A New Camera for High-Resolution Infrared Imaging of Works of Art

David Saunders, Rachel Billinge, John Cupitt, Nick Atkinson, and Haida Liang

Summary – A new camera – SIRIS (scanning infrared imaging system) – developed at the National Gallery in London allows high-resolution images to be made in the near infrared region (900–1700 nm). The camera is based on a commercially available 320 × 256 pixel indium gallium arsenide area array sensor. This relatively small sensor is moved across the focal plane of the camera using two orthogonal translation stages to give images of *c*. 5000 × 5000 pixels. The main advantages of the SIRIS camera over scanning infrared devices or sequential image capture and mosaic assembly are its comparative portability and rapid image acquisition – making a 5000 × 5000 pixel image takes less than 20 minutes. The SIRIS camera can operate at a range of resolutions; from around 2.5 pixels per millimetre over an area of up to 2 × 2 m to 10 pixels per millimetre when examining an area measuring 0.5 × 0.5 m. The development of the mechanical, optical and electronic components of the camera, including the design of a new lens, is described. The software used to control image capture and to assemble the individual frames into a seamless mosaic image is mentioned. The camera was designed primarily to examine underdrawings in paintings; preliminary results from test targets and paintings imaged in situ are presented and the quality of the images compared with those from other cameras currently used for this application.

Introduction [head]

For many years, near infrared imaging has been used routinely to examine paintings to highlight changes in the composition, to detect retouchings or overpaint, and to study the underdrawing, which can give valuable information concerning, among other factors, the genesis of the painting or the involvement of different hands. Infrared photography, using film sensitive in the spectral range 700–900 nm, has been used to examine works of art since 1930s [1], it was not until the late 1960s that van Asperen de Boer developed infrared reflectography, which, using radiation in the 1000–2000 nm range, gives greater penetration through the surface paint layers than infrared photographic techniques, revealing greater detail, particularly in the underdrawing [2].

Throughout the 1970s and 1980s many museums and galleries made use of infrared reflectography equipment based on infrared vidicon tubes, most notably those manufactured by Hamamatsu. To make a permanent record of the ephemeral images produced by these infrared vidicon tubes, the image was displayed on a TV monitor and a photograph of the image was made using standard black and white film. By the end of the 1980s it was quite common for the signal from the vidicon camera to be digitized, processed and stored [3]. Images from vidicon cameras are, however, plagued by geometric and radiometric stability problems, which can only be partly addressed by modifying the camera [4]. Solid-state cameras sensitive to radiation in the near infrared have become more widely available over the last 15 years, and promise better-quality, distortion-free images [5]. Some museums have purchased such solid-state infrared cameras, mainly based on either platinum silicide (PtSi) [5], or indium gallium arsenide (InGaAs) sensors.

However, the solid-state and vidicon infrared imaging devices share a common drawback: they have much lower resolution compared to visible region CCD (charged-coupled device) cameras. Vidicon cameras usually produce images at standard video resolutions, 768 × 576 pixels for PAL or 640 × 480 for NTSC.[1] Solid-state cameras are less tied to video formats, but arrays larger than 640 × 480 for InGaAs and 800 × 512 for PtSi tend to be custom-built for use in astronomical instruments and extremely expensive. The size of image needed for a whole painting depends on the level of detail that is required – for example, a resolution of around 10 pixels per millimetre is needed to examine brushstrokes and the majority of craquelure in visible images [6]. At a resolution of 10 pixels per millimetre, images from any of the cameras described above will only cover between 60 × 50 and 80 × 60 mm on the painting surface. If the whole painting or large areas of interest are to be examined, then current practice is to make a series of images covering the region of interest and assemble a mosaic from these using image processing software. Such image assembly procedures have been commonly used for decades in astronomy and satellite mapping, and were applied to digitized infrared reflectogram images of paintings from the late 1980s [3], although the procedures for image capture, correction, assembly and balancing have subsequently been refined through modifications to the standard hardware and through improved software [4, 7, 8].

Concurrently, instruments to make infrared reflectogram images that are based on the principle of scanning an infrared-sensitive point detector over the surface of a painting, or part of a painting, have been developed [9–11].

However, the two methods described above (making a mosaic assembly or scanning with a point sensor) have two main disadvantages. First, making an infrared image of a whole painting takes many hours, or even days if the time required for image assembly is included. Second, the equipment needed to scan the point sensor or camera across the surface of the paintings is generally heavy and large. The project reported here set out to construct and test a system that was fast, and as compact and portable as possible, building on experience gained during the earlier development of a scanning colour camera.

In the early 1990s, the National Gallery, London had participated in a project to build a high-resolution colour camera to image paintings, based on the notion of moving an area array across the focal plane of a large format lens by means of two orthogonal motorized stages. The sensor comes to rest at a number of positions, at each of which a frame is recorded. The individual frames are joined into a seamless image by the software that drives the camera. The resulting prototype camera produced images with a resolution of up to 20000 × 20000 pixels using a sensor with only 500 × 290 pixels [12]. A much faster, improved version of the camera, based on the same principles, was subsequently developed which could produce a 10000 × 10000 pixel colour image in less than three minutes. This camera (the MARC II camera) was used during 2000–2002 to make images of all the paintings in the National Gallery collection [13]. An obvious application of the principles behind these visible region cameras was to construct an analogous camera containing a sensor that responded in the near infrared region of the spectrum. The resulting camera, named SIRIS (scanning infrared imaging system) and its application to the study of paintings are described here.

Camera Elements [head]

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[1] PAL and NTSC are the and European and American broadcast video standards respectively

Near infrared focal plane array [sub-head]

The choice of sensor was determined by three principal factors: spectral sensitivity, cost and practical considerations. The first criterion was that the wavelength range needed to reveal underdrawings. A study of the visibility of underdrawing lines had concluded that a wavelength of around 1800 nm gave optimal visibility, but as the materials comprising the overlying layers vary, the optimum wavelength to reveal a particular area of underdrawing would probably need to be determined empirically [14]. It has been claimed that lead sulphide vidicon cameras are sensitive to wavelengths as long as 2000 nm, but Walmsley et al. estimate that under normal operating conditions, the system responds only to radiation up to 1600 nm and is most sensitive in the range from around 1000 to 1400 nm [5]; however, no focal plane sensors based on lead sulphide are currently available. Walmsley et al. also concluded that germanium (Ge) sensors gave good results in terms of revealing underdrawing [5], but no germanium-based arrays are available either.
Four solid-state sensor technologies were considered: those based on PtSi, InGaAs, mercury cadmium telluride (MCT or HgCdTe) and indium antimonide (InSb). All four have been used in spectroscopic applications in the field of astronomy and their intrinsic properties have been widely reported [15, 16]. The spectral sensitivity of these detectors can be highly dependent on operating temperature, and some of the sensors require cooling (to as low as c. 77K) to obtain acceptable signal-to-noise ratios. The need to include a cooling apparatus (for example a closed-cycle Stirling system) within the camera, and to move it in concert with the detector array, would have increased the potential cost of the sensor unit greatly and made its incorporation into a scanning camera impractical, so the different materials were evaluated in terms of both their spectral response and their sensitivity when operating at near ambient temperature.

Although PtSi cameras have previously been used widely to examine works of art they have the dual disadvantages that their response lies principally in the 3000–5000 nm range, reflecting their principal use as thermal imagers, and that the detector array must be cryogenically cooled, typically by liquid nitrogen or a closed-cycle Stirling cooler [17, 18]. Over recent years cameras with InSb or HgCdTe sensors have largely superseded PtSi devices in the thermal imaging field. InSb detectors have better sensitivity in the 3000–5000 nm region than PtSi sensors but require cooling to operate satisfactorily. The spectral response of HgCdTe sensors can be tuned by adjusting the ratio of mercury to cadmium. Figure 1 shows the response curve for a HgCdTe detector designed to operate in the 3000–5000 nm range; this sensor again requires cooling to obtain an acceptable signal-to-noise ratio. The main drawback with arrays based on PtSi, InSb or HgCdTe is that they are all tailored to operate as thermal imagers and have peak responses at much longer wavelengths than those used for infrared reflectography.

InGaAs detectors have several key advantages. First, they operate efficiently at, or near, room temperature, giving low dark current and good quantum efficiency (60–70%) at 20ºC [19]. Second, they have a peak response in the region (c. 1000–2000 nm) previously identified as most appropriate for infrared reflectography (Figure 1) [14]. Although the upper wavelength limit of standard InGaAs arrays is only around 1800 nm, this should be adequate to examine most underdrawing in traditional easel paintings. Based on the ease of use and spectral sensitivity, it was decided to pursue a solution based on an InGaAs array. During the late 1990s, trials were conducted at the National Gallery with two different InGaAs focal plane array cameras.

Incorporating an InGaAs sensor into a scanning camera presented additional challenges compared to the construction of the MARC II camera. The sensor pitch for the MARC camera is 6.7 µm and, using super-sampling,[2] produces a 10000 × 10000 pixel image over a focal plane that is 33.5 × 33.5 mm [13]. Because the fill factor of the InGaAs array is over 90%, super-sampling was not considered and, as the sensor pitch for the sensor is c. 30 µm, a focal plane measuring 300 × 300 mm would have been required to make an image of 10000 × 10000 pixels. This would have created a large unwieldy camera, too large to be easily portable: one aim of the project was to build a camera that is sufficiently portable to permit it to make images in situ. A lower resolution was adopted and the design based on scanning a 5000 × 5000 pixel image by moving the sensor chip across a 150 × 150 mm focal plane. An Indigo Alpha 320 × 256 pixel camera was selected as the

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[2] When a camera super-samples an image, the array is displaced by a fraction of a pixel (usually one half) in both the horizontal and vertical directions, which increases the resolution of the resulting image.

basis for the scanning camera [20]. This choice of sensor size was the result of a compromise between size, cost and availability. The larger the sensor size, the fewer images are needed to cover the focal plane (for example, had a 640 × 512 pixel sensor been used, four times fewer individual frames would need to be made). However, the cost of the larger sensor and export controls on near infrared arrays led to the use of the lower-resolution device.

Near infrared large format lens [sub-head]

The camera was intended to be used not only to image large paintings in situ, but to make more detailed images of smaller paintings or portions of a painting. Three conditions were defined in the design (see Table 1), ranging from imaging large paintings, up to 2000 × 2000 mm, with a camera-to-object distance of c. 4000 mm to examining smaller areas (500 × 500 mm) with a camera-to-object distance of c. 1000 mm. For an image of 5000 × 5000 pixels, this gives a resolution range from 2.5 to 10 pixels per millimetre, suitable for a general inspection of a painting and a detailed study of the underdrawing respectively. These object sizes and object-to-camera distances define the field-of-view that is free from vignetting, which in this case needs to be at least 39º.

The lens needed to provide a suitable magnification factor, have sufficient resolving power and be free of aberration across the field of view. A lens with a focal length of 280 mm gives a magnification factor of 0.075 at an object–sensor distance of 4000 mm, which corresponds to a resolution of 2.5 pixels per millimetre on the object plane; to achieve a resolution of 5 or 10 pixels per millimetre the operating distance would be 2150 or 1200 mm respectively, similar to the specification in Table 1. The diameter of the lens determines the diffraction-limited resolution or point spread function (PSF) of the lens, although as a result of aberration the actual PSF of the lens is usually worse than the diffraction-limited resolution. Increasing the f-number of the lens results in a smaller lens diameter, and hence reduces the mass of the lens, but the exposure time and the PSF are increased. As a compromise, an f-number of 10 was chosen, which has an aperture of 28mm, giving a diffraction-limited resolution of c. 5 pixels per millimetre at an object distance of 4000 mm. Hence, the combined resolution of the system is limited by the pixel size rather than the diffraction limit of the lens. However, to cope with aberration a larger diameter lens that could be stopped down to f/10 was designed.

Large format lenses made for the visible range are available to meet these criteria, but a lens designed for the visible range will be adversely affected by chromatic aberration in the infrared region. In addition, these large format lenses are frequently optimized for the visible range by applying anti-reflection coatings that also reduce their transmission in the infrared region. Lenses that are intended for use in the near infrared (900–1700 nm) are designed to operate with the relatively small infrared sensors described earlier; none met the requirement for high resolution and large field of view.

There was little alternative but to design a lens specifically for the new camera. A new five-element lens comprising a meniscus followed by two cemented doublets, with an internal fixed aperture stop was specified. The design was refined after the polished glass for each element was delivered, to account for small differences from the theoretical specification, and an anti-reflection coating was applied that reduced the average reflection to <1.5% in the 900–1700 nm region. The lens elements were assembled in a tubular mount. The final lens has a focal length of 242 mm and was found to show minimal aberration, so that the PSF of the lens was essentially diffraction-limited (Table 1). The front of the lens barrel has a standard 67 mm diameter thread to allow a 100 × 100 mm filter holder to be attached. This contains a Kodak 87 filter, which prevents visible light from entering the camera. In future it is intended to investigate the use of other filters that transmit a narrower range of wavelengths in the infrared region.

Sensor positioning system [sub-head]

To move the sensor across the focal plane, two conventional stepper-driven ‘Unislide’ stages, each capable of a displacement of 150 mm with an accuracy of <0.05 mm per 100 mm, were selected. Using 4000 steps per revolution the stages have an accuracy of 0.25 μm and a repeatability of <10 μm. To improve the repeatability, the stages are always driven in the same direction when positioning the sensor prior to image capture. The InGaAs sensor unit was mounted on to the upper stage using a custom-designed bracket that ensured its focal plane was parallel to the motion of the stages.

The stages are driven by high-torque stepping motors, controlled individually by Xli type controllers from Parker Automation; these are linked to a computer by a serial (RS232) cable. A home sensor mounted on each stage allows repositioning to a known, repeatable point. For stability the stages are mounted on the thick aluminium back plate of the camera (Figure 2); the back plate is pocketed to reduce the overall mass of the camera while ensuring rigidity where required.

Camera body and power supply [sub-head]

In addition to forming a light-tight enclosure, the camera body must also provide a rigid base for the translation stages holding the sensor and must maintain the lens in position so that its optical axis remains perpendicular to the focal plane while it moves along its focal axis by up to c. 62 mm to achieve the different image resolutions given in Table 1. As the camera was intended to be relatively portable and lightweight, rigidity was achieved by attaching both the back plate and the lens to a strong horizontal element (Figure 3). This rigid support is in turn mounted on an adaptor plate that fits either to an astronomical tripod or, for fieldwork and imaging in situ, to a heavy-duty photographic tripod (Figure 4). The movement of the lens with respect to the focal plane is achieved by mounting the lens unit on an adjustable stage. The rough position of the lens is adjusted by moving a rod marked with the correct positions of three commonly used imaging resolutions, and the fine focus is then adjusted using a micrometer attached to this stage (Figure 5).

For transportation, the lens can be removed from the stage, and the rigid base, which is hinged, can be folded towards the camera to reduce its overall size (Figure 6). Between the lens and the case housing the stages and the camera electronics are two sets of bellows: a rigid self-supporting set nearest the case and a more flexible set nearer the lens. The bellows can be collapsed and a blanking plate attached to protect the sensor and electronics in the main camera case while the camera is folded.

The body also houses the camera electronics, which are mounted to one side of the translation stages and connected to the sensor head using a very flexible 44-way ribbon cable (Figure 2). All the internal elements of the case are anodized black to reduce unwanted reflectance.

A separate box was constructed to house the motor and camera power supplies, the motor controllers and the image capture card. This control box provides all the control and power connections needed to run the camera from a single mains socket; five cables connect the box to the camera, including that connecting the image capture card to the camera electronics. Each has a unique connector so that it should not be possible to connect the camera to the control box incorrectly. Inside the box, the image capture card is connected to an adapter, so that the images can be read through the PCMCIA port on a laptop computer. A serial link from the laptop to the control box is used to control the motion of the stages.

Control and capture and calibration software [sub-head]

The camera is controlled by a modified version of the software written in the Scientific Department at the National Gallery for the earlier MARC cameras [13, 21]. The modules to view, select, capture and save areas of the focal plane are essentially identical, with the main difference from the earlier software being the number of images to be made – with an image overlap of 60 pixels, a grid of 18 × 24 images, each of 320 × 256 pixels, was needed to give a final image resolution of 4740 × 4764 pixels. The software for the SIRIS camera uses the National Instruments NI-IMAQ software that is supplied with the interface card to grab frames from the sensor. A complete capture and assembly of all 432 tiles takes around 18 minutes.

Probably as a result of the cable between sensor and electronics, the SIRIS camera has a higher dark current than the original camera from which the components derive. The dark current varies between the two read-out circuits on the chip, with the dark current for the odd columns having a bias set at below the zero of the analogue-to-digital (A–D) converter. To correct for the dark current, the software uses an image of an evenly lit uniform white target taken while the camera is defocused. Neutral density filters are used to reduce the signal to the point where the leakage for both odd and even columns is just greater than zero; 32 frames are captured and averaged. If this average image was simply subtracted from every frame it would tend to clip the signal at zero in dark parts of the image, so an additional constant positive offset of the dark frame average plus 128 is added.

To compensate for variations in pixel sensitivity, the software uses a set of dark-current corrected images of a well-lit uniform white target. For each pixel in each tile a scaling factor is calculated to normalize the sensitivity of that pixel relative to the brightest part of the white reference image. This correction also compensates for two other factors: lens vignetting and the variation of sensitivity with the angle of illumination as the sensor travels across the focal plane. The sensor also has a number of 'dead' pixels, (pixels for which the value at a given point in the illumination range differs from the average value by more than a number of standard deviations). The software uses a map of the dead pixels (about 34 for the sensor in the SIRIS camera) to replace each dead pixel with the median value of the eight surrounding pixels.

When the tiles are joined together to make the final image, the software analyses the overlap areas and displaces each tile by a small amount to reduce mosaic artefacts. This removes errors caused by, for example, sagging of the easel over the exposure period. At the same time the relative brightness of the overlap areas is checked and tiles adjusted in brightness to remove any visible tile boundaries caused by changes in lighting intensity.

Results [head]

The individual components of the camera were tested prior to assembly and a series of tests was performed to ensure that, among other things, the case was light-tight, the motors did not drive the stages beyond their end points and that the cable did not become trapped during scanning. The next stage was to image a test panel kept in the Scientific Department at the National Gallery. This comprises a white ground, with underdrawing in a number of typical materials, including black ink, charcoal and coloured chalks. Each type of material is covered with one or more paint layers containing traditional pigment mixtures representative of the paintings in which underdrawing is usually detected. This test chart had already been imaged using a Hamamatsu vidicon camera and had been examined with InGaAs and PtSi cameras during their evaluation in the 1990s. Figure 7 compares the image made with the vidicon camera (Figure 7a) with that made with the SIRIS camera (Figure 7b). The penetration of the paint layers to reveal the underdrawing is broadly similar in each case, but while the resolution (in pixels per millimetre on the panel) is the same in both images, that made with the SIRIS camera is much sharper, allowing individual underdrawing lines to be seen clearly. Figures 7c and 7d show images for one patch on the chart; an underdrawing in bone black in a gum medium over two layers of lead-tin yellow in oil that has been covered with a further layer of lead-tin yellow in oil. In the image made with the SIRIS camera (Figure 7d), more detail is visible, showing the 'beading' of the ink within the brush strokes, the result of poor wetting during its application.

Comparative images were made of a number of paintings as they passed through the conservation studio, using the current method of grabbing a sequence of images with the Hamamatsu vidicon camera and the SIRIS camera. The example illustrated here is from *The Adoration of the Name of Jesus* by El Greco (National Gallery, London No. 6260) (Figure 8). With the vidicon 55 images (in a 5 × 11 grid) were required to give a final image of 4376 × 2677 pixels, corresponding to a resolution of approximately 8 pixels per millimetre on the surface of the painting. To obtain an image at maximum resolution, two images were made with the SIRIS camera and joined together to yield an image of 6048 × 3794 pixels, corresponding to a resolution of 11 pixels per millimetre; comparative details from the vidicon and SIRIS images are shown in Figure 9a and 9b respectively. The mosaic image from the vidicon would be considered a very good image, perfectly suited for publication. However, the image from the SIRIS camera shows better sharpness and contrast and does not have the slight 'banding' often found in the darker areas of mosaic images made with the vidicon, which are due to differences in the response of the tube as the camera warms up during an acquisition and which cannot fully be corrected during image assembly and balancing; the SIRIS image does not suffer these problems as the sensor is temperature-stabilized. Another advantage of the new camera will be the speed with which images can be made. In this example, the vidicon images were made by an experienced user of the camera who was also familiar with the image assembly software; an hour was necessary to capture the images and a further hour required to assemble the 55 frames. In contrast, it took about half an hour to set up the SIRIS camera and around 20 minutes to capture and (automatically) assemble the sub-images. It is expected that with practice and use, the time for set-up might be reduced somewhat. These timings also compare favourably with point scanning infrared systems, which would take several hours to set up and scan an equivalent area.

As can be seen from Figure 4, the SIRIS camera has also been used to make images of paintings in situ at the National Gallery; this was not possible using the vidicon, as a mechanical system was required to move either the camera or the painting. The flexibility of the optics and the speed of set-up and acquisition allow the camera to be used to make a quick preliminary assessment to assess whether it is worthwhile to make a more systematic, higher-resolution survey of all or part of a larger painting. A good example is the large altarpiece of *The Virgin and Child with Saints Jerome and Francis* by Perugino (NG 1075) (Figure 10a). This is a large panel painting on which considerable underdrawing is visible through the paint under visible light. It was hoped, however, that an infrared study might help improve the understanding of the artist’s use of cartoons for all or part of the drawing. In particular it had been suggested that the two angels might derive from a single cartoon, inverted to give a symmetrical pair. If a cartoon had been used it was hoped that some signs of the transfer of the design, such as pouncing, might be seen in the infrared reflectogram. The SIRIS camera was used to make a low-resolution scan of the whole painting while it was still on display in the Gallery (Figure 11). The reflectogram image (Figure 10b) has a few problems, mainly with light distribution due to the fact that positioning of the lights was restricted by the proximity of other paintings in the Gallery, but it is good enough to show that a cartoon was indeed used for the underdrawing of the angels and that there is interesting underdrawing in the main figures. The painting was therefore taken off display so that a higher-resolution reflectogram could be made under studio conditions. The resulting image (Figure 10c) made by joining together a number of sub-images, is 8030 x 9610 pixels, which gives a resolution of about 4 pixels per millimetre. This image reveals the dots made by pouncing a pricked cartoon (see detail in Figure 10d) and analysis of the results has allowed it to be shown convincingly that the same cartoon was used for both angels, as well as providing evidence of cartoon use for the main figures.

Conclusions [head]

The SIRIS camera uses a well-established technology (the InGaAs sensor) in a novel application, scanning a small (320 × 256 pixel array) across the focal plane of a specially designed infrared lens. The resulting high-resolution images clearly reveal the underdrawing and give sharper, more homogeneous images than are produced by current infrared reflectographic devices, partly because the sensor does not ‘overload’ in areas where there is a strong dark–light interface. The camera has the dual advantages of speed, as a full c. 5000 × 5000 pixel image can be made in around 20 minutes, and portability, as the camera, control box, tripod and laptop computer can be moved relatively easily. Although the camera has thus far only been used within the Gallery or in the London area, it has been designed to ‘fold’ (Figure 6), so that in a suitable case it could be transported by air as hand luggage, while the control box is rugged enough to travel as cargo. The tripod adaptor allows the camera to be used wherever a suitable photographic tripod is available.

The speed of operation makes the camera ideally suited for preliminary investigations in situ, where it is often necessary to examine the entire surface of a large number of paintings to determine whether any underdrawing is present and highlight those areas worthy of in-depth investigation. The camera can then be used in a higher-resolution mode to make these more detailed studies, either in situ, or in the studio. The camera can also be used to make images that might otherwise be considered too speculative or time-consuming; examples include examining the back of a painting to look for an inscription, examining paintings that contain a high proportion of dark areas and potentially very little underdrawing, and examining paintings that might not be expected to contain underdrawing. Finally, the depth of focus provided by the new lens allows paintings with severe curvature to be examined and the results recorded, an almost impossible task with the old technology.

The assembly of infrared images into mosaics has often consumed the time of those interested in the conservation and art-historical implications of the underdrawing technique or design. The SIRIS camera makes the acquisition of high-quality images a simpler, faster process, freeing time for the more intriguing task of interpreting the underdrawing.

Suppliers [head]

Alpha NIR camera: LOT-Oriel UK, 1 Mole Business Park, Leatherhead, Surrey KT22 7BA, UK.

Unislide stages and Parker Automation Xli controllers: Time and Precision Industries Ltd, Stroudley Road, Daneshill, Basingstoke, Hampshire RG24 8UG, UK.

Lens: Optical Surfaces Limited, Godstone Road, Kenley, Surrey CR8 5AA, UK.

Camera and control box bodies: Oxford Precision Components, Unit 1, Holywell Business Centre, Oxford OX2 0ES, UK.

Bellows: Camera Bellows, Units 3–5, St Paul's Road, Balsall Heath, Birmingham B12 8NG, UK.

Tripods: Green Witch, Unit 6, Dry Drayton Industries, Dry Drayton, Cambridge CB3 8AT, UK.

The approximate cost of constructing this camera was €80000, the major components being the sensor and lens. The authors estimate that the construction of a second camera might cost c. €50000, as the fees for design and tool-making would not recur and several prototype stages would not be required.

Acknowledgements [head]

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References [head]

1. Rawlins, F.I.G., ‘Beneath the surface of old pictures’, *Journal of the Royal Society of Arts* **41** (1943) 150–154.
2. van Asperen de Boer, J.R.J., ‘Reflectography of paintings using an infra-red vidicon television system’, *Studies in Conservation* **14** (1969) 96–118.
3. Wecksung, G., Evans, R., Walker, J., Ainsworth, M., Brealey, J., and Carriveau, G., ‘Assembly of infra-red reflectograms by digital processing using a portable data collecting system’, in *ICOM Committee for Conservation, 8th Triennial Meeting, Sydney 6 – 11 September,* Getty Conservation Institute, Los Angeles (1987) 107–109.
4. Burmester, A., and Bayerer, F., ‘Towards improved infrared-reflectograms’, *Studies in Conservation* **38** (1993) 145–154.
5. Walmsley, E., Fletcher, C., and Delaney, J., ‘Evaluation of system performance of near infrared imaging devices’, *Studies in Conservation* **37** (1992) 120–131.
6. Saunders, D., and Cupitt, J., ‘Image processing at the National Gallery: The VASARI project’, *National Gallery Technical Bulletin* **14** (1993) 72–85.
7. Billinge, R., Cupitt, J., Dessipris, N., and Saunders, D., ‘A note on an improved procedure for the rapid assembly of infrared reflectogram mosaics’, *Studies in Conservation* **38** (1993) 92–98.
8. Saunders, D., Burmester, A., Cupitt, J., and Raffelt, L.**,** ‘Recent applications of digital imaging in painting conservation: Transportation, colour change and infrared reflectographic studies’, in *Tradition and Innovation: Advances in Conservation*, ed. A. Roy and P. Smith, IIC, London (2000) 170–176.
9. Bertani, D., Cetica, M., Poggi, P., Puccioni, G., Buzzegoli, E., Kunzelman, D., and Cecchi, S., ‘A scanning device for infrared reflectography’, *Studies in Conservation* **35** (1990) 113–116.
10. Bertani, D., ‘La riflettografia infrarossa’, in *Oltre il visiblile: indagini riflettografiche*, Università degli studi di Milano, Milan (2001) 3–18.

11. Pezzati, L., Materazzi, M., and Poggi, P., ‘IR-colour scanning reflectography’, in *The Painting Technique of Pieretro Vannucci, called il Perugino*, ed. B. Brunetti, C. Seccaroni and A. Sgamellotti, Nardini Editore, Florence (2004) 65–70.
12. Lenz, R., Beutelhauser, R., and Lenz, U., ‘A microscan/macroscan 3 × 12 bit digital color CCD camera with programmable resolution up to 20,992 × 20,480 picture elements’, *Proceedings of the Commission V Symposium: Close Range Techniques and Machine Vision, Melbourne, Australia, International Archives of Photogrammetry and Remote Sensing* **30**(5) (1994) 225–230.
13. Saunders, D., Cupitt, J., White, C., and Holt, S., ‘The MARC II camera and the scanning initiative at the National Gallery’, *National Gallery Technical Bulletin* **23** (2002) 76–82.
14. Delaney, J., Metzger, C., Walmsley, E., and Fletcher, C., ‘Examination of the visibility of underdrawing lines as a function of wavelength’, in *ICOM Committee for Conservation, 10th Triennial Meeting*, *Washington DC, 22 – 27 August 1993,* ICOM Committee for Conservation, Paris (1993) 15–19.
15. Dereniak, E.L., and Boreman, G.D., *Infrared Detectors and Systems*, Wiley-Interscience, New York (1996) 239–329.
16. Rogalski, A., *Infrared Detectors*, Gordon and Breach Science Publishers, Amsterdam (2000).
17. Walmsley, E., Metzger, C., Fletcher, C., and Delaney, J., ‘Evaluation of platinum silicide cameras for use in infrared reflectography’, in *ICOM Committee for Conservation, 10th Triennial Meeting*, *Washington DC, 22 – 27 August 1993,* ICOM Committee for Conservation, Paris (1993) 57–62.
18. Coddington, J., and Siano, S., ‘Infrared imaging of twentieth-century works of art’, in *Tradition and Innovation: Advances in Conservation, Contributions to the IIC Melbourne Congress, 10–14 October 2000*, ed. A. Roy and P. Smith, International Institute for Conservation, London (2000) 39–44.
19. Manissadjian, A., Tribolet, P., Chorier, P., and Fillon, P., ‘Short-wave infrared detector trade-offs and applications’, *Proceedings of the SPIE: Infrared Technology and Applications XXVIII* **4820** (2003) 446–452.
20. www.indigosystems.com/products/core_alphaNIR.html (accessed 5 December 2005).

21. Cupitt, J., Martinez, K., and Saunders, D., ‘A methodology for art reproduction in colour: The MARC project’, *Computers and the History of Art* **6**(2) (1996) 1–20.

Figure 1. Typical spectral response characteristics for three of the sensors considered; D* is the detectivity in $\mathrm{cm \cdot Hz^{0.5} \cdot W^{-1}}$.

Figure 2. The scanning stages attached to the camera back plate. The InGaAs sensor is mounted on the upper stage and connected to the camera electronics (seen at the top left) by a 44-way ribbon cable.

Figure 3. The SIRIS camera from the side. The lens is mounted on an adjustable stage to the right, which is in turn attached to the rigid base on to which the camera unit is also fixed. The rigid (left) and flexible (right) bellows units allow the lens to move freely and collapse for transportation.

Figure 4. The SIRIS camera in use in the Gallery to make images of *Pietà* attributed to the workshop of Rogier van der Weyden (NG 6265). Note the laptop computer and control box on the accompanying trolley.

Figure 5. The adjustable stage for the lens; the metal rod to the left allows the magnification factor to be adjusted rapidly, while the micrometer is used for fine focus.

Figure 6. The camera folded for transportation. The lens and flexible bellows have been removed and the blanking plate attached to the rigid bellows, while a bracket supports the front of the stage at a right angle to the rear.

Figure 7. Images of the underdrawing test chart: (a) made with a vidicon camera; (b) made with the SIRIS camera; (c) image of one patch from the underdrawing test chart (lead-tin yellow paint over a black ink underdrawing) made with the vidicon camera; (d) equivalent image of a single patch from the SIRIS camera.

Figure 8. Visible image of *The Adoration of the Name of Jesus* by El Greco (NG 6260).

Figure 9. Image of *The Adoration of the Name of Jesus* by El Greco (NG 6260): (a) detail of the lower centre from the infrared reflectogram mosaic image made with the vidicon camera; (b) equivalent detail from the image made with the SIRIS camera.

Figure 10. Images of *The Virgin and Child with Saints Jerome and Francis* by Perugino (NG 1075): (a) visible image; (b) low-resolution infrared reflectogram made with the SIRIS camera in situ in the Gallery; (c) high-resolution infrared reflectogram made with the SIRIS camera under studio conditions; (d) detail of Figure 8c to show the underdrawing and pouncing dots in the angel on the right.

Figure 11. The SIRIS camera in use in the Gallery to make images of *The Virgin and Child with Saints Jerome and Francis* by Perugino (NG 1075).

Table 1. The operating conditions used to obtain images at low, medium and high resolutions and the error at the edge of the field of view for each of these configurations

Field of view at object plane (mm)	Resolution (pixels per mm)	Object-to-lens distance (mm)	Error at edge of field (%)
2000 × 2000	2.3	3677.9	0.022
1000 × 1000	4.6	1927.2	0.002
500 × 500	9.2	1052.3	0.053

DAVID SAUNDERS recently joined the British Museum after 20 years in the Scientific Department at the National Gallery in London, UK, where his areas of research included the effect of the environment on paintings and on artists' materials, preventive conservation, and the application of imaging techniques to the examination of paintings. He has been one of the editors of *Studies in Conservation* since 1990 and served on the technical committees for the 1994 and 2000 congresses. Since January 2003 he has been Director of Publications for the IIC and a member of the IIC Council. Address: The British Museum, Great Russell Street, London WC1B 3DG, UK. Email: DSaunders@thebritishmuseum.ac.uk

RACHEL BILLINGE graduated from Oxford University, UK, with a degree in engineering science in 1984. In 1990 she obtained an MA in the conservation of easel paintings at Newcastle-upon-Tyne Polytechnic, UK. She joined the Conservation Department of the National Gallery in 1991 as Leverhulme Research Fellow in infrared reflectography and worked closely with Dr Lorne Campbell on the technical examination of the paintings studied for his catalogue of paintings by artists of *The Fifteenth-Century Netherlandish Schools*. She is now employed at the National Gallery as a research associate, specializing in infrared reflectography and studying paintings from the thirteenth to late nineteenth centuries. Address: The National Gallery, Trafalgar Square, London WC2N 5DN, UK. Email: rachel.billinge@ng-london.org.uk

JOHN CUPITT gained a PhD in theoretical computer science at the University of Kent, UK, then worked for 15 years in the Scientific Department of the National Gallery, London, on camera calibration, image processing systems, user-interface design, the measurement of colour change in paintings, and infrared imaging of paintings. He has since moved to Imperial College, Hammersmith Campus, where he is a research fellow in bioinformatics on the modelling of lung disease processes. Address: Faculty of Medicine, Imperial College London, Hammersmith Campus, Du Cane Road, London W12 0NN, UK. Email: jcupitt@imperial.ac.uk

NICK ATKINSON graduated from Sheffield University, UK, with a master's degree in electronic, control and systems engineering in 2004. He worked on the development of the SIRIS camera as a summer placement in the Scientific Department of the National Gallery in 2003 and 2004, funded by a grant from Hewlett Packard. Currently, he is a process engineer for 3M Healthcare Ltd. Address: 3M Healthcare Ltd, Up Brooks, Clitheroe, Lancashire BB7 1NX, UK. Email: njwatkinson@gmail.com

HAIDA LIANG is a senior lecturer in physics at Nottingham Trent University, UK. She obtained a BSc (Hons) in physics from the University of Sydney, Australia, and a PhD in astronomy and astrophysics from the Australian National University. Prior to her current post, she worked at the Scientific Department of the National Gallery, London, on the development of non-invasive techniques for the examination of paintings, the Physics Department of the University of Bristol, UK, and the Service d'Astrophysique of the Commissariat à l'Energie Atomique, Saclay, France, on various astrophysics projects. Her main research interests in conservation science are the development and application of non-invasive imaging techniques and the study of optical properties of materials as they age. She has experience working on various international and national collaborative projects involving academia, museums and industry. Address: School of Biomedical

and Natural Sciences, Nottingham Trent University, Clifton Lane, Nottingham NG11 8NS, UK.
Email: haida.liang@ntu.ac.uk