determines dimension, luminosity and form of the specular highlight.
The denominator $4(n\cdot l)(n\cdot v)$ is a correction factor that takes into account quantities that need to be transformed between the local space of the microfacets and that of the whole macrosurface.

The Fresnel reflectance term calculates the fraction of light reflected by an optically flat surface. Its value depends on two factors: the angle between the light vector and the normal surface, and the refraction index of the material.

Papas *et al*. found that in the case of smooth dielectric surfaces such as glossy and lustre paper, the Fresnel transmission equations provide a good match with measurements, while for rough surfaces such as matt paper, which is our case, the match is very marginal. An attenuation function was therefore introduced for matt paper, modelled on the basis of the goniometric measurements taken.

This basic scheme was used for *ISLe* and implemented in the chosen rendering software, *Unity 3D,*[96] a videogame engine that supports Physically Based Shading (PBR) exploiting the Open Graphics Library (OpenGL) API (Fig. 27).

We can summarize the main features of this shader and the implementations made in order to correctly represent the materials contained in the *Paesaggio:* paper, iron gall ink, red chalk, black chalk.

For reflection and refraction the base BRDF model is the one proposed by the Torrance-Sparrow microfacet theory,[97] implemented in the diffused reflection part according to the solution of the Walt Disney Animation Studios;[98] this involves calculating the Fresnel refraction twice, once when coming into the surface and then when going out, to preserve the Helmholtz principle of reciprocity, exactly as in the model of Papas *et al*. The Smith solution was used for *G(l,v,h)*, as in the original formulation of the microfacet model, while the multiscattering anysotropic GGX introduced by Walter et al. was used for the *D(h),*[99] written as in Heitz 2014.[100] The Schlick approximation was used for Fresnel, as it is simple but sufficiently accurate (the error introduced by the approximation is significantly lower than the one due to other factors),[101] with the raking retroreflection response passing to a specific value determined by the roughness rather than value zero. This makes it possible to take account of shortcomings in Fresnel when matt paper is involved, as in the formulation in Papas *et al.*, improving the original non-natural response to raking light.

The Walt Disney Animation Studios solution is also used to get the subsurface scattering.[102] This introduces a refactorization of the diffused reflection to consider scattering effects, and a sheen component that models the raking microsuperficial transmission.

Operatively, the shader was written on the basis of what was reported in Doppioslash,[103] introducing as missing coefficients evaluations drawn from measures taken on the paper used by Leonardo on previous occasions (Fig. 28).

Finally, as regards the iron gall ink, a channel was made with a transparency mask on paper, and the metallic behaviour of the ink was rendered through the Fresnel effect and specular mapping. The composition of the ink was determined on literary bases (Fig. 29).[104]

b. Mapping of the normals and heights

The mesostructure and part of the macrostructure are reproduced in *ISLe* by means of two maps, in order to ensure efficient management in the rendering pipeline in real-time through multitexture methods: a map of the normals at the surface (normal map) and a map of heights (height map).

A normal map is a map in tangent space that simulates the effect of light on a surface without having to geometrically model the surface itself. The normal vectors are represented through the RGB channels made to correspond to the x y z components of the normal vector, normalized pixel by pixel following Table 7.

A height map is an image in a grey scale used as a discrete global grid for describing the differences in the height of a surface point by point. In the height map the white pixels represent the points of the surface with the greatest absolute height, while the black pixels represent those with the least absolute height, along the Z direction.[105]

Both maps are useful for digitally representing a surface with complementary data. The height map is generally used for modelling the mesoscopic deformations of the surface, while the normal map is generally used to simulate microscopic surface details.

Radiometric techniques such as shape from shading,[106] which are commonplace in computer graphics, are certainly the most appropriate and simplest ways of extracting normal and height maps, because they directly measure the normal at the surface. The most developed of these is unquestionably the photometric stereo technique, which estimates the surface normal from perfectly diffuse (Lambertian) behaviour, photographing it in different lighting conditions.[107] In the original photometric stereo formulation introduced by Horn,[108] the light sources were assumed to infinity, the camera was orthographic and the surface of the object Lambertian and convex (that is, without shadows or inter-reflections).

The photometric stereo solution adopted here draws on applications and developments of the method produced by Cox and Berns.[109] They proposed and tested a technique for acquiring the information relating to the normal maps to use in rendering the surfaces of paintings which uses illumination from four light sources positioned at a 45° angle to the surface of the drawing, and 90° from each other with respect to the four sides of the drawing and the camera (positioned perpendicular to the surface of the drawing itself), rather than a whole hemisphere of light positions as in classic photometric stereo.

The solution, developed from an earlier method devised by Berns *et al.,*[110] employs a selective technique to remove highlights. In practice, it eliminates the light values of the highest single pixels among the four obtained by the acquired images.

Four series of photographs (one for each light) of the object to reproduce and a neutral piece of cardboard (a shiny black billiard ball and a ColorChecker Classic target) were taken. The images of the neutral cardboard were used to compensate possible non-uniform light distributions; the black ball was used to define the position of the four lights accurately; and the ColorChecker Classic was meant for the CC.

The application of the method resulted in the two maps, detailed in Figs. 30a and b. These were also used as a starting point for producing the height maps.

Examination of the results showed, however, the presence of artefacts attributable to a not perfectly regular distribution of the lighting, despite the correction of the luminous uniformity with flat fielding techniques, and to imprecise measuring of the position of the four lights, as the reflecting sphere produces significant errors when the light sources violate the distant illumination assumption and end up being effectively close to the object

Fig. 18. Real-time rendering of the paper in the three positions of observation: zenithal, at 45° and with raking light.

Fig. 19. Real-time rendering of the inks in the three positions of observation: zenithal, at 45° and with raking light.

(less than 4 times the size of the object), as in our case.[111]

This fact tends to be irrelevant when making the albedo map or using the map of the normals just to simulate the microscopic surface details. The erroneous correction of the lighting in the map of the normals does however become a significant factor if we wish to use it to produce a height map by means of a gradient operator,[112] and from this to reconstruct the displacement in the normal direction to the plane of the sheet.

A two-step procedure was adopted to correct this error.

An evaluation was conducted using a model produced with Grasshopper[113] and the plug-in Kangaroo, which converts the normal map into the modelled surface by means of an algorithm that obeys a principle of error minimization. The algorithm extracts the positions of the central points of each pixel and calculates the orientation of the normal vectors towards the surface through the XYZ components extracted from the normal map. It then applies the normal vectors to the centre of the relative pixel. Subsequently, it creates a polygonal, rectangular-faced mesh on the pixel grid of the image; later it applies to this a geometric restriction that enables the vertices of the mesh to move freely along axis Z alone, then imposes a second geometric restriction that draws the vertices of each face of the mesh to the plane perpendicular to the vector (the orientation of which is calculated and invariable) applied to the centre of each of the faces. Once all the geometric restrictions are set, an optimization process is activated, which iteratively minimizes the total weighted sum of the squares of the displacement distances generated by each geometric restriction. The effect of this is that the mesh tends to deform along axis Z, trying to make each face perpendicular to the relative normal vector.

The model in Fig. 31, built on the basis of the normal map obtained by applying the technique of Cox and Berns, displays an evident global concavity not present in the real model. The reason for the deformation must be attributed to the erroneous distribution of light in the red, green and blue channels of the normal map, as a result of which the error is more marked in the points closest to and furthest away from the light source, in other words, those with most and least luminous intensity.

The correction was therefore carried out in the following way: an algorithm was applied to the original image to attenuate the effect of light decay on the reproduced surface. The correction was made by comparing the photos of the neutral cardboard with the photo of the drawing with the same lighting conditions relative to the channel of luminosity. Having precisely identified the decay of light from the photo of the neutral cardboard, a filter was applied to the photo of the drawing in order to eliminate the radiometric non-uniformity (Fig. 32). The image thus finished was used to produce a new normal map with the Cox and Berns method. The height map was then obtained by using Knald Technologies' implementation of the gradient operator,[114] which enables the minimization of cumulative errors due to residual noise.

The algorithm based on Grasshopper and Kangaroo remained as verification of the results produced by Knald and as an instrument for calculating the effective extrusion value to assign to the displacement modifier making use of the height map extracted by Knald, calibrating it by means of three models of sheets of paper representative of configurations similar to those of the drawing filmed under the same set of lights and whose geometric characteristics were defined with automatic photogrammetric techniques which permitted the extraction of 3D models accurate to 50 µm, from which a mean model was extracted.[115] Comparison between the two 3D models made it possible to calibrate the result obtainable from the developed procedure and produce displacements in line with real ones.

Finally, once the map was extracted, a genuine 3D surface was generated with a resolution of 20 µm, using the traditional algorithms of geometric displacement mapping for linear interpolation of the grey values 0–255 of the map with respect to the two extremes, as per the results of the calibration.

Fig. 33 visualizes the conformation of the mesostructure of the sheet, while Fig. 34 features the maps that globally define the appearance of the drawing.

The drawing viewed digitally

This section summarizes the main features of the drawing that emerge from a visual analysis with *ISLe*. The observations date back to October–November 2018, when the work had just finished. There were two kinds of limitations: that of being non-experts in art history, and principally, in Leonardo (with the consequent inability to contextualize observations), and that of an absence of comparison with the other contributions in this catalogue (inability to actualize observations).

Finally, another operation will be carried out, which will probably appear highly implausible to experts, namely a comparison between the paper, ink and graphic techniques of the 1473 drawing and that of the *Uomo Vitruviano,* which we digitalized in 2014.[116] In this case too we will draw on visual observations, which coincide in large part with those made in the essay by Loretta Salvador, who restored the drawing a few years earlier.[117]

A fundamental work of reference was the very fine essay by Alessandro Nova, "'Addj 5 daghossto 1473': l'oggetto e le sue interpretazioni",[118] which describes the most recent material analysis of the work.

Our observations concern five themes: the paper, the inks, the line, the underdrawing and the deposits left by time.

The paper

The paper has a regularly spaced laid pattern, horizontal with respect to the reading of the image. It is clearly distinguishable on the *recto* and almost indistinguishable on the *verso.* An average of 13 impressed lines was detected in a space of 10 mm, and so the impressed lines constituting the paper have a size of around 800 µm.

The fact that the impressed lines are not visible on the *verso* indicates that this was the part of the paper treated completely in line with the recommendations of Cennino Cennini,[119] unlike what is the case for the paper of the *Uomo Vitruviano,* where the lines are visible on the *verso* but not on the *recto.*

Virtual raking light observation of the *Paesaggio* shows the surface of the paper, emphasizing the lumps in the fibrous mix. There are no apparent holes or stylus marks.

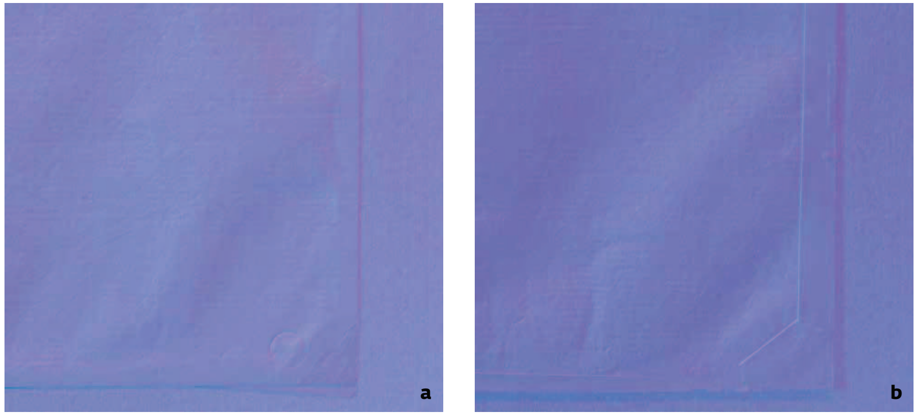


Fig. 20. Detail of the normal maps of the drawing: a. *recto*, b. *verso*.

The surface of the *verso* is particularly smooth, luminous and almost glossy, while the *recto* is more opaque and rough, and has small superficial imperfections that are most accentuated in the lower part of the sheet. This latter observation confirms that the *verso* of the sheet was subjected to fuller treatment, something which is also borne out in the colorimetric analysis conducted in the CIE Lab system. Indeed, the two drawings have different lightnesses on the *recto:* the *Paesaggio* has a lightness value of L=82, while *Uomo vitruviano* has a value of L=87.

In terms of colour, the two sheets are entirely similar. Having taken three areas of 250 x 150 pixels in different parts of the drawing, both on the *recto* and on the *verso,* and having normalized the lightness and subjected the areas to blurring using a bilateral filter,[120] the values detected for the *recto* were Lab = 88, 4, 11 for the *Paesaggio* and Lab = 88, 4, 13 for *Uomo Vitruviano.* On the *verso* the mean values for both drawings were Lab = 87, 4, 15.

The inks

Alessandro Nova notes that "in recent times only Hugo Chapman seems to have realized that Leonardo used ink with two different tones, returning to and accentuating at a later date, impossible to say when, some parts of the composition. The only one of the more modern critics, however, because Anny Popp had already realized this in 1928, in what is perhaps the most accurate technical description of the *recto,* before the minor traumas later suffered by the sheet."[121]

The presence of two inks is readily discernible to the naked eye. Of greater interest is the colorimetric analysis, which assigns to the two inks two clearly distinct layers of the drawing. The first, used for the general structure of the composition, with what has been interpreted as the Fucecchio Marshes, the hill on the right, the mountains in the background, the trees, described by Mazia Faietti as an "analogic representation of nature",[122] and the structure of the hill on the left. The second ink was instead used in a layer to which there belong the spur above the square division of the rocks, the waterfall, a series of retouches in the lower part, the confluence between the two rivers and what has been identified by some authors as the castle of Montevettolini.[123]

The differentiation fits with two established behaviours of the iron gall ink used by Leonardo. Composed of oak gall or other tannin-rich products, and iron sulphate, over time, and as it oxidizes rapidly, the original violet-grey colour changes into very variable shades of brown: from a very dark brown to paler shades, tending towards a rusty hue and pale orange. When there is an excess of iron sulphate, the original black ink turns into a dark rusty-brown colour. When there is an excess of tannin, the ink takes on a reddish-brown colour. An ink with a good balance will end up turning into a rusty brown.[124] One of the two inks – that of the background layer – is balanced, and one displays an excess of iron sulphate.

Table 8 records the Lab scale values relating to the extracted samples, localized in the same table, while Fig. 35 includes details extracted from the application, which clearly show the execution with two different inks/instruments.

Fig. 36 subdivides the lines of the drawing into the two large families, identified by using the algorithm of colour-based automatic segmentation through K-Means Clustering.[125]

The colourimetric analysis shows that two different inks were used for the *verso* of the drawing as well. In terms of their current colour change, these are also different from the ones on the *recto.* One ink was used for the naked moving man, the head in profile to the man's left and the words "Jo Morando dant[oni]o sono chontento".[126] The second was used to sketch the mountainous landscape with the bridge over a watercourse and the canopies of the trees.

Table 9 records the Lab scale values relating to the extracted samples, localized in the figure contained in the same table. Note that the values of the inks used on the *recto* do not match the values of the inks used on the *verso.*

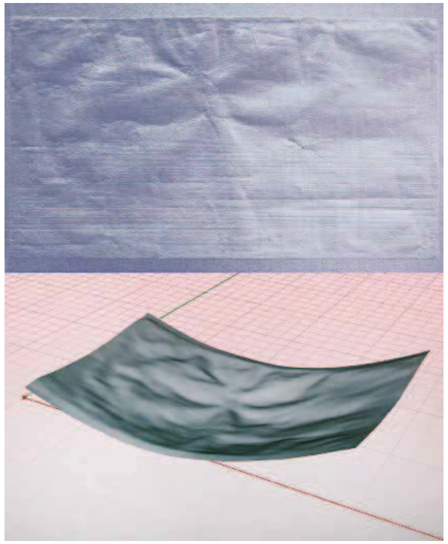


Fig. 21. Top: map of the normals obtained without attenuation of light decay on the reproduced surface. Bottom: the model of the mesh, to which a deformation was applied along the vertical axis in keeping with the map of the normals. The scale of the units of measurement along the vertical axis has been amplified to make the deformation more visible.

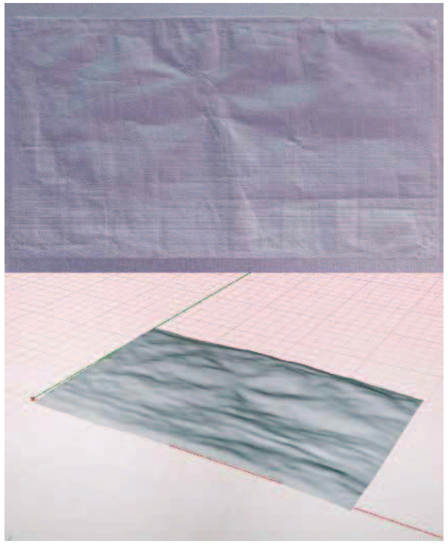


Fig. 22. Top: map of the normals obtained after attenuation of light decay on the reproduced surface. Bottom: the model of the mesh, to which a deformation was applied along the vertical axis in keeping with the map of the normals.

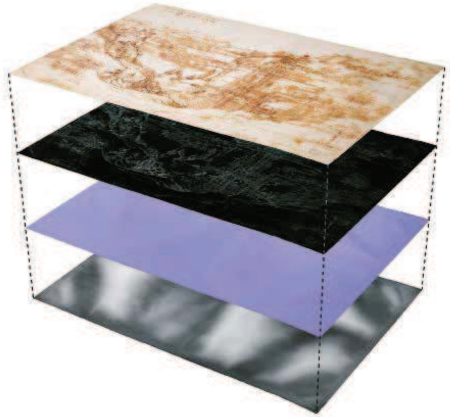


Fig. 23. Representation of the map of the heights of the sheet on which the *Landscape* was drawn.

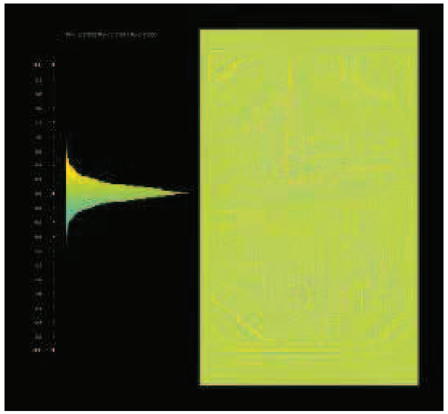


Fig. 24. Reconstruction maps of the mesostructure and microstructure of the surface: albedo, normals, depth, specular map.

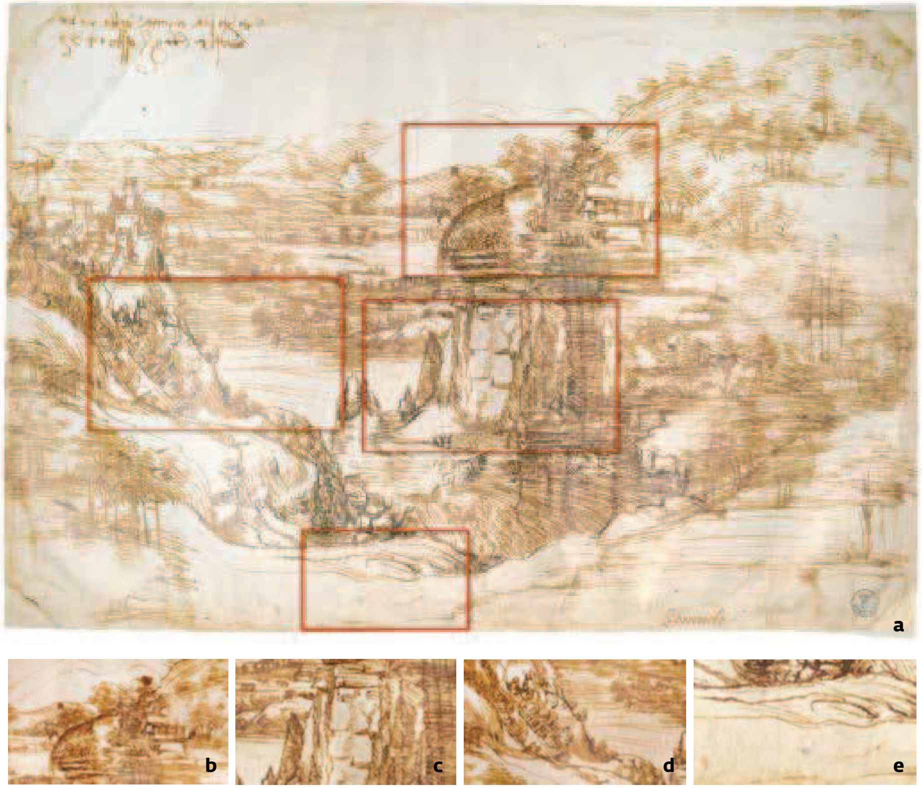


Fig. 25. Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P, different inks/instruments on the *recto* of the drawing: a. position of the details b., c., d., e., visualized in 3D.

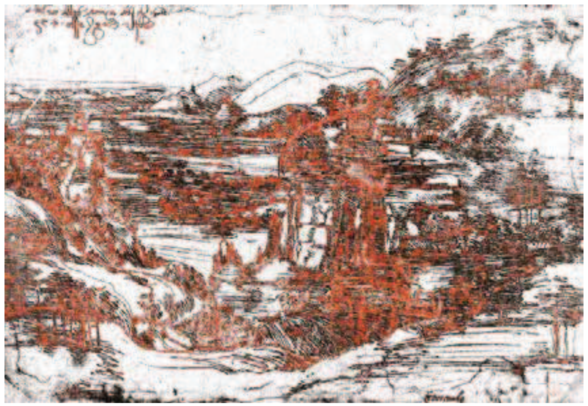


Fig. 26. Identification of the two big families of homogenous colour of the ink through the K-Means Clustering segmentation algorithm.

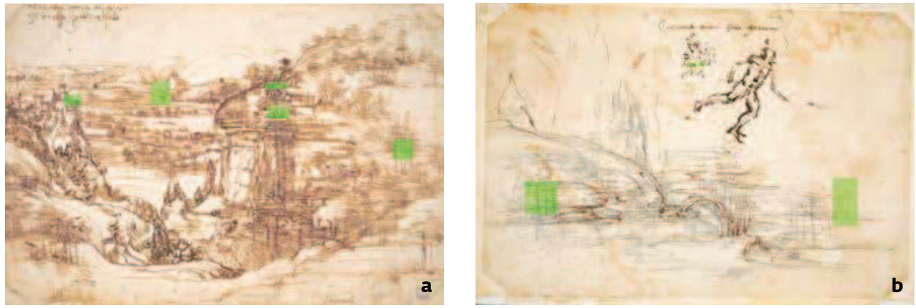


Fig. 27 a, b. Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P. Evidenced in green are areas with strokes from right to left and bottom to top.

Compared to *Uomo Vitruviano,* in which the colour differentiation between writing and drawing is only discernible to an expert eye, the variation in colour between the inks in the *Paesaggio* is much more marked.

The line

The instrument used to apply ink is usually the pen, for which Cennini gave specific suggestions about how it is to be used and prepared,[127] fully congruent with what can be found in the *Paesaggio*. Therefore, the instrument used for the ink is, in this case too, the pen. On the *recto* of 8P we can note the use of two different types of pen: one used for what was described above as the background layer, which left a variable line, with a broader sign and a larger amount of ink where the pressure of the hand was greater; the other, used to delineate the layer with darker ink, left a clean, thicker and more uniform line. Metrologically speaking, the width of the line used for the background layer is between 0.7 and 1.5 mm (usually 1.2 mm), while the line of the darker layer ranges between 1.2 and 2 mm (usually 1.7 mm).

On the other hand, the pen mark on the *verso* is an almost constant 0.3–0.4 mm (with a thickness of 0.7 mm in a few areas) for the landscape, while the thickness of line in the figure and writing is greater; the thickness is usually regular on each stroke, with a variance between 0.2 and 0.7 and a mean value close to the latter.

Overall the general pattern is very different from that of the drawing conserved in Venice, in which the free-hand strokes have a virtually constant width of 0.3 mm, while the ones on the line furrow are 0.2 mm. Likewise, in the Venice drawing there are no smudges, "perfect for a technical drawing intended to 'demonstrate' proportions".[128]

A series of other observations can be made regarding the way the line is made. Carmen Bambach, in her fine essay "Leonardo, left-handed draftsman and writer", clearly identifies the features of the left-handed draughtsman, in particular when she carefully describes the elements characterizing the stroke (from right to left) and the hatching (from bottom right to top left if from the bottom), which are different from those of a right-handed draughtsman. She also points out another typical feature that helps to understand the direction of the stroke: "One can often determine where the artist began his hatching strokes by finding the tips of the lines of hatching that show a greater pressure of the hand wielding the pen or the chalk. Especially in drawings done with pen and ink or with a sharp red chalk stick, this tip at the beginning of a line sometimes appears to be marked by a slightly indented point from which the stroke departs, after which it curves slightly upward, at times also creating a very slight angular hook at the end. The initial pressure of the pen sometimes slightly indents the paper, because of the pressure of the hand, and the line, at the beginning, usually seems thicker because of the greater accumulation of ink. As the artist's hand continues to move rapidly across the paper, decreasing pressure causes the line to become

Fig. 28. Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P, traces of black chalk (?)

Fig. 29. Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P, detail of the *verso*, geometric figures drawn in black chalk (?)

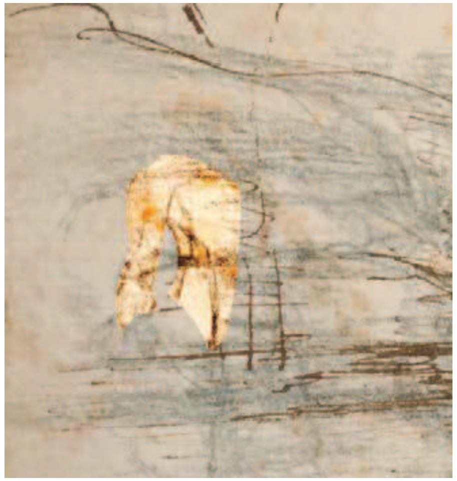


Fig. 30. Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P, detail of the *verso*, drawing of a bust with angled forearm and a view of the ribs beneath the armpit in black chalk (?)

Fig. 31. Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P, detail of the *verso*, female figure and a head that appears to be of a young boy.

thinner, tapering out at the end of a stroke, as the pen or chalk is lifted from the paper, or creating a very loopy, thin terminus."[129]

If we apply Bambach's notations to the 8P it is possible to discern the features of the left-handed draughtsman both in the two inks on the front side and on the two inks on the rear. Figs 37a, b exemplify areas with strokes running from bottom to top and from right to left, highlighted in green. It should be noted however, for example in the case of the figure of the warrior, while the tracing of upward lines is evident, the same is not true for that of the lines from right to left. They are more visible in the head in profile, but in this case as well the judgment is not definitive.

The underdrawing

The most interesting part of the drawing, as observed with *ISLe,* is certainly the part executed with what the majority of scholars call *pietra nera,* or black chalk.

First of all, it can be seen that signs of furrows or holes are hardly perceivable on either of the two sides. From our perspective, this could indicate that we are not dealing with a stylus that leaves a more or less evident furrow on the basis of the size of the point or the pressure exercised by the artist's hand without leaving any trace of colouration, nor that a pair of compasses was used in any part, or that there was any tracing or that measurements were taken.

Starting with the *recto,* we can turn to Nova who cites the essay by Anny Popp: "… if we are to lend credence to her words, the pen drawing was sketched onto a pencil preparation of which traces could still be discerned […] to orient his composition in space, Leonardo made use of some graphic signs of which all trace would seem to be lost today."[130]

Analysis with *ISLe* shows that these traces still exist. In particular it is possible to observe them in what we called the Fucecchio Marshes, just to the side of the crag, and then in various parts of the crag itself; there are black chalk signs on the castle, and finally traces are present low down beneath the waterfall. We have highlighted all of these in pale blue in Fig. 38.

The analysis of the underdrawing is particularly interesting for the *verso.* As Nova notes: "On the *verso* – over a preparatory drawing in black chalk, which also offers a glimpse of studies of regular geometric forms – there is a pen sketch of a mountain landscape with, in the centre, a bridge over a watercourse. […] Finally, it is likely that the sketches in natural red chalk in the top right were by another hand, albeit contemporary: it is possible to see a female half-figure and, with difficulty, a head fragment."

Here we will focus on the "preparatory drawing", which yields unexpected surprises. In the bottom left it is possible to discern a six-lobe figure, while a second one with a regular 45° chequer-board pattern is in the top left. A third figure with intersecting circumferences, executed with the same thickness (on average, 0.4–0.5 mm), is half way up the sheet on the right, in the heart of the mountain (Fig. 39).

Also ascribable to the same tip and the same author is the drawing of a bust with an angled forearm and a view of the ribs beneath the armpits, located on the far left between the two geometric figures. The remaining traces are insufficiently clear, at least for us, to identify whether it is of a man or a woman (Fig. 40).

Other figures appear to have been executed with another, and much finer, instrument, with a measurable thickness of 0.2–0.3 mm. There are traces under the run-

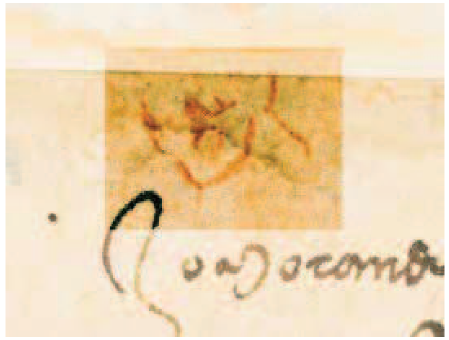


Fig. 32. Leonardo da Vinci, *Landscape*, 1473, Florence, Uffizi Gallery, Gabinetto dei Disegni e delle Stampe, inv. 8P, detail of the *verso*, figure, probably a face, drawn in red chalk above the words «Jo Morando».

ning man (a series of curves that end in a multi-lobated form) and in the section in the top left (vertical, horizontal and 45° degree lines in both directions).

The other signs, executed with a third instrument, appear ascribable to preparatory marks for the pen and ink landscape, replicating or indeed probably preceding it. The tool used here is thicker and more dispersive, producing a mark of 1.5 mm or more, probably of a different material.

Overall, the presence of a particularly shiny and probably prepared sheet point not to black chalk but to lead styluses – due to their characteristics, stylus marks could be erased simply with breadcrumb without dirtying the sheet, and were hence long used to outline the first draft of a drawing – and to silver styluses, which also leave a grey mark, but one that is more rigid, thin and clean.[131]

On the other hand, the colour and visual effects produced by various types of chalk depend on their type. The mark left by natural black chalk varies from black to cool grey, and varies considerably in intensity and thickness. The lines made with natural chalks are granular and irregular, and remain on the surface of the paper.[132] Only the draughtsmanship corresponding to the landscape has these characteristics, while the regular drawings of more limited thickness certainly do not. It is in any case hard to exactly identify the metal used for the stylus without specific analysis, which, moreover, is not for us to undertake.

Finally, coming to the natural red chalk figures in the top right, Nova's description is still valid. The chest and waist of the female figure can be seen, while the head appears to be that of a young boy placed alongside the woman (Fig. 41). Another figure, which can reliably be considered a face, is above the writing "Jo Morando", now partially covered by the strip delimiting the drawing (Fig. 42). Other red chalk marks are clearly visible on the left, beneath the raised leg and in the pubic area of the running man, in correspondence to the spires. As they are groups of sloping, parallel lines, they appear to be marks left while testing the instrument prior to use, a typical routine of artists at that time.

Finally, the analysis provided by the superimposition of the front and rear shows that the two drawings seem to have elements in common in the lower part, both in the hollow and in the bridge by the hill, the mark of the left-hand part being common to both (Fig. 43).

(Perhaps) sediments of time

The drawing also shows various signs not ascribable to the period in which it was executed, but in all likelihood to its subsequent conservation and collection. In the bottom left Nova detects "the residue of a collection mark", later replaced by the Uffizi stamp in the bottom right. This was affixed twice. On the top right-hand edge of the *recto* there is an 8 in pencil, while a further mark appears in the centre of the drawing at the bottom, to the right of the old stamp (Fig. 44). There is an ink mark in the bottom left corner of undeterminable appurtenance, and above all a pen mark above the word "s[an]ta", which seems to be part of a piece of writing. The *verso* also has an abundance of collection marks on the edges: "Leonardo da Vinci 8" at the top right, "8P" on the left, while the strips of paper seem to cover red chalk signs. Finally, in the bottom left there is some writing in pencil.

To conclude, it can be said that for the *Paesaggio* as well, in a similar fashion to what happened for *Uomo Vitruviano,* observation of the drawing with the help of *ISLe* made it possible to pinpoint aspects that would otherwise have been difficult to observe (Figs. 45–49).

In the case of the drawing held in Venice, these aspects essentially concerned Leonardo's extraordinary technique, backed by a regular pen mark over the whole drawing, rendered "perfect" by preparation with a series of furrows produced with a stylus; the presence of other furrows all over the drawing was probably the result of efforts to copy it, perhaps by Giuseppe Bossi; and finally, the appraisal, by Paola Salvi, of the position of the centre of the circle containing the human figure.[133]

Instead, what emerges in the *Paesaggio,* completely in line with what Nova says, is the idea of a complex graphic system that was certainly produced in a number of different phases. It is a kind of work in progress that generated various figurations, of which what appears today on the *recto* is the most striking one due to its completeness, even though it was certainly the result of at least two different instruments, with which whole homogeneous sections of the drawing were produced. This "work in progress" nature of the work is also borne out by the use of innumerable instruments (the writers, while having no claim to be experts, have identified at least seven) but above all by the *verso* of the drawing. From it we saw appearing, as we continued to observe it on *ISLe,* geometric and human figures, simple lines indicating that the sheet passed into expert hands, scraps of writing deposited in time and signs that can probably be seen directly as well, but which would have been hard to quantify. We are confident that the scholars who are able to see the work and the world it contains will find much better explanations for it than the rough and ready one supplied by us, who would not even think of calling ourselves, as Carlo Pedretti, one of the greatest admirers of the reproduction system illustrated here, used to do, "servants of the servants of Leonardo".

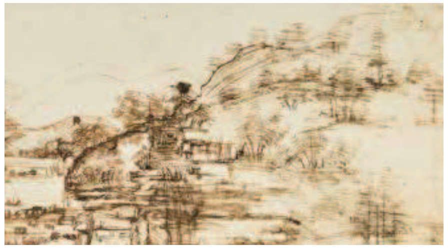


Fig. 33. ISLe – *Landscape*, *recto*: detail of trees.

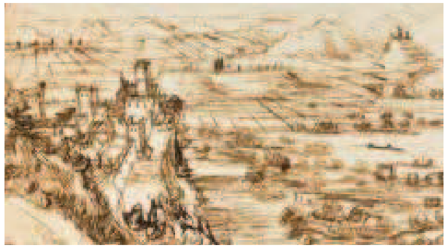


Fig. 34. ISLe – *Landscape*, *recto*: detail of the castle of Montevettolini.

Fig. 35. *Landscape*, *recto*: detail with the name «Leonardo» and the double stamp..

Tab. 1 – Vertical MTF. Comparison between the acquisition values in the two acquisitions: *Vitruvian Man*, Accademia, 2014; *Landscape*, Uffizi, 2018 for the sample area L3-H.

Basic Acquisition Values

	Venice	Florence
MTF50	0.099 Cy/Px	0.1425 Cy/Px
LW/PH	1600	2280
MTF10	0.26 Cy/Px	0.415 Cy/Pxl
MTF at Nyquist	0.00602	0.0545
10-90% rise	5.37 Px = 1490 per PH	4.34 px = 1845 per PH
Effective resolution	335 Px/inch	483 Px/inch

Acquisition Values with the Application of Unsharp Masking
Venice [Intensity: 200; Radius: 1; Threshold: 6,00; Edge Offset: 0,00] - Florence [Intensity: 150; Radius: 1; Threshold: 4,00; Edge Offset: 0,00]

	Venice	Florence
MTF50	0.1699 Cy/Px	0.1791 cy/Pxl
LW/PH	2718	2865
MTF10	0.373 Cy/Px	0.452 Cy/Px
MTF at Nyquist	0.137	0.067
10-90% rise	4.99 Px = 1604 per PH	4.76 Px = 1682 per PH
Effective resolution	575 Px/inch	683 Px/inch

Tab. 2 – Comparison between the values of acquisition with the application of a contrast mask in the two acquisitions: *Vitruvian Man*, Accademia, 2014; *Landscape*, Uffizi, 2018.

Venice		L3-H	L4-V	T2-V2	T1-V1	L1-B	L2-A
MTF50	Cy/Px	0.1699	0.161	0.1687	0.1282	0.1281	0.1766
LW/PH		2718	2575	2699	2051	2050	2825
MTF10	Cy/Px	0.373	0.359	0.366	0.307	0.299	0.314
MTF at Nyquist		0.137	0.126	0.131	0.111	0.109	0.102
10-90% rise	px	4.99	5.51	5.14	5.72	5.70	5.31
	per PH	1604	1452	1558	1399	1404	1506
Resolution	Px/inch	575	545	571	434	434	598

Florence		L3-H	L4-V	T2-V2	T1-V1	L1-B	L2-A
MTF50	Cy/Px	0.1791	0.2371	0.233	0.187	0.177	0.1513
LW/PH		2865	3794	3728	2992	2827	2420
MTF10	Cy/Px	0.452	0.525	0.486	0.586	0.431	0.416
MTF at Nyquist	%	0.067	0.116	0.092	0.189	0.041	0.02
10-90% rise	px	4.76	4.25	4.07	5	5.72	6.15
	per PH	1682	1882	1965	1601	1398	1472
Resolution	Px/inch	683	904	888	713	674	577

Tab. 3 – Exposure to light and UV rays for the acquistion in the acquisition of Leonardo's *Vitruvian Man* in Venice in 2014, cumulated for *recto* and *verso*.

Lux	UV	Scan time (max.)	Exposure in lux/hours	Equivalent exposure time at 50 lux
3000	50 W/lumens	20 minutes	600	12 hours

Tab. 4 – Technical specifications of the Relio² light with CCT - 4000K.

LED lamp predicted life	>50000h	At ambient temperatures up to 40ºC
Optics type	TIR + Honeycomb pattern	
Optics aperture (nominal)	10º, 25º, 60º, 90º, 10x70º	Nominal aperture, not FWHM
Power consumption	5Wh	@ 100% brightness
Body-radiated heat	2W	@ 100% brightness; estimated, not including visible light energy emitted by the LED
Temperature, Operating	0ºC ~ 60ºC	Temperature gradient (non-condensing): 20ºC/h
LED light ripple	<2% @ 750kHz	@ full range of brightness, using a high-quality power source
Flicker-free up to	10000 fps	
External, logic-level brightness control	PWM @ 20kHz	Incoming PWM is RC-integrated to a voltage curve
Brightness dimming curve	Proprietary	Inspired by CIE1931 scotopic curve
CCT	4047K	±50K tolerance, with 10º optic installed
CRI (Ra)	95	
CRI (Re)	92	
TLCI	96	
CQS	94	
TM-30-15 Rf	91	
TM-30-15 Rg	98	
CIE1931	x = 0.3793, y = 0.3788	
CIE1976	x = 0.2235, y = 0.5023	
IEC-SDCM	<1 SDCM	1-step MacAdam Ellipse
Illumination	39731 lux @ 0.25m	With 10º optic installed
PPFD (400-700nm)	625.44 µmol/m2s	With 10º optic installed

Tab. 5 – Exposure to light and UV rays for the acquistion in the acquisition of Leonardo's *Landscape* in Florence in 2018, cumulated for *recto* and *verso*.

Lux	UV	Scan time (max.)	Exposure in lux/hours	Equivalent exposure time at 50 lux
3000	0 W/lumens	8 minutes	250	5 hours

Tab. 6 – Margins of error in colour reproduction indicated by FADGI and METAMORFOZE.

	FADGI 4-Star (ΔE* 2000)	METAMORFOZE-Strict (ΔE* 1976)
Maximum error	6	10
Mean error	3	4

Tab. 7 – Table of admissable RGB values for the description of the normal vector in a point of the surface.

Red: 0 to 255	X: -1 to +1
Green 0 to 255	Y: -1 to +1
Blue 128 to 255	Z: 0 to +1

Tab. 8 – Leonardo da Vinci, *Landscape*, colorometric analysis of the inks starting with the acquired images, *recto*.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9
L	55	54	54	47	45	44	41	42	47
a	12	12	16	12	12	13	13	11	10
b	26	24	26	16	14	14	16	13	14

Tab. 9 – Leonardo da Vinci, *Landscape*, colorometric analysis of the inks starting with the acquired images, *verso*.

	Point 1	Point 2	Point 3	Point 4	Point 5
L	36	36	37	44	44
a	5	9	7	12	10
b	8	10	12	17	15

[1] Da Vinci 1468–1475, inv. 428 E.
[2] Gaiani 2011.
[3] Da Vinci (undated), cat. no. 228.
[4] At the exhibition "Perfecto e Virtuale – L'Uomo Vitruviano di Leonardo" (Fano, 24 October 2014 – 6 January 2015).
[5] Salvi 2013.
[6] Royal Library, Windsor, RCIN 919013v, K/P 144 v, note I.
[7] The raking light technique consists of illuminating objects with a light source positioned very close and oblique to the surface.
[8] Malzbender 2001.
[9] http://culturalheritageimaging.org/Technologies/RTI/
[10] Woodham 1980.
[11] Pitzalis 2009.
[12] https://artsandculture.google.com/
[13] Chen 2007.
[14] Wilkie 2009.
[15] Greenberg 2009.
[16] Nicodemus 1965; Dorsey 2007.
[17] Gardner 2003.
[18] Meseth 2012.
[19] Gaiani 2015; Apollonio 2015.
[20] Da Vinci 1473, inv. 8P; for more about the drawing, see the entry by Cristina Casoli in Milano 2015, p. 525.
[21] https://www.rencay.com/en/rencay-products/products-rencay-direct-camera-systems/
[22] The sensor was renamed the ON semiconductor, following acquisition of the rights from Kodak (https://www.onsemi.com/).
[23] Witwer 2015.
[24] https://www.xyzprinting.com/it-IT/product/da-vinci-pro.
[25] The limit of resolution is the shortest distance separating two lines that can be distinguished as distinct. The estimation of this distance is expressed as a corresponding spatial frequency, interpretable as a surrogate of the value derivable from a visual evaluation of that image.
[26] The sampling resolution is the implicit one from the sampling of the image file. If expressed in pixels, the sampling interval is one pixel, and in the measurement interval it is measurable in ppi: pixels per inch.
[27] Apollonio 2015.
[28] Jacobson 1995.
[29] ISO 12233:2017.
[30] Williams 1998; Burns 2000.
[31] Thomson 1994; Cuttle 2007.
[32] Cuttle 1996; Cuttle 1988; Hoon 2000; Schaeffer 2001; CIE 157:2004.
[33] Weintraub 2010; CIE 89:1991.
[34] The lux is a unit measure of illuminance, that is of the amount of flux spread over a square metre, and is used to describe how much light arrives on a surface.
[35] CIE 157:2004.
[36] Michalski 1996.
[37] Saunders 1996.
[38] Colour rendering is the capacity of a white light source to faithfully represent the colours of the objects and surfaces it illuminates.
[39] Scuello 2004a; Scuello 2004b.
[40] Hydragyrum Medium Arc-length Iodide. These are totally stable discharge lamps with a colour temperature of 5,500 °K, equal to sunlight. They heat up to a limited degree and have a very high light output. As a consequence, energy consumption is reduced considerably.
[41] The CRI or Colour Rendering Index is the measure of a light source's ability to render colours "realistically", and corresponds to the CIE 1965–74 standard, which introduced, for the classification of light sources, the Ra general colour rendering index (absolute).
[42] Forcolini 2011.
[43] Scuello 2004b; Piccablotto 2015; Di Salvo 2014; Salata 2015.
[44] Boissard 2009.
[45] Ishii 2007.
[46] Piccablotto 2015.
[47] Berns 2011.
[48] Jiang 2013.
[49] Lyon 2002.
[50] Hong 2011.
[51] CIE XYZ is a colour space defined by the CIE in 1931. In this model, Y is luminosity, Z is almost identical to the blue stimulation and X is a mixture similar to the red sensitivity of the curve of the cones.
[52] RGB is a colour space, the specifications of which were described by the CIE in 1936. In this model the colours are defined as the sum of the three colours Red, Green and Blue.
[53] Reinhard 2008.
[54] Viggiano 2004.
[55] Borrino 2017.
[56] Gaiani 2016.
[57] McCamy 1976.
[58] Cheung 2004.
[59] Gaiani 2017.
[60] RAGS, http://www.rags-int-inc.com/PhotoTechStuff/ColorCalibration
[61] Gaiani 2016.
[62] Süsstrunk 1999.
[63] Stokes 1996.
[64] Lukac 2007.
[65] Delta-E (ΔE) is a single number that represents the "distance" between two colours. The idea is that an ΔE of 1.0 is the smallest colour difference that the human eye can detect.
[66] Sharma 2005.
[67] CIE 142:2001; Luo 2001; ISO/CIE 11664-6:2014.
[68] CIE 101:1993.
[69] Luo 2001.
[70] Melgosa 2017.
[71] Oleari 2011; Melgosa 2013.
[72] Huang 2015.
[73] Berns 2016.
[74] Melgosa 2017.
[75] http://www.digitizationguidelines.gov/guidelines/digitize-technical.html
[76] https://www.metamorfoze.nl/english/digitization
[77] Berns 2005b; Kurečić 2005; Trumpy 2010; Berns 2005a; Williams 2010.
[78] Williams 2012.
[79] https://www.nec-display-solutions.com/p/uk/en/support/productsupport/rp/Reference2690.xhtml; https://www.nec-display-solutions.com/p/it/it/support/productsupport/t/Desktop-Displays/Colour-Accurate-Desktop-Displays/rp/Reference302.xhtml
[80] Hao 2011.
[81] Kajiya 1986.
[82] Dorsey 2007; Weyrich 2008; Guarnera 2016.
[83] Jensen 2001.
[84] Goesele 2004.
[85] Bartell 1981.
[86] Aittala 2013; Ghosh 2009; Tunwattanapong 2013.
[87] Torrance 1967; Sia 1976; Foo 1997; Wang 2008; Dong 2010.
[88] Marschner 1999; Debevec 2000; Matusik 2003; Han 2003; Ngan 2005; Rump 2008; Francken 2008; Guarnera 2012; Riviere 2016.
[89] Westin 1992.
[90] Gaiani 2015.
[91] Goral 1984.
[92] Papas 2014.
[93] Donner 2005.
[94] Hanrahan 1993.
[95] Walter 2007.
[96] Unity3D, https://unity3d.com/
[97] Torrance 1967; Cook 1981.
[98] Burley 2012.
[99] Walter 2007.
[100] Heitz 2014.
[101] Schlick 1994.
[102] Burley 2015.
[103] Doppioslash 2018.
[104] James 2010.
[105] Horn 1989; Brooks 1985.
[106] Horn 1975; Horn 1978; Horn 1979; Ikeuchi 1979; Silver 1980; Woodhan 1980.
[107] Woodham 1978.
[108] Horn 1975.
[109] Cox 2015.
[110] Berns 2012.
[111] Huang 2015.
[112] Frankot 1988; Ando 2000.
[113] Grasshopper (https://www.grasshopper3d.com/) is a visual programming language and an environment developed by David Rutten. It is executed in the CAD application Rhinoceros (https://www.rhino3d.com/). Grasshopper is chiefly used to create generative algorithms for 3D geometries. Kangaroo is an interactive physics/constraint solver and Grasshopper plugin for designers (http://kangaroo3d.com/).
[114] https://docs.knaldtech.com
[115] Gonzalez-Aguilera 2018.
[116] Da Vinci (undated), cat. no. 228.
[117] Salvador 2009.
[118] Nova 2015.
[119] Cennini 2009, p. 12.
[120] Paris 2009.
[121] Nova 2015, p. 286.
[122] Faietti 2015; Faietti 2008.
[123] The place names are as in Nanni 1999.
[124] James 2010.
[125] Arthur 2007.
[126] Nova *2015*, p. 287.
[127] Cennini 2009, pp. 14–15.
[128] Loretta 2009, p. 62.
[129] Bambach 2003, p. 36.
[130] Nova 2015, p. 286.
[131] Loretta 2009, p. 62.
[132] Mayhew 2010.
[133] Salvi 2016.

Abbreviations

MANUSCRIPTS

AR = Codex Arundel (London, British Library)
CA = Codex Atlantico (Milan, Biblioteca Ambrosiana)
CL = Codex Leicester (Collection Melinda & Bill Gates Foundation)
Libro di Pittura = Codice Urb. lat. 1270 (Vatican City, Biblioteca Apostolica Vaticana)
Ms. A = Manuscript A (Paris, Institut de France)
Ms. C = Manuscript C (Paris, Institut de France)
Ms. H = Manuscript H (Paris, Institut de France)

ARCHIVES AND OTHER INSTITUTIONS

ASCG = Archivio storico comunale di Cerreto Guidi
ASCV = Archivio storico comunale di Vinci
ASFi = Archivio di Stato di Firenze
ASPi = Archivio di Stato di Pisa
ASGF = Archivio storico delle Gallerie degli Uffizi
BU = Biblioteca delle Gallerie degli Uffizi
GDS = Gabinetto dei Disegni e delle Stampe delle Gallerie degli Uffizi
GFGU = Gabinetto Fotografico delle Gallerie degli Uffizi
OPD = Opificio delle Pietre Dure

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edited by
Monica Taddei, Alice Meini

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