TOWARDS IMPROVED INFRARED REFLECTOGRAMS

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Abstract—This contribution attempts a better understanding and, where possible, an optimization of the components in the 'image chain' of infrared reflectography. It aims to protect the object against radiation in excess of that required for image acquisition, to reveal more of the underdrawing than does the conventional procedure, and to increase the image quality of both the single reflectograms and the assembled mosaic. The automatic acquisition uses a positioning system in which the camera is moved while the object remains stationary. Processing and automatic mosaicing of the digitized reflectograms are done on a computer workstation. The results are demonstrated on a late eighteenth-century painting by J. G. von Dilis.

1 Introduction

Since van Asperen de Boer laid the foundations in the mid 1960s, infrared reflectography has become an indispensable tool for the non-destructive investigation of paintings [1]. Many applications have been published and the results have been used by art historians in many ways. Surprisingly, not much effort has been put into the improvement of the technique itself [2-4] or its use for the investigation of objects other than paintings [5]. Our own work on the application of infrared techniques to the investigation of drawings revealed a hitherto unexploited potential of infrared reflectography and provided by its spectrophotometric approach an understanding of the spectral characteristics of drawing materials [6-8].

The components used to collect infrared reflectograms usually include an infrared video camera, a video monitor, a controller unit, photographic lamps and a tripod. The camera is equipped with a tube sensitive in the near-infrared, a lens and a high-pass filter. The painting is mounted on an easel. Photographs of the infrared reflectogram are taken from the monitor. The photographs are mosaiced by hand, resulting in what are known as 'photographic' infrared mosaics. In some institutions this manual mosaicing technique has reached a high standard. Mosaic assembly on PC-based systems is done by a few institutions [9, 10] while using the digitized video signal from an infrared camera. However, until recently these systems did not find any wider application. A milestone is a scanning device described by Bertani et al. [11] where a one-element sensor is used, resulting in infrared reflectograms of excellent quality.

This contribution attempts to improve infrared reflectography in the following way:

1. It seemed worth making better use of the components described above, which in the first instance meant higher resolution and improved image quality.
2. More appropriate lighting had to be selected since the powerful illumination sometimes used during image acquisition is considered inappropriate to the conservation of the painting.
3. Additionally, we aimed to introduce an automatic mosaicing procedure.

We have not been in a position to develop a new camera or optical system. This has the advantage that most of our results are applicable in other institutions where infrared reflectography is commonly used.

2 From the imaging unit to the digitized infrared reflectogram

During this work, the actual characteristics of the more important components of the 'image chain' were compared with the characteristics described in the corresponding technical data sheets (for example [12]). Although the components interact with one another in practice, we tried to isolate individual characteristics. Spectral sensitivity curves (Figure 1) provided a useful tool to evaluate the spectral characteristics of the chosen components or of the proposed modifications.

2.1 The camera

In the first instance our interest focussed on the
camera. All experiments were conducted with a Hamamatsu infrared camera which consists of the camera case C2400-03-DSC and the vidicon tube N2606-06. Inside the tube is a lead sulphide sensor sensitive in the visible and the near-infrared. The Hamamatsu camera controller C2400 allows the contrast, the sensitivity and the shading to be influenced electronically. Its video signal is displayed on a monitor. Our camera is equipped with a Leica Macro-Elmarit 60 R/1:2.8 lens with C-mount adapter (Opto Sonderbedarf).

![Graph showing spectral sensitivity curves](image)

**Figure 1** Total spectral sensitivity curves given as logarithmic absolute intensity ($10^5$ A/m² ster) versus wavelength (nm) for various tube and filter combinations. Each curve is based on a halogen illumination with a colour temperature of 3200K.

### 2.1.1 Spectral sensitivity

According to van Asperen de Boer, paint layers exhibit an optimum transparency for infrared radiation in the range of about 2000nm [1]. However, some of the common drawing materials used for underdrawings (such as iron-gall inks and sepia) become ‘invisible’ in this range [8] and can only be made visible in a lower wavelength range. A successful application of infrared reflectography will therefore require all the information in the range from 800nm to 2000nm, which means that the system should be able to use any wavelength by the choice of an appropriate set of filters.

A set up widely used—a N214-06 tube combined with, for instance, Kodak 87 or 87C gelatine filters [2] or Schott RG 1000 glass filter [6] before or after the optics—only partly fulfilled these requirements. Therefore the use of an infrared tube with increased sensitivity, such as the Hamamatsu infrared N2606-06 tube, promised to be of benefit, because it would allow us to decrease the level of radiation illuminating the object. Its sensitivity is, for instance, six times higher in the 1600nm region compared to the Hamamatsu N214-06 tube (Figure 2). By means of experimental comparison this increased sensitivity of the N2606-06 tube could be practically demonstrated.

![Graph showing spectral sensitivity curves of different tubes](image)

**Figure 2** Typical spectral sensitivity curves of different tubes (from [12]).

### 2.1.2 The resolution

In addition to the sensitivity mentioned above, the resolution of the integrated system is a key issue. A resolution of a minimum of 500 TV lines is guaranteed in the Hamamatsu data sheet mentioned, and 650 lines are said to be typical. As specified by Hamamatsu, a resolution of 500 TV lines means that 250 black-and-white pairs of lines can just be resolved if they are imaged exactly to occupy the full vertical dimension of the sensor. As mentioned in the data sheet [12], the resolution is measured using a Toshiba IR-D80A filter (800nm long-pass filter). The resolution is then evaluated by human eye, which is in

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Figure 3 Resolution test pattern at a sensor temperature of 30°C (a) and 1°C (b).

our view not the most appropriate way.

Much effort has been put into the verification of these specifications. Our experiments at the local Hamamatsu office revealed that the guaranteed 500 TV lines could only just be resolved, and only under special conditions (excellent high-resolution black-and-white monitor and special photographic test patterns illuminated from the back) not corresponding to a real situation. The typical resolution of 650 lines could not be reached.

Moreover, our experiments showed that under practical conditions (objects of lower contrast with lower light levels in reflection mode) an inferior resolution of only 100 to 200 lines can be expected. This contradicts statements by Mairinger who confirms the resolution given by Hamamatsu [13] and by Walmsley et al. who report 'a limiting resolution of 3 to 5 lines/cm with no filter' [4, p.127].

To overcome the low resolution observed in our experiments the only answer is to decrease the area to be imaged, either by moving the camera closer to the painting or by using a telephoto lens. However, the smaller the area covered, the higher the number of images to be mosaiced.

2.1.3 Long-term stability
If a larger object is imaged for subsequent mosaicing—i.e. if a series of reflectograms taken under exactly the same conditions is required—the long-term stability of the overall system is crucial. Two factors proved to affect the long-term stability and thus the quality of the images:

(1) During exposure, the temperature of the sensor goes up to about 30°C [14] and the image becomes less sharp. Our experiments with a camera cooled to 1°C resulted in less noisy images (Figure 3). However, because of the camera and tube architecture, it is difficult to cool the camera sensor.

(2) On the C2400 controller, the optimum sensitivity has to be regulated manually. The regulated value is not stable and should be readjusted during image acquisition. However, this is not feasible if many reflectograms are taken for mosaicing.

2.1.4 Electrical interference
During our experiments we found that the camera had to be wrapped in a copper wire gauze to suppress electrical interference. Obviously the camera casing as delivered is not sufficiently shielded. The interference signal resulted in a regular and disturbing pattern on the digitized image. In our case, the source of this pattern turned out to be the stepper-motors of the positioning unit discussed below, but for other set-ups it might be any other item in the neighbourhood of the camera.

2.2 Optics
As mentioned, we decided to adapt a Leica Macro-Elmarit 60 R/1.2.8 to the camera. Besides this lens, a series of other commercial lenses (such as the Nikon Micro Nikkor 55/1.2.8 sold with the Hamamatsu camera or the Zeiss Jena Lantar 35mm/1.2.8) was included in our experiments.


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All of these lenses are corrected and designed to be used in the visible range for reproduction purposes. Therefore the commonly used combination of one of these lenses and the Hamamatsu camera is not the best. In the near-infrared, theoretical considerations suggest the use of specially coated apochromatic macro lenses. This coating diminishes stray light between the single optical lenses, which in turn will increase the contrast. In the near-infrared, apochromatic lenses show a more fixed position of the optical image when the wavelength is changed. Therefore, using these lenses, a sharper image can be expected, especially when the wavelength range is considerably expanded. Infrared coated lenses can only be obtained on request, and were not available for this study.

2.3 Illumination and filters
A deliberate selection of the illumination used led to a modification of the set-up, where light, passing from the light source to the painting, is reflected into the optics of the camera.

2.3.1 The light on its way from the light source to the painting
Hitherto, conventional photographic lighting including standard bulbs and halogen lamps has been used to illuminate the painting or the area of interest. High light levels (including UV and visible) and the resulting heat are a major cause of concern. Therefore, our main aim was to improve the lighting to fit better with conservation needs. This is done by using high-intensity light sources while blocking out unwanted radiation (especially UV and visible) falling on the object. This filtering was regarded as unnecessary by other authors [2] and is not even considered in most recent contributions [4].

In practice, we use two Götschmann G67P slide projectors with 400W halogen lamps. The main advantage of using slide projectors is that the light is directed to the region of interest and 3 x 5cm filters can be easily introduced by using the slide changing mechanism. It should be mentioned that the low-pass heat filter in the projector has to be removed; for fire protection reasons, this suggests projectors with, for example, metal cases. A Schott RG 1000 glass filter (3mm thick) cuts out radiation below about 1000nm. During the accurate positioning of the painting on the easel a Schott RG 665 filter bathes the selected area in a dark red light.

2.3.2 The light on its way from the painting to the optics of the camera
As mentioned above, depending on the type of drawing material used for the underdrawing a distinct wavelength range has to be selected which can be as high as 2000nm. In the latter case, a Schott BG 39 band filter (1mm thick) is placed in front of the lens. In other cases a lower wavelength band filter of the BG series may be selected to increase readability. This is clearly limited by the hiding power of the overlying paint layers. Because the BG series has high transmission in the visible range, image acquisition has to take place in a dark room. If this is not conven-
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2.4 The integrated system

As mentioned before, Figure 1 includes several sensitivity curves which allow a useful visualization of the total sensitivity of the set-up proposed:

1. Without filtering of any kind, i.e. using a conventional light source combined with the new infrared N2606-06 tube, the maximum of the sensitivity curve is in the region of about 800nm.

2. With the RG 1000 filter in front of the light source, the maximum would only be shifted to some extent towards the range of interest. But higher energy radiation, i.e. the visible and UV, is excluded, which is a clear benefit from the conservator’s point of view.

3. With the filter combination proposed here—the RG 1000 (in front of the light source) in combination with the BG 39 (in front of the camera) giving a cut-on wavelength of 1650nm—a further shift towards 2000nm is obtained. Any further shift would be limited by a drop in the spectral sensitivity of the tube, which could only be compensated by stronger light sources.

4. Most important, the set-up guarantees an additional reduction in radiation (Figure 1).

5. In all cases where a carbon-rich ink is used, the set-up yields a much better image of the underdrawing than the filters used in the conventional procedure (Figure 4).
(6) However, the slightly noisy image is not yet ideal. This is due to the broad band characteristic of the filter combination proposed and the low resolution of the camera. Consequently, small band filtering with high transmission can result in much improved infrared reflectograms. This is currently under investigation.

(7) Some of our experiments used both the RG 1000 and the BG 39 filters in front of the light source and no filter at the camera. This once again reduces the amount of radiation falling on the painting. However, a considerable loss of sensitivity at the camera end was observed. This unexpected effect is currently thought to be caused by infrared fluorescence.

2.5 The digitization process
To allow image processing the analogue video images have to be converted into digital images by digitization. We use an A/D-converter (VideoPix 1-0 from Sun), which transforms the analogue signal of the camera into an 8-bit digital image (768 x 575 pixels).

The quality of an infrared reflectogram is to a great extent determined by its contrast and its dynamics. Both are dependent on the number of grey levels which in any case is lower for digitized images than for any analogue technique. As noted, the maximum output voltage of the Hamamatsu is lower by a factor of 0.7 than the input voltage of the VideoPix card required for saturation. To compensate for this, the signal is scaled, resulting in 7 bits. These 7 bits are then artificially expanded to 8. Thus, every second grey level is unoccupied. During our experiments we observed a number of grey levels (with values such as 0, 2, 4, 6, 10, 12, 16, 18, 20, ... ) were observed, which corresponds to about 6-5 bits spread over a virtual 8 bits. The result is that arched forms can be observed in regions of low contrast (Figure 5).

Additionally, we noticed a 10% horizontal distortion of the image, which is diminished to 5% by internal corrections of the VideoPix A/D-converter by duplicating every fifteenth pixel [15].

3 Assembling the infrared mosaic
There were five main reasons for using a computer-based procedure:

(1) The curvature of the video monitors commonly used to take a photograph of the infrared reflectogram results in a considerably distorted secondary image which is then assembled with unsatisfactory results.

(2) Any geometrical distortion of the sensor can be corrected by the computer, which is not possible in the purely photographic approach.

(3) In the photographic procedure, adjacent images may show different brightness values caused by inhomogeneities of the sensor, the illumination or the video monitor.

(4) The photographic image acquisition and the subsequent manual process are very time-consuming.

(5) Finally and most importantly, the increased resolution can only be reached by putting a much higher number of single exposures together. For practical reasons, during the photographic procedure this number of exposures is limited.

3.1 The mosaicing procedure
To assemble the infrared mosaic, we used the VASARI system. This consists of a rigid positioning unit which allows any kind of camera to be moved precisely in front of an object mounted on the easel (Figure 6) [16]. The system is fully controlled by a computer (Sun Sparstation 2 with the UNIX operating system SunOS 4.1.1), which also handles and processes the images. The high performance of the work-
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(i) station enables us to handle quite large infrared mosaics.

Two useful C-routines (in part from the VIPS package [17]) and a shell script allow the automatic assembly of a mosaic. The only parameters to be entered are the format of the painting and the desired resolution. The procedure then:

(i) calculates the relative distances the camera has to be moved, which are dependent on the type of lens used. Then the camera is moved vertically and horizontally by the positioning unit (see 3.2) to distinct positions from where

(ii) the images are captured. To suppress thermal noise each frame is taken up to 64 times. These single frames are averaged to result in a less noisy image. The light distribution is then

(iii) imaged, usually by using one out of a set of five grey cards which shows a lightness comparable to the mean lightness of the painting. Although this procedure will take the same time as for the object itself, no further supervision of the system is necessary because the object has been removed from the easel. The computer then

(iv) corrects the light distribution of all the single frames (see 3.3). In a further step,

(v) the resulting images are corrected with respect to the overall geometric distortion (see 3.4).

3.2 Positioning unit
To automate the mosaicing procedure in the way described, either the camera or the painting [18] has to be moved in two dimensions. However, from a conservation point of view, movement of the painting should be avoided whenever possible. Therefore the VASARI positioning unit (described in detail elsewhere [16]) is used to move the camera in a very accurate and reproducible way, controlled by computer.

3.3 Lighting correction
One of the disadvantages of the set-up chosen is that the painting and the light sources are static and the whole painting is illuminated, resulting in an inhomogeneous distribution of light on the painting. Therefore the illumination control card mentioned above (see 3.1) has to be imaged in the same way as the painting. This will yield the light distribution.

3.4 Geometric distortion
We observed that all the infrared images captured showed slight distortion. This is only partly due to the geometric distortion of the camera which is said by Hamamatsu not to exceed 2%, including any defects of the sensor and a tilted but fixed mounting within the tube. The geometric distortion is also influenced by the mounting of the camera on the positioning unit. Since the camera remains fixed on the positioning unit, the overall geometric distortion is the same for each individual frame, but only valid for our specific set-up. By imaging a piece of graph paper, we observed a slight rhomboid distortion of 1.2% (Figure 7). A further C-routine allows a
second-order correction of the distorted images. This correction step is indispensable for subsequent mosaicing.

Figure 7 Schematic representation of the specific rhomboid distortion observed. The distortion is given in pixels referring to a 768 × 575 pixel image.

3.5 The output of the results
To visualize the results on something other than a monitor, digital proofs can be produced on our dye sublimation printer (Mitsubishi S3410-30D).

4 Applications
To demonstrate the quality of the improved set-up, the ‘photographic’ infrared mosaic [N214-06 with RG 1000 (camera), 4 × 5 reflectograms] of a painting by J. G. von Dillis is contrasted with the ‘computer’ infrared mosaic composed of 5 × 5 reflectograms (Figure 8). The size of the painting is 28.2 × 25.8cm and the theoretical resolution is about 10 lines/mm on the painting. The 25 frames were captured in about 15 minutes and the whole procedure took about two hours. Because the operator has to be present only during the first 15 minutes, this is a great advance compared to the conventional procedure, where the time spent by an experienced photographer would be about one day. Most important, more of the underdrawing is visible in the resulting homogeneous mosaic. However, the contrast enhancement applied reveals artefacts in the sky, as described (see Figure 5).

Figure 8 Johann Georg von Dillis, ‘Das Trivashlößchen’, signed and dated ‘G. v. Dillis f. 1797’, paper on oak panel, 28.2 × 25.8cm (Bayerische Staatsgemäldesammlungen, Munich, Inv. No. 9392). As black-and-white photograph (a), as ‘photographic’ infrared mosaic [N214-06 + RG 1000 (camera)] (b), and as ‘computer’ infrared mosaic [N2606-06 + RG 1000 (illumination) + RG 1000 and BG 39 (camera)] (c).
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5 Conclusion

This contribution proposes modifications which may result in improved infrared reflectograms. Although little could be done to improve the imaging device itself, for example using specially designed lenses or cooling the sensor, three main benefits can be noted:

(1) Improved lighting results in a considerable reduction in the amount of energy falling on the painting during acquisition. This is seen as the major benefit.

(2) Improved filtering in combination with the N2606-06 tube reveals more of the underdrawing.

(3) Automatic acquisition and processing software facilitates the capture of more infrared reflectograms with high resolution in a short time. The homogeneity of the resulting mosaic is improved.

Acknowledgements

The authors are grateful to Dipl.-Ing. M. Müller for valuable discussions, daily computer care and programming advice. This work has been improved by contributions from Dr. habil. R. Lenz and P. Powell. All ‘photographic’ infrared mosaics and reproductions are by B. Hartinger, Bayerische Staatsgemäldesammlungen, Munich.

Suppliers

Götschmann Diaprojektoren, Linprunstr. 19–21, 8000 Munich 2, Germany.
Hamamatsu Photonics Deutschland GmbH, Arzbergerstrasse 10, 8036 Herrsching, Germany.
Leica Vertrieb GmbH, Königstr. 11, 8000 Munich 22, Germany.
Opto Sonderbedarf GmbH, Königstr. 11, 8000 Munich 22, Germany.
Schott Glaswerke, Geschäftsbereich Optik, Verkauf Optische Filter, Hattenbergrasse 10, 6500 Mainz, Germany.
SUN Microsystems GmbH, Bretonischer Ring 3, 8011 Grasbrunn 1, Germany.

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Résumé—Cet article tente d’apporter une meilleure compréhension, et si possible une optimisation des étapes de la chaîne de traitement d’images de réflectographie infrarouge. Il vise à protéger l’objet des radiations qui ne sont pas nécessaires à l’acquisition de l’image, à révéler plus de dessin sous-jacent que ne le fait le procédé conventionnel, et à accroître la qualité de l’image à la fois pour les réflectogrammes isolés et les assemblages. L’acquisition automatique emploie un système de positionnement dans lequel seule la caméra se déplace pendant que l’objet reste immobile. Le traitement et l’assemblage automatique des réflectogrammes numérisés sont effectués sur une station de travail. Les résultats sont montrés sur une peinture du XVIIIe S. de J.G. von Dillis.