Ill. 1. *Enclosed Garden with Sts Elisabeth, Ursula and Catherine*, *c.* 1524-1530, mixed-media, 134.5 x 194 x 25 cm, Mechelen, Museum Hof van Busleyden – Collection Sisters of the Hospital of Our Lady, inv. no. GHZ BH002 © KIK-IRPA (Watteeuw & Iterbeke 2018: 26-27, G2)

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The painted panels of the early sixteenth century Mechelen Enclosed Gardens

Art technical Examination with the Photometric Stereo: White Light and Multispectral Microdomes

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1. Investigating the painted wings of the Mechelen Enclosed Gardens

During the sixteenth century, a unique form of religious art, that combined a wide and intriguing range of artefacts emerged in the Low Countries: The Enclosed Garden. The Gardens are exceptional mixed-media representations of an idealised spiritual and paradisiacal world. In addition to the characteristic silk flowers, they include polychromed statuettes, metal pilgrim badges, wax medallions, relics and objects crafted from alabaster, parchment, paper, and pipe clay; additional decorative touches include spangles, pearls and beads made of glass, bone, coral, and amber; painted panels from shutters to reveal or conceal the treasures within are also seen. They were kept closed in the cells of the religious women, they belonged to. The first part of this essay focuses on the imaging of the painted panels of the Enclosed Garden featuring Ursula, Elisabeth and Catherine, ca. 1524-1530 (G2, 134,4, x 194 x 25 cm) (Ill. 1). The right shutter shows the male patron, with behind him the apostle St. James the Great, modelled freely after a woodcut by Jacob Cornelis van Oostsanen (c. 1521)[1]. The left shutter depicts the female members of the Van den Putte family: the mother and her daughter Maria, the latter professed in 1524. St. Margaret and the dragon are standing behind them[2]. The painter of these patron images stays anonymous. The second part of the essay will discuss the shutters of the Enclosed Garden with Daniel in the Lion's' Den, ca. 1530 (G4) (Ill. 6). This garden is much smaller (88 x 142 x 23,5 cm) and has two painted shutters with on the left St Peter and on the right St. John the Evangelist.

In recent years the technical characteristics of panel painting were examined successfully, and in great detail with IRR and MA-Xrf. In addition, recent evolutions in photogrammetry[3] and multi- or hyperspectral imaging[4] methods, allows new approaches in documenting structures, compositions, and conditions of these panels and the materials used on these paintings. Another new method produces relightable images[5] or multi-light reflectance (MLR) images based on the principles of polynomial texture mapping, hemispherical harmonics, and/or photometric stereo. Again, for art-technical studies and art-conservation practices these methods have already proven their added value in terms of panel painting.[6] At KU Leuven two such MLR systems have been developed, one that documents the surface characteristics, with bundles of visible white light, another that emits five separate spectral bands. This essay presents and documents the methodology and the results through imaging with these White light (WL) and Multispectral (MS) Portable Light Dome (PLD) systems of the KU Leuven, as they have been used for study of the painted surfaces seen on the shutters of the Enclosed Gardens. This PLD system is an easy and fast to operate acquisition tool to visually document a surface under investigation. The processed results allow relighting of the surface within various virtual lighting conditions; the obtained information can be visualised using a number of enhancement filters, and those same datasets can be used for detailed topographic and material characterisation. Furthermore, this essay will introduce a methodology for the study of the obtained and processed spectral responses stored in the PLD datasets, and in what way they can be used to accurately compare and monitor conditions in time, by placing different recordings in register.

This experimental approach is complementary to the standard IRR imaging of the panels done simultaneously in the KIK-IRPA in 2017-2018[7] and published in the monograph on the Mechelen Enclosed Gardens[8]. The research presented in this essay was performed in 2017-2018 in context of the ArtGarden Project (Art Technical Research and Preservation of Historical Mixed-Media Ensembles: 'Enclosed Gardens').[9]

2. Equipment

The two applied MLR recording devices have been developed at the KU Leuven, their dome shaped component measures Ø 30 x 30cm and are, on the inside, equipped with 228 LED emitters.[10] For the White Light Microdome (WLMD) these LEDs are LZ1-30NW00-0000 (neutral white), for the Multispectral Microdome (MSMD) these are five sets of LED Engin: LZ1-00UV00 (λ_D 365nm), LZ1-30DB00 (λ_D 460nm), LZ1-30G100 (λ_D 523nm), LZ1-30R100 (λ_D 623nm), LZ1-30R400 (λ_D 850nm). The used sensors are the Allied Vision Prosilica colour (WLMD) and monochrome (MSMD) GX 6600, high-resolution 35mm CCD (6576x4384pixels) with digital shutter and spectral response between 350-1000nm. The selected lenses are the Nikon AF-D 60mm F/2.8 macro (WLMD) and the Jenoptik inc. CoastalOpt UV-VIS-IR 60mm Apo Macro (MSMD) equipped with calcium fluoride lens elements enabling true apochromatic performance: 315-1100nm. The Microdomes can be attached to a tripod or Foba studio stand; this option made it possible to position and manoeuvre them closely in front of the Enclosed gardens and their painted panels in a safe and controlled manner (Ill. 2).

3. Methodology

The painted panels of the closed Gardens were recorded with both PLD systems: WLMD and MSMD. Specific details, area surfaces or features were targeted. A number of them were recorded before and after restoration treatments. During a recording sequence the PLD system registers how a surface reflects incident light from 228 different angles. Based on these changing responses, the applied photometric stereo algorithm estimates per recorded pixel in the frame the albedo (fraction of incident light reflected by a material) and the normal (surface orientation). The spectra applied during the recording phase with the MSMD, interact dissimilar with the various materials and pigments on the surface and therefore will reveal distinct features. Via the systems' software interface this gamma of results can be interactively combined into various tri-chromatic renderings, the texture maps can be excluded, and 3D representations (Polygon File Format,. ply) of the imaged surfaces can be generated.

This mapping allows the documenting and visualizing of the 3D topographic features of the paintings' outer surface; to enhance faded pigments based on their albedo responses in the five applied spectra, to detect underdrawings, and to characterize and differentiate the imaged materials based on their spectral responses (BRDF). As the recording sequence consists of a one-in-all documentation, all the spectral bands in addition to all the incident light angles with the same settings and physical set-up, and all the rendered output is in perfect order. It allows an accurate comparison of the surface characteristics as detected between many simulated spectral variations.

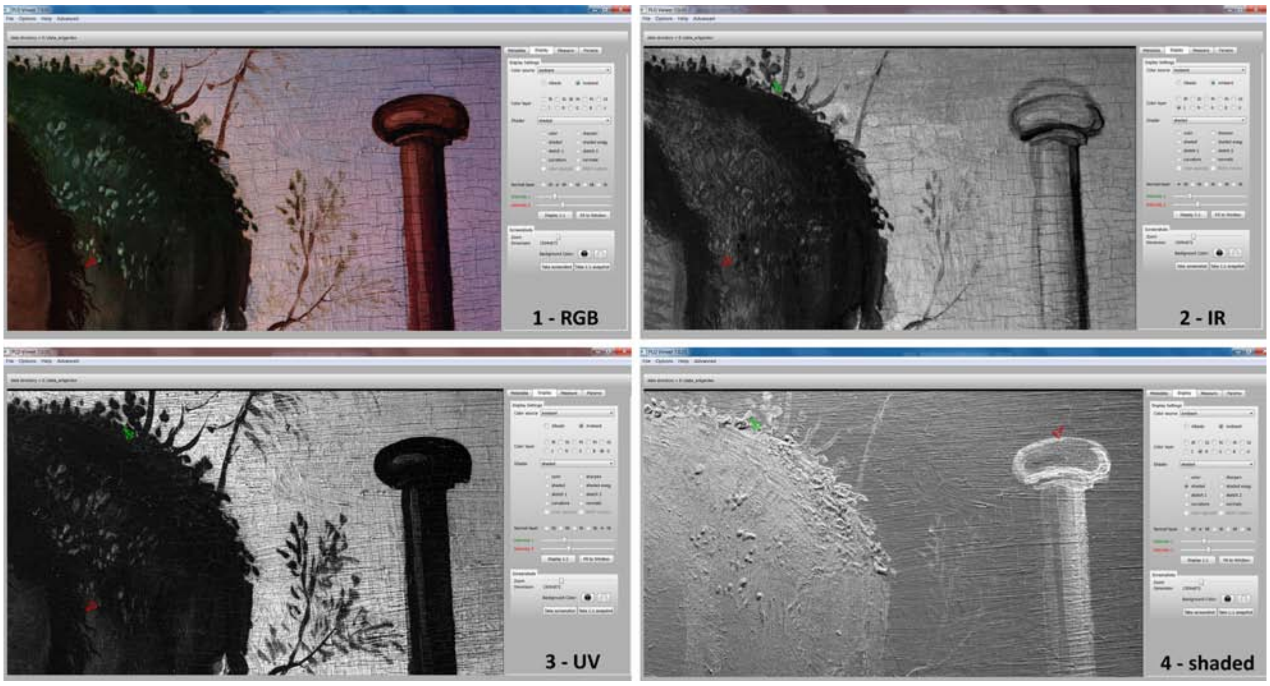
Ill. 2. Imaging of the *Enclosed Garden of St. Ursula* with the WL minidome (left) and the panel with St. Margaret with the MS microdome (right), mounted on a large horizontal copy stand © KU Leuven

4. Results

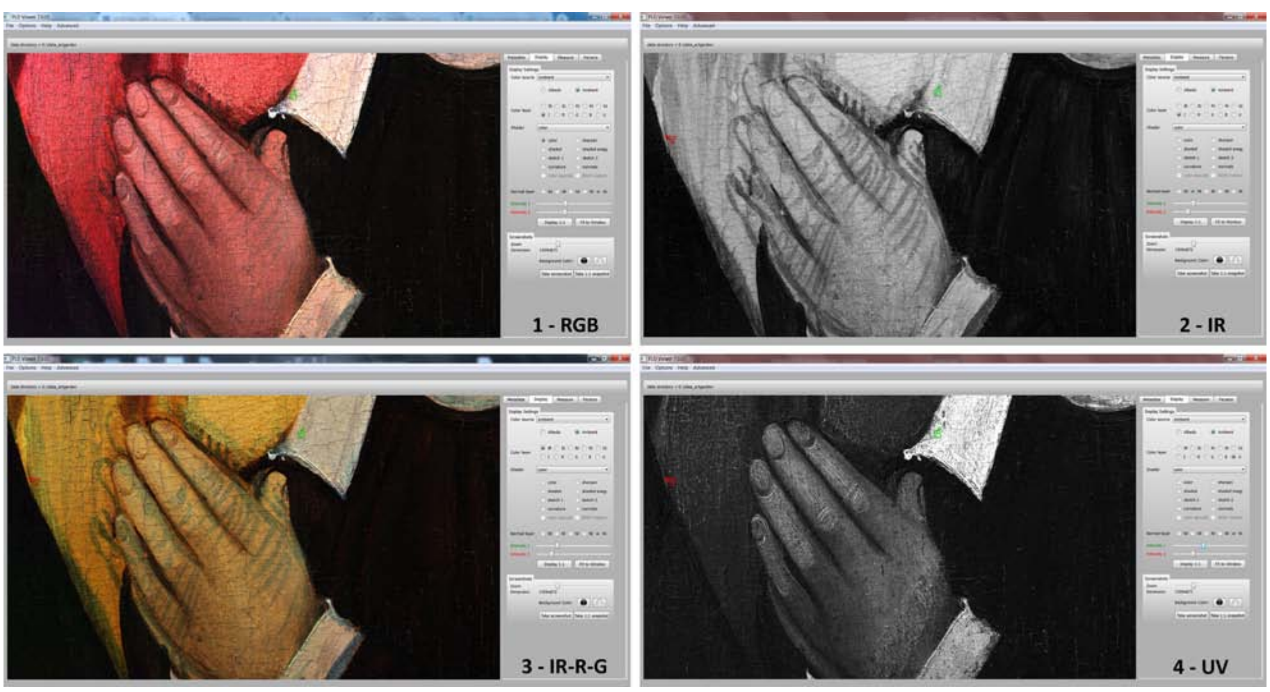
4.1. *Visual analyses of faded features, relief and underdrawings*

The infrared reflectography (IRR) executed by the Royal Institute for Cultural Heritage on the painted wing panels of the Enclosed Gardens revealed clear underdrawings[11]. With the MSMD, some of the areas which revealed these underdrawings were re-imaged and allowed a prompt comparison between the reflective results in the RGB colour space, as it appears to the human eye, and the infrared responses. The MSMD near-infrared (NIR) LEDs emit light at 850 nm, sufficient to detect some of the carbon-based underdrawings which were also detected with the IRR (Figs. 3-5). The surplus of the PLD method is the straightforward manner in which such (N)IR results can be compared with the RGB, ultraviolet, or even with untextured generated images. The original design, the eventual painting, later interventions or decay can all be visualised and studied within one viewing environment based on one 5 minutes recording process.

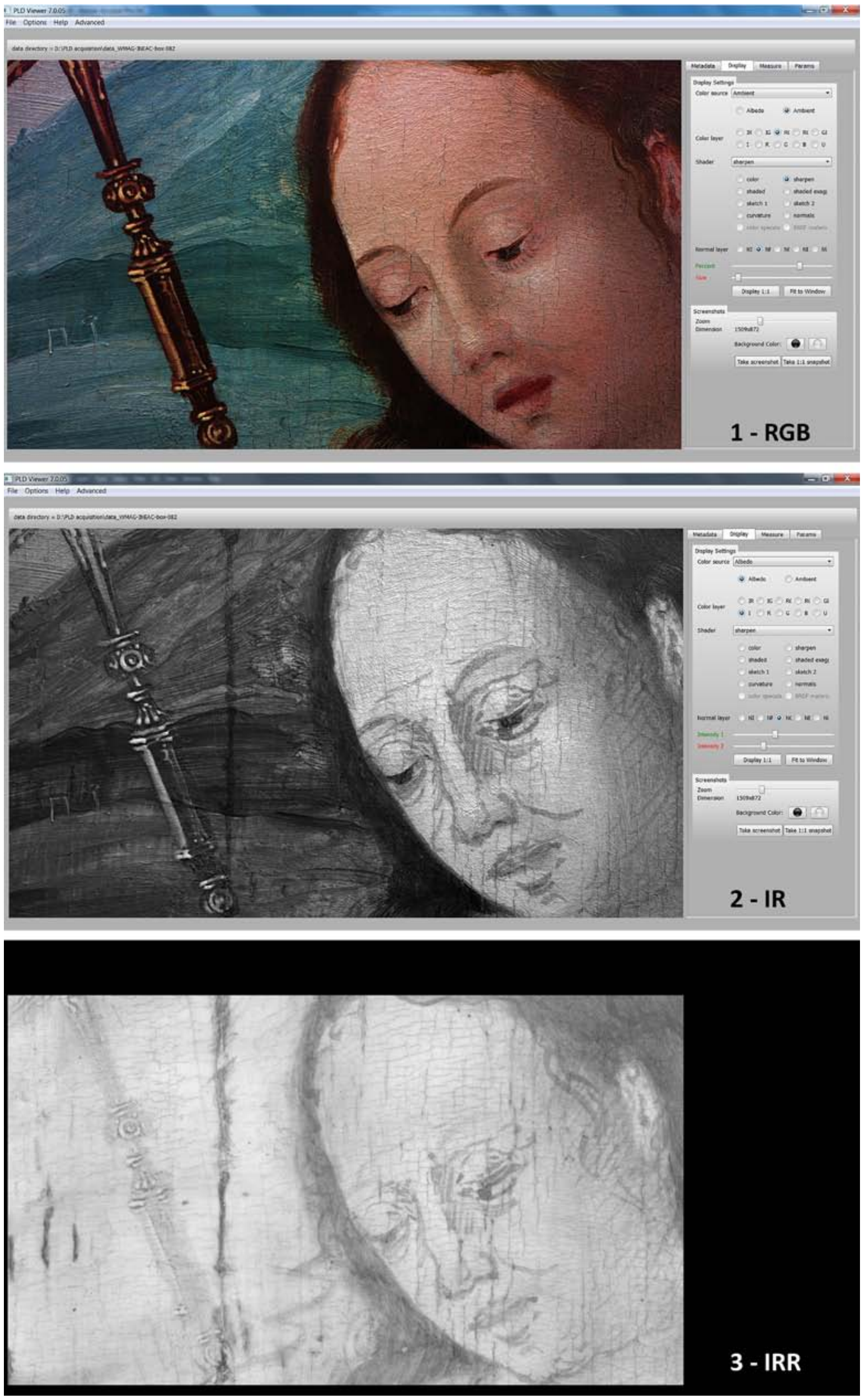
The underdrawing is executed in a liquid carbon containing medium with a brush. On the left wing panel of the Garden with St Ursula (G2), the top of the staff of St James has been flattened out (Ill. 3). With the same recording, by excluding the colour (shaded visualisation), other surface features such as the relief left behind by the touching with ticker white paint (lead white?) on the vegetation become very prominent as well. A similar situation was seen on the right wing panel of the same Garden depicting St. Margaret. The IRR results had already revealed that the painter had, in comparison to the underdrawing, tilted the face of sister Marie Van de Putte to the right and slightly downwards[12]. The same can be observed when examining the hands of the sister (Ill. 4). In the IR (850nm), the hands shifted towards the right and downwards. The IR rendering enhances extensively and differentiates the visibility of the parallel hatching strokes below the main paint layer seen in the area showing the hands' skin tone. These preparations darken the subsequently applied pigments. On the other hand, the UV responses in that specific dataset highlight the white paint accentuations on the fingers and nails. The same effect has been repeatedly seen in the MSMD recording of



Ill. 3. Detail on the right wing panel of G2 with St. James, as visualized in the PLD software interface; underdrawing of the pilgrim staff; visualising the thickness of the black and white paint layers © KU Leuven



Ill. 4. Detail on the left wing panel of G2 depicting the hands of the nun, as visualized in the PLD software interface; underdrawing/hatching under the skin colour paint layer of the hand visualising the rendering of the skin © KU Leuven



Ill. 5. Detail on the left wing panel of G2 depicting St Margaret, for 1 & 2 as visualized in the PLD software interface. For comparison: 3 Infrared Reflectography: underdrawing/hatching under the skin tones of the face. The underdrawing is executed with a brush in a liquid carbon containing medium © KIK-IRPA

Ill. 6. *Enclosed Garden with the Virgin and Child with St Anne, Daniel in the Lions' Den and St Jerome, c.* 1530, mixed-media, 88 x 142 x 23.5 cm, Mechelen, Museum Hof van Busleyden – Collection Sisters of the Hospital of Our Lady, inv. no. GHZ BH004, with the image of St. Peter on the left panel © KIK-IRPA (Watteeuw & Iterbeke 2018: 34-35, G4)

the face of St. Margaret on the same panel. Hatchings and strokes which follow the facial contours are prominently visible in the IR responses, and lead to darkened and shadowed stretches (Ill. 5).

4.2. *Spectral analysis of pigments and materials*

The multi-light reflectance datasets of the PLD system, conceal the reflection intensities for every pixel. For the MSMD that comprises the results of the five applied spectral bands separately. Thus, any selected cluster of pixels, representing a particular pigment/material on the imaged surface, can be characterised by these specific reflection intensities. For a given selected area, the MS PLD system puts them in a histogram. It shows the distribution of the calculated albedo responses for each of the spectral bands. The albedo response is given by the x-axis, while the y-axis gives the probability distribution for each of the spectral components for the given area. As different bands are increasingly being plotted to the right, the higher their reflective response became for the selected area. When the recording settings are identical across the painted panels, such a tool could be used to identify similar pigments and materials.

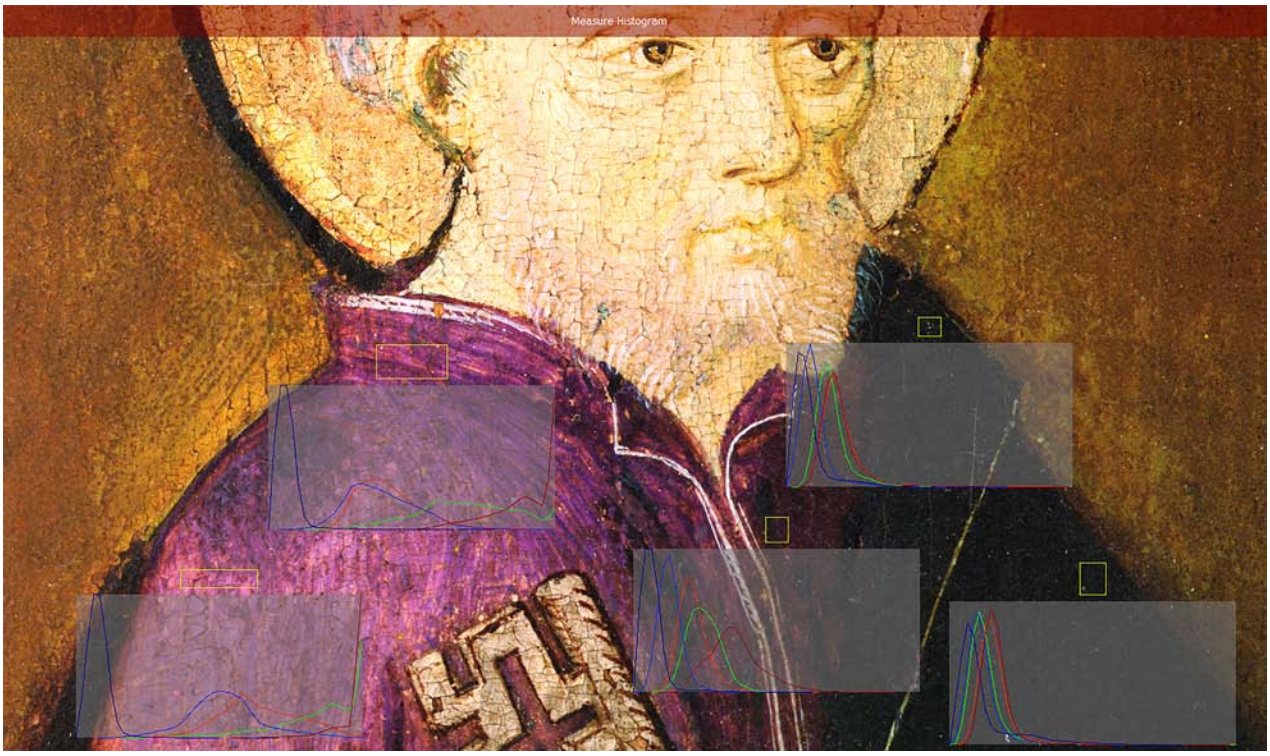
This type of data mining can be combined with trichromatic renderings produced with the same dataset[13]. In the software interface of the PLD system, the MSMD datasets and the responses of the 5 spectral bands can be combined in 5 pre-set trichromatic renderings (i.e. false colours): Infrared-Red-Green; Infrared-Green-Blue, Red-Green-Blue, Red-Green-Ultraviolet, Green-Blue-Ultraviolet.

On the enclosed garden with Daniel in the Lion's Den (G4) (Ill. 6), with the left painted panel depicting St Peter, this approach was used to characterise some of the pigments. Simultaneously the

Ill. 7. Detail on St Peter on the left wing panel of G4 recorded with MSMD; Left: Red-Green-Blue trichromatic rendering; Right: Infrared-Red-Green trichromatic rendering © KU Leuven

study with analytical element mapping[14] of the panel, before conservation treatment in 2017 in KIK-IRPA was applied. The blue-green undergarment of St. Peter (right shoulder, arm and parts of the chest) and the dark blue-green cloak (left shoulder, arm and from the chest downwards) showed, through Xrf mapping, that both paint layers contain concentrations of lead (Pb-Lα) and copper (Cu-Kα). Visually, the dark overpainting and/or darkening varnish, made it challenging to differentiate the two garments when imaged with the MSMD in 2017. The darkened varnish alters the identification of the pigments through imaging, they fade into each other.[15] Nonetheless, the reflective behaviour of the two paint layers is distinctive when imaged with the MSMD. For this example, a trichromatic rendering (including the IR, and excluding the Blue spectral responses) was able to sharply delineate the transition between the undergarment (purple) and the cloak (dark blue) (Ill. 7, mark the zone on the right side of the chest).

Because of the degraded layers on top of the original pictorial layer (overpainting & darkened varnish) the histogram-tool of the PLD system could unfortunately not be used for the identification of specific pigments; a method which has nonetheless recently proven its value in combination with X ray-fluorescence and raman spectroscopy on manuscript illuminations.[16] But, when applied across the surface of the paint layers of the clothing, it does provide insights on the overall



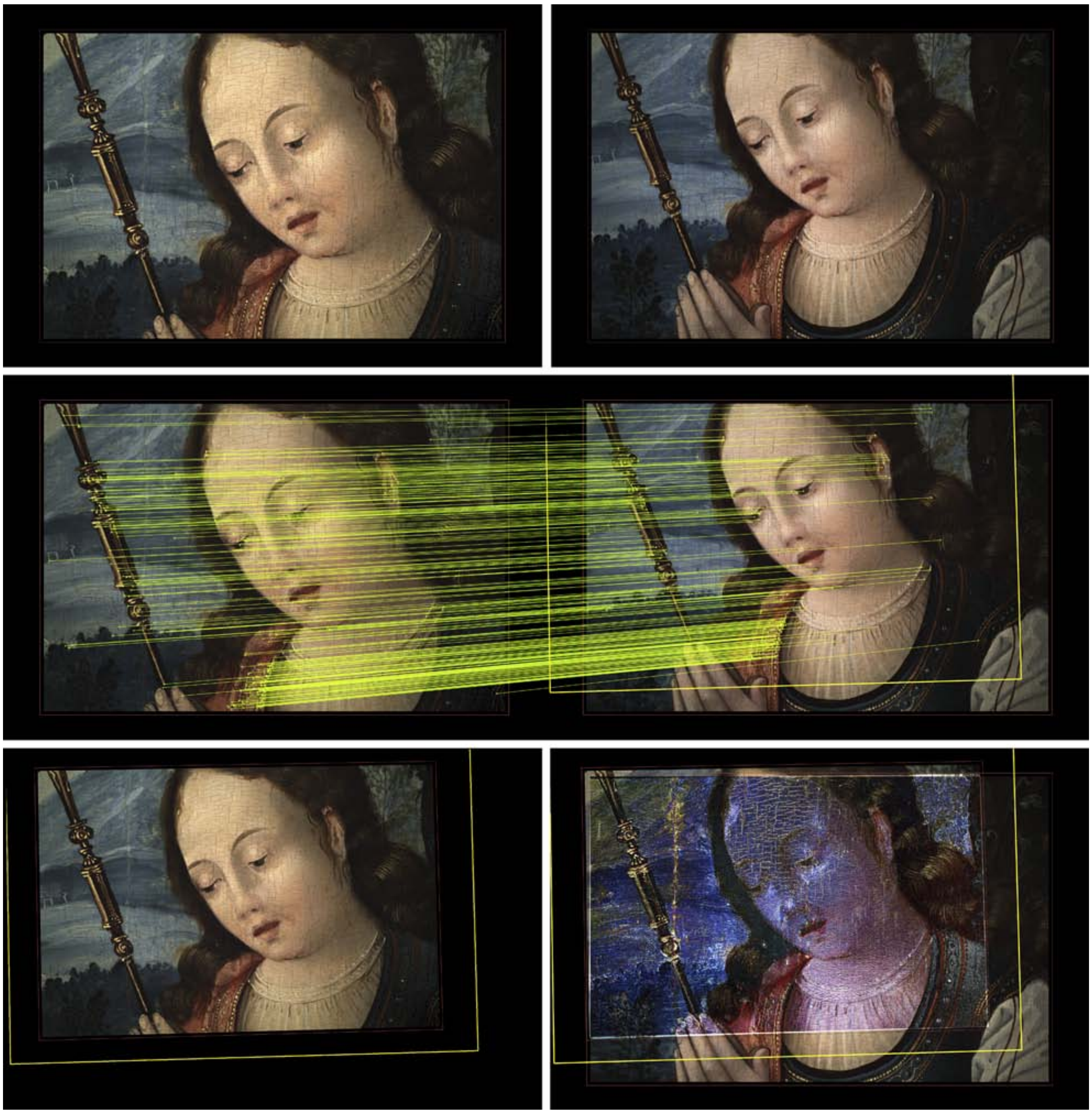
Ill. 8. Detail on the figure of St Peter on the left wing panel of G4 recorded with MSMD; Infrared-Red-Green trichromatic rendering, with generated 5-band histograms on 5 selected zones © KU Leuven

condition. Plotted on top of the false colour trichromatic rendering and combining the reflective responses of infrared (850nm), red (623nm) and green (523nm), the histograms define the influence of the overpainting & darkened varnish on the visual appearance. Compared to the right part of St Peter's undergarment, the left part (Ill. 8, middle histogram) reveals distinctively other reflective responses; already more closely resembling the histograms generated on the painted surface of the cloak. An effect which must be attributed to subsequently added paint and/or varnish layers.

4.3. *Comparing images before and after conservation treatment – Alignment of images*

While digitizing the status of a restoration or aging process, e.g. before and after a certain treatment or point in time, it is difficult to guarantee the exact same position, viewpoint, and settings of the recording device, e.g. camera. If this issue is ignored or insufficiently considered, visual documentations, for which the setup is not 1:1 the same, will lead to incorrect interpretations. In order to allow intuitive comparison, between the various documentations with the WLMD and/or MSMD, we propose a software solution where one recording is registered (i.e. image registration) to the other. The registrations are carried out between the albedo images determined from the PLD recordings. The albedo is a measure of diffuse reflection, it is dimensionless and not depending on the amount of light radiated on the surface, and therefore lends itself perfectly to achieve optimal results.

For the test cases, two details on the painted wings of the Enclosed Garden with St. Ursula (G2) have been recorded before and after the restoration process in 2018[17], one result is discussed below. For all tests, the same WL Microdome recording device was deployed. During the acquisition, the WLMD was, more or less, positioned perpendicularly to the



Ill. 9. Comparison between pre- and post-restoration phases based on the WLMD recordings of the face of St. Margaret, G2 © KU Leuven

targeted zone on the painted panel. The applied sensor and objective were the same. The distance between the sensor and the painted surface differed, and the exposure time was different as well.

The approach is illustrated using the test case with the face of St. Margaret on the left wing, referred to previously in this essay (see Ills. 1-2, 5, 9). The top of Ill.9 shows the albedo calculated for the recording before restoration (left) and after restoration (right). As can be observed and was anticipated, the field of view of both recordings is not the same. The recording on the left, approached the painted surface closer comparing to the recording on the right, and furthermore, there is a slight difference in rotation and viewpoint direction on the surface.

From the perspective of state-of-the-art computer vision, the relationship between two such image recordings of a flat painting are related by a homography, which is basically a linear relationship between the corresponding features point coordinates between the two images.

These feature points can be interpreted as distinct local image structures, which can be described by their location, and a visual descriptor, for instance corners, edges, curves, etc.

We used OpenCV, an open source computer vision library, to carry out the initial experiments.[18] First, the feature extraction is executed on the left and right image separately. In a next step, the features are selected for which a corresponding match can be found. The middle section of ill.9 shows the resulting corresponding features by a set of lines connecting their respective coordinates. The yellow rectangle shows how the image area on the left can be projected in the field of view of the recording oftheright.

The homography is used to warp/transform the left image into the view space of the right image. As a consequence, the left warped image and the right image can be overlaid and can be compared in a pixel-wise fashion. The bottom right part of ill. 9 shows a colour coded difference between the two views. It allows the visualizing of effects of the cleaning of the varnish and restoration in a variety of ways. For instance, the overlay of the registered recordings shows the skin colour has been cleaned up, a large part of the craquelure disappeared, there are clear retouches around the nostrils and lips. The result of the overlay also accentuates that the gap of a few millimetres between the two vertical oak panels, painted blue in the background, was stabilised, filled in, and delicately retouched.

Conclusions

The study and testing of the imaging of the painted wings of the Enclosed Gardens with the PLD system has explored the possibilities of the photometric stereo for oil panel paintings. One of the advantages of imaging with the PLD is the easy way in which (N)IR results can be compared/superimposed with the RGB, ultraviolet or even untextured (accentuating the relief) generated images. The original design, the pictorial layers, later interventions or decay can be visualized and studied within one viewing environment based on one 5 minutes recording process. The researcher, after processing and with the PLD viewer access to information concerning the underdrawing, receives the topography and structure (thickness - smoothness) of the paint layers. The multispectral imaging gives information on the materiality of the present pigments and their condition. Combined with standard procedures such as HR photography, XRF MA, and IRR used in panel painting examination, the device gives complementary data on characteristics in the pictorial layers. An important current limitation is that the examined surface per recording cannot be larger than 12 x 18 cm. Research that allows the stitching together of individual recordings as a mosaic without losing functionalities processed in the PLD datasets is in progress.

Notes

1 Iterbeke 2018: 26.

2 Pearson 2018: 122-131.

3 Abate 2019.

4 Legrand *et al.* 2014; Cosentino 2015: 6-9.

5 Pintus *et al.* 2018: 87-96.

6 Boute *et al.* 2018; Van der Perre & Hameeuw 2015: 164-165; on canvas: Salvant *et al.* 2017.

7 Currie & Weissenborn 2018: 250-255.

8 Watteeuw & Iterbeke 2018.

9 ArtGarden is a network-project funded by the Belgian Federal Public Planning Service Science Policy (Belspo, 2016-2020). It is part of the BRAIN-be research-program (Belgian Research Action through Interdisciplinary Networks). The project focuses on the conservation treatment of seven Enclosed Gardens and on the complex issues of long-term preservation of historic mix-media objects. Scientific partners of ArtGarden KU Leuven (Illuminare - Book Heritage Lab, ESAT & Digital Lab - University Libraries), the Chemistry Department (AXES and Heritage Science) of the University of Antwerp, and the Laboratories and the Preventive Conservation Unit of the Royal Institute for Cultural Heritage (KIK-IRPA, coordinator). The presented research is part of the art technical and imaging study of the Enclosed Gardens by the team of KU Leuven (2017-2018).

10 For the development of the KU Leuven Microdome(s), PLD see: Watteeuw *et al.* 2016; Vandermeulen *et al.* 2018: 64-69; Vanweddingen *et al.* 2018: 204-211; Van der Perre *et al.* 2016: 163-192.

11 Currie & Weissenborn 2018: 250-255. The painted wings of G2 were not examined with MA XRF, no data on the pigment composition are available.

12 Currie & Weissenborn 2018: 251.

13 Vandermeulen *et al.* 2018: ill. 7.

14 MA-XRF; see Van Bos, Weissenborn & Watteeuw 2018: 256-257.

15 The conservation report of Hilde Weissenborn (March 2019) mentions at least two varnish layers: an early brushed one, and a more recent one dating to the restoration campaign of 2006. The recent varnish was applied with a pressure pump and had a satin, powdery and dusty appearance. Old retouches and alterations were present under both varnish layers. During the earliest restoration campaign (date unknown) the green cloak was almost completely overpainted.

16 Vandermeulen *et al.* 2018: 64-69; Watteeuw *et al.* 2016.

17 Vandermeersch, Weissenborn & Watteeuw 2018: 218-249.

18 OpenCV: Open source computer vision library https://opencv.org/