Advanced imaging systems for diagnostic investigations applied to Cultural Heritage

E Peccenini¹,²,³, F Albertin⁴, M Bettuzzi¹,²,³, R Brancaccio¹,²,³, F Casali¹,², M P Morigi¹,²,³, F Petrucci⁵,⁶,⁷
¹Centro Fermi, Roma
²Dipartimento di Fisica e Astronomia, Università di Bologna, Italy
³INFN sezione di Bologna, Italy
⁴Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
⁵Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Italy
⁶INFN sezione di Ferrara, Italy
⁷Laboratorio TekneHub, Tecnopolo di Ferrara, Italy

E-mail: eva.peccenini@unibo.it

Abstract. The diagnostic investigations are an important resource in the studies on Cultural Heritage to enhance the knowledge on execution techniques, materials and conservation status of a work of art. In this field, due to the great historical and artistic value of the objects, preservation is the main concern; for this reason, new technological equipment has been designed and developed in the Physics Departments of the Universities of Ferrara and Bologna to enhance the non-invasive approach to the study of pictorial artworks and other objects of cultural interest. Infrared (IR) reflectography, X-ray radiography and computed tomography (CT), applied to works of art, are joined by the same goal: to get hidden information on execution techniques and inner structure pursuing the non-invasiveness of the methods, although using different setup and physical principles. In this work transportable imaging systems to investigate large objects in museums and galleries are presented. In particular, 2D scanning devices for IR reflectography and X-ray radiography, CT systems and some applications to the Cultural Heritage are described.

1. Introduction

Works of art and archaeological objects constitute the main part of the tangible Cultural Heritage, they have the common features of uniqueness and irreplaceability; for these reasons, they are often kept in museums or galleries for preservation purposes and they can hardly be moved.

These objects of cultural interest are also extremely different from each other, characterized by different materials and sizes, therefore, industrial and medical diagnostics apparatus cannot be used for applications in this field. Developing custom imaging devices becomes essential to meet specific needs as: non-invasiveness, transportability and versatility.

The devices presented in this paper have been designed and realized by two research groups: the X-ray Imaging group at the Department of Physics and Astronomy of Bologna University and the Archaeometry group at the Department of Physics and Earth Science of Ferrara University. These two groups have been involved for several years in the development of non-invasive experimental apparatus using X-rays and other types of radiation for applications on cultural heritage.
2. Scanning device for wide band infrared reflectography

IR reflectography is a non-invasive image diagnostic technique widely used to reveal underdrawing in paintings. It benefits from the property of near-IR radiation (700-2500 µm in wavelength) to be less scattered by pictorial layers than shorter wavelengths. Consequently it may often reach the deepest layers, hidden by superimposed colours and bring back the information stored there. The reflectographic capability depends on the optical properties of the pictorial layer and on the characteristics of the detector [1] [2].

The main devices used to this aim have been: Vidicon Tube, Si CCD cameras and scanning systems. Vidicon tube, with a spectral response up to 2.2 µm was for over 20 years, the only choice for IR Reflectography. The spectral response of Vidicon tube allowed a good detection of underdrawing, but it had low imaging performance and high cost. During the 90’s, the Vidicon tube was replaced by the Silicon CCD infrared camera more handy and cheaper, but with spectral response limited at 1.1 µm. The need of high-quality optical images and wider spectral response led, in the 90’s, to the development of IR scanning systems [3]. The device presented here has a spectral response extended up to 2.5 µm to improve reflectography capability to read the underdrawing in paintings [4].

2.1. Scanning device and optical apparatus

The scanning device, developed at the Department of Physics and Earth Science in Ferrara University, is composed of two motorized linear guides, supported by a structure of aluminum profiles. The image sampling is acquired during the horizontal movement, 90 cm wide, performed at 0.2 m/sec mean speed. Signals from the photodiode are acquired with a horizontal pitch of 5 µm, at 12 bit/pixel.

The optical system is a binocular microscope head mounted on a Y-axis, provided by a revolver with selectable magnification steps. The choice of the microscope is justified to enlarge the area focused on the detector to cover the active area of photodiode, to warrant a working distance of about 10 cm, suitable to avoid damage to the painting, and to allow a depth of field of about 0.5 cm, compatible with the roughness of pictorial surfaces.

The lighting system includes two halogen lamps, placed at 45°, equipped with a quartz lens (f = 850 mm), to concentrate the light to the target area, and a silicon filter to cut wavelengths shorter than 1100 nm, to avoid heating of the painting by non-IR radiation.

A Two-color© detector by Hamamatsu with thermoelectric cooling is used. It contain a Si photodiode (spectral range from 0.27 to 1.1 µm), mounted over an InGaAs PIN photodiode (spectral range from 0.94 to 2.57 µm), along the same optical axis. Due to transparency of Silicon at wavelength over 1.1 µm, this detector delivers the possibility of acquiring two images simultaneously in different spectral bands.

However, for applications of wide band reflectography the InGaAs detector is used. With 4x magnification the InGaAs photodiode has a resolution of 2 lp/mm [4].

![Figure 1](image.png)
2.2. Examinations of paintings

The application shows the comparison between Si and InGaAs detector to highlight the better readability of the underdrawings using a spectral band extended to longer wavelength. The painting, showed in Figure 1 (a), has thin and uniform layer of not treated paper. The artist reproduces the flowers in a very realistic way, like in a herbarium, typical features of academic approach characterized by a fine technique. The infrared reflectography with Si detector discloses the underdrawing along the edge of the white petals, where the paint layer is thinner, and under the light green of the leaves, (Figure 1 b). Instead, the dark green appears more absorbent. In the image acquired by InGaAs detector, the underdrawing is visible under both green pigments. Moreover, the drawing under the white pigment, hardly recognizable by Silicon detector, appears here well clear (Figure 1 c) [4].

3. X-ray digital radiography: comparison of two devices

X-ray radiography provides a wealth of information not obtainable with other imaging techniques, for its capability to cross all layers of a painting. X-ray imaging has evolved over time. In digital radiography, semiconductor detectors have replaced the traditional photographic film. In Cultural Heritage field this transition has been slowest for two basic reasons: the need of handy and lightweight devices for application on site and the high cost of digital detectors. Therefore, an intermediate solution of photostimulable phosphor plates are still widely used. The radiographic data are captured and stored in the phosphor plates, and then, they are converted in a digital image using a scanner by laser stimulation. This system warrant a good dynamic range, but, unlike digital detectors, does not provide an immediate availability of the radiographic image.

The digital detectors such as CCD, CMOS or flat panel allow a real-time image capture but need motorized devices to warrant the movement during the acquisition.

![Figure 2](image-url) (a) Landscape, oil on wood, 20th century, private collection. (b) Digital X-ray radiography, (c) detail of radiography [5].

The radiography of the landscape in Figure 2 has been acquired at 30 kV using a CMOS detector mounted on a scanning device. The radiographic image reveals the presence of a woman portrait hidden under the pictorial layers. Due to dynamic range of 12-bit digitalization, the visualization of all details of the painting is performed by adjusting contrast and brightness settings.

In Figure 2 c elements with high absorption as nails inside the support are visible, but in the same image, details of low absorption, like as the outer edge, probably made of leather or cardboard, and the canvas applied on the support are also visible [5].

Two scanning devices for digital radiography with different setup are presented: a transportable X-ray scanning device for on-site applications and an X-ray scanning device for large paintings.
The main difference between the two systems is the distance between the source and the detector: In the transportable system the source is independent by the detector movement, conversely, in the system for large paintings the X-ray tube is at a fixed distance of about 60 cm and moves with the detector during the scan, this allows to use a low current and shorter exposure time, but a smaller focal spot of the X-ray source is required (table 1).

The sources used have different kVp, but typically 45 kV are enough for the thicker paintings on wood, such as the altarpieces, however, in these cases the transportable system are preferable to perform in situ analysis. On the contrary, the system for large paintings is suitable for applications on paintings on large canvas for the ability to perform acquisition on larger areas (up to 2 m²) and for the possibility to use a lower voltage (up to 20 kV).

The choice of the detectors was based on the pixel size, in order to be able to distinguish craquelure of at least 100 µm. Both detectors are indirect conversion and contain a two-dimensional CMOS photodiode array. They have similar resolution, but the Hamamatsu detector mounted on the transportable device has a larger field of view, 12 x 12 cm² instead of 10 x 10 cm² of Rad eye detector (table 1).

In both devices the tile scanning technique is performed. The radiographic images are acquired according to a grid that warrants an overlap of few centimetres between the images. In the processing phase, several commercial or open source software are used to merge the single images, such as PTGui, PanaVue ImageAssembler, ImageJ or Adobe Photoshop.

### Table 1. Main characteristics of sources and detectors used in the devices

| Devices                        | X-ray tubes | Detectors                      |
|--------------------------------|-------------|--------------------------------|
| Transportable X-ray scanner    | Gilardoni MHF 200D, tungsten anode, high voltage range 30–200 kV, current range 1–8 mA, max power 900 W, beryllium window, focal spot 1.5 x 1.5 mm. | Hamamatsu C10900D, CsI scintillator, Pixel size 100x100 µm, active area 12x12 cm² (1216x1232 pixels), 16-bit digital output. |
| X-ray scanner for large paintings | Varian M147, molybdenum anode, high voltage range 20–50 kV, max current 15 mA, beryllium window, nominal focal spot 0.1 – 0.3 mm. | Rad eye 200, GOS scintillator, Pixel size 96x96 µm, active area 10x10 cm² (1024x1000) pixels, 16-bit digital output. |

#### 3.1. Transportable X-ray scanning device for on-site applications

In the Department of Physics and Astronomy at University of Bologna a scanning device easy to disassemble and transport has been developed specifically for in situ applications. The system is composed of a pair of orthogonal lightweight and decomposable axes, each consisting of a single aluminium profile. The axes allow the translation of the detector, with a stroke of 1.5 m. The X-ray tube is separated from the structure and is placed opposite to painting at a proper distance in order to irradiate the whole scanned area (figure 3). In this system, the high-energy source has been chosen for a further upgrade for tomographic applications. The maximum size of detectable area is 1.5 x 1.5 m² with resolution of 100 µm.

#### 3.2. X-ray scanning device for large paintings.

The scanner allows the investigation of paintings of size up to 2 x 2 m² with a spatial resolution of 96 µm, it has been designed and realized at the Larix Lab of Department of Physics and Earth Science in Ferrara University. The system can be disassembled and moved to perform in situ X-ray scan.

The X-ray tube and the detector are mounted specularly on a double aluminium motorized arm. This setup provides the best detector-source stability. The painting is locked in a central frame, while the X-ray...
ray tube and the detector are moved (Figure 4). Movement, emission and acquisition are synchronized [6].

**Figure 3.** Transportable X-ray scanning device.

**Figure 4.** X-ray scanning device for large paintings.

### 4. Computed tomography systems

Tomographic systems, routinely used in medical or industrial field, consist in stationary devices intended to investigate objects, or patients, very similar to each other in size, structure and composition.

This technique requires, for applications on cultural heritage, the development of tomographic systems versatile and transportable, able to carry out *in situ* investigations, where the works of art or archaeological finds are preserved.

To make a CT system, three items are required: an X-ray source, a detector and a rotating table.

The data acquisition phase requires the rotation of the object around a fixed axis. The object is mounted on a support locked on the rotating table, which moves with high precision by means of a control software. At every rotation step, a radiographic image is acquired. In this process an X-ray projection of the object is projected on the detector and the geometry of the system source-object-detector defines its size. The processing of the set of data with a reconstruction procedure and specific algorithms allows the reconstruction of the external and internal structure of the object [7]. Below is a description of two X-ray CT systems developed at the Department of Physics and Astronomy of Bologna University and at the Te.Co.Re Lab.

#### 4.1. Transportable X-ray CT system for small-medium size object

In the X-ray Imaging Lab at the Department of Physics and Astronomy of Bologna University a CT system has been realized for applications on small-medium objects. This system uses an X-ray tube with a maximum voltage of 120 kV and an indirect conversion flat-panel detector (with structured cesium iodide scintillator) of 25 x 20 cm$^2$, mounted on two orthogonal translation axes which extend the area up to 50x50 cm$^2$. This detector allows to perform CT with a good resolution of 127 µm, it is particular useful for applications on bones remains. The lightweight of components give the system easily transportable for application on-site.

#### 4.2. X-Ray CT system for large objects

A CT equipment for application on large objects is set up at Te.Co.Re. Lab located in Ravenna. It is equipped with an X-ray tube with energy up to 200 keV. The detector consists of a box containing a CCD camera (2184x1472 pixels) with interchangeable lens, a mirror, and a structured cesium iodide scintillator screen (45x45 cm$^2$ size and 1mm thick). Part of the X-rays emitted by the source passes through the object and reaches the scintillator screen, which converts radiation to visible light. The mirror, placed in the box at 45°, reflects the light from the screen to the CCD camera for acquisition of the radiographic projections.
Figure 5. F. Deflorian, 2012, wooden statue, 90 x 30 cm, private collection. 3D reconstruction of tomographic data. (a) Whole and axial section, (b) sagittal section of the bust, (c) head and its unconventional rendering.

The detection system has a maximum resolution of 132 um, but it is characterized by presence of outlier artifact due to the scattered radiation that reach the ccd camera, therefore, generally the CT are carried with a resolution of 264, applying a binning 2x2 in the acquisition phase, to reduce the noise and the acquisition time.

The active area of the detector is 45x45 cm² which can be extended up to almost 3.5 x 1.0 m² using a mechanical axis with horizontal stroke of 3 meters and a vertical lift of 70 cm [7].

The wide field of view allows the use of the system for CT on objects of 1 - 2 m in size. On the contrary of the other, this system is used only in the laboratory.

Figure 5 show an application to a wooden statue of contemporary art. It is the 3D reconstruction obtained from tomography data set. Scrolling the slices of the volume is possible to inspect the inner part of the object. In the axial and sagittal sections (Figure 5 a, b) the different blocks of wood that compose the statue have been identified. Through a rendering tool, the single blocks have been split to highlight the structure of the artwork (Figure 5 c).

5. Conclusions

The growing interest of museums, superintendencies and restoration centers in image diagnostic has brought several groups to focus their research on new systems for application on Cultural Heritage. The collaboration among institutions and research centers, such as Universities, INFN and TekneHub has allowed the realization of the systems presented in this paper.

All the systems described are an evolution of traditional systems. The scanning system for IR reflectography has been developed to fulfill the need to increase the spectral range and eliminate the aberrations of the images. The X-ray systems, already widely used in medical and industrial applications, have been adapted to the cultural heritage applications. They have to be brought where the works of art are kept, with setup dedicated to objects of different size and appropriate energy range to investigate different materials.

The next goal of the X-ray Imaging Group of the University of Bologna, with the collaboration of INFN and the Fermi Centre of Rome, will be the construction of a higher energy CT system using a 320 kV X-ray tube to extend applications to objects denser or thicker, than those currently accessible.
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