Appl. Phys. A (2016) 122:1043
DOI 10.1007/s00339-016-0579-5

Applied Physics A
Materials Science & Processing

A new scanner for in situ digital radiography of paintings

Anna Impallaria[1,2] · Federico Evangelisti[1] · Ferruccio Petrucci[1,2] · Flavia Tisato[1,2] · Lisa Castelli[3] · Francesco Taccetti[3]

Received: 14 July 2016 / Accepted: 17 November 2016 / Published online: 23 November 2016

Abstract X-ray radiography is one of the most widely used imaging techniques in the field of cultural heritage, both for conservation and for investigation purposes. Performing radiographies in museums, thus avoiding movements of works of art, has been recently made easy by digital acquisition of images, but when the whole scan of a large painting is required, technical solutions for a portable device are still not at hand. The inherent weight of the X-ray tube and of the high-voltage generator makes the design of a portable device very difficult. In this project, the solution of the puzzle was separating devices devoted to different tasks, in order to maintain each item under 60 kg weight, thus being transportable with reasonable effort.

1 Introduction

X-ray radiography is one of the most widely used and powerful imaging techniques for conservation and restoration purposes [1]. At the Dept. of Physics and Earth Science of the University of Ferrara, the Archaeometry Laboratory is specialized in the design and realization of scanner prototypes for imaging of cultural heritage: not only for radiographies, but also for IR reflectography [2].

✉ Anna Impallaria
impallaria@fe.infn.it

1 Department of Physics and Earth Science and INFN-Sezione di Ferrara, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy

2 TekneHub Ferrara, Via Saragat 13, 44122 Ferrara, Italy

3 INFN-Sezione di Firenze, Via G. Sansone 1, 50019 Sesto Fiorentino, Italy

The instrument here described is one of the scanners suited to perform digital radiography. Scanning systems exploit all the potentialities of digital radiography: first the immediate control of the radiographic image; second the huge range of grey levels obtained (4096 for 12-bit digitization, to be compared with the ca. 100 of old X-ray plates), which involves the registration of a bigger number of information than radiographies on films and on fluorescent screens; and finally, the digital elaboration of images allows to obtain no segmentation and more uniformity in the resulting radiography of whole paintings. These advantages, in the last few years, have become clear also to curators and restorers in museums.

Nowadays, the main task is to perform digital radiography directly in situ, avoiding to move the artworks to dedicated places. But when the whole scan of a large painting is required, technical solutions for a portable device are not yet at hand. The best radiographic instrument should be easy transported and should not give any limitation in the dimensions of the work of art under analysis. Some efforts have been done following these two *criteria*. One of them is the radiographic scanning system developed at the Dept. of Physics and Earth Science and National Institute of Nuclear Physics (INFN) of Ferrara [3, 4], which was designed to perform radiographies of large paintings, until 1.5×2.5 m. The system moves at the same time the X-ray tube (a Varian M-147 source with anode of molybdenum) and the detector (a silicon CCD flat panel sensor of 176×220.8 mm and pixel dimension of 50 µm by Hamamatsu). Such motion is possible by using one motor for the X translation and one for the Y, since the two devices are mechanically bound. In this way, the two devices move together and their relative position is exactly the same. Although the RX scanner was designed to be transportable, it is too big ($2.56 \times 2.26 \times 1$ m) and too heavy for a real easy transfer. Moreover, despite the possibility to perform radiographies on large paintings, the physical limitation on its dimensions can be an obstacle in the field of cultural heritage, due to their variability in size.

The Italian neu_ART project [5], the "neutron and x-ray tomography and imaging for cultural heritage" project of the Piedmont region (Italy), in collaboration with the University of Torino, INFN and the restoration centre CCR "La Venaria Reale", provided a solution. The system is located at the restoration laboratories of "La Venaria Reale", and it allows to perform radiographies on paintings up to 3×4 m by scanning their surface with an X-ray linear detector (an Hamamatsu C10650, which is a linear TDI CCD detector 22 cm long, with a pixel size of 48 μm). The motors only move the detector on a grid attached to the wall, while the X-ray tube (a General Electric Eresco 42MF4 with tungsten anode) is fixed and irradiates the whole painting during the scan. The main problem of this RX scanner is that it is not transportable, so the painting must be moved to the laboratories.

Starting from these two experiences, the Archaeometry Laboratory of the University of Ferrara, with the support of INFN, has developed a new scanning system for in situ radiography. The main aim was to mechanically separate the X-ray source and the detector, by means of two smaller and lighter devices. Such an expedient allows easily transporting the system to the place where the artwork is preserved. Another goal was to have no limitations in the dimensions of the work of art, allowing the analysis of both small and big paintings.

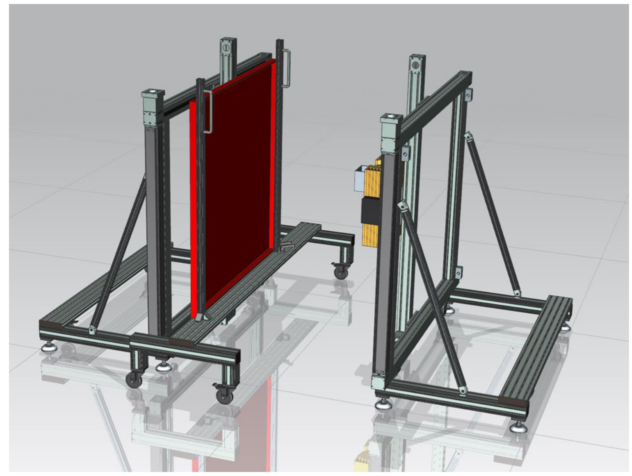

Fig. 1 Project of the scanner for digital radiography. The detector is hidden by the painting and is aligned with the X-ray tube, mounted on the frame to the *right*

Table 1 Servo motors specifications

AC servo motors	G5 Omron electronics
Model	R88D-KN04H-ECT
Voltage	280V AC
Servo motor capacity	400W
Rated rotation speed	3000 r/min
Brake	Y
Software	NS-Runtime© rel.1.2. by Omron

2 The equipment

In Fig. 1, the project of the RX scanner is shown. Two independent modules in aluminium are devoted to move the X-ray tube and the digital detector. A third frame supports the painting in front of the sensor. The X-ray tube is a Varian M-143T with tungsten anode, maximum anode voltage 49 kV, and maximum current 500 mAs, air cooled. The detector is a Teledyne DALSA (Canada) RadEye200, a two-dimensional CMOS photodiode array combined with a Gd_2O_2S scintillator screen. It is composed of 1024×1000 pixel, of 96 μm side length. The depth of digitization is 12 bit/pixel, and PC is connected via Ethernet. Shadocam© is the dedicated acquisition software. The two stages have dimensions of $1.40 \times 1.53 \times 0.74$ m and weight of ca. 55 kg. Each axis is equipped with a linear rail (KLE60 by ITEM Industrietechnik GmbH, Germany), 1 m long, with integrated roller guide, free of play. Its accuracy of repeatability is given at 0.1 mm. The detector and the X-ray tube move simultaneously on X- and Y-axis, thanks to a couple of AC servo motors (G5 by Omron Electronics Ltd, UK. More details are given in Table 1).

In Fig. 2, the connections between all devices are depicted. Two motors per unit are connected to the scan control system via Ethernet, through the servo drivers, directly located on the modules. The acquisition device is composed of the detector and its interface, and communicates with the DAQ workstation. The latter also controls the X-ray shots, according to the parameters set on the X-ray console. Close to the workstation, an oscilloscope monitors the emission of the radiation. All the controls and the oscilloscope are collocated at the security distance from the X-ray tube for the protection of users from radiation damage, and near them there is a stop button for X-rays. Furthermore, when it is possible, the controls and the units are located in two different rooms in order to isolate the radiation source.

The scanned area is 1 m^2. The motion speed can be chosen from 5 up to 50 mm/s. Both units may be moved or installed on a scaffold in order to scan wider paintings. The scan is performed by horizontal lines. It is possible to start each line from the same side, or change it at each line, in the coil mode. The acquisition of the radiographic images is made when both RX tube and detector are stationary. The distance between the two units is usually set at 1 m, while 0.66 m separates the tube focus and the sensor. The

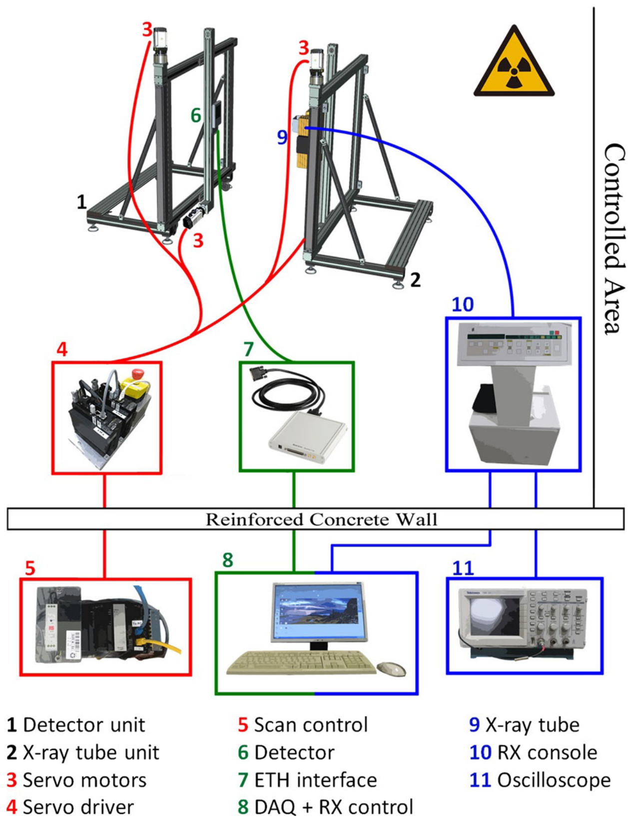

Fig. 2 Devices connection diagram: motion system (*red*), acquisition devices (*green*) and X-ray source components (*blue*)

Fig. 3 Anonymous, portrait of Giacomo Masino, sixteenth century, oil on canvas, 62 × 80 cm, private collection

work of art is located as close as possible to the detector, to minimize magnification and penumbra effects.

Levelling of the units is performed by setting the levelling feet. A first alignment is obtained by using mechanical plugs that fasten the units each other. Finally, the plugs are removed and the beam is collimated with a small pinhole, for a more accurate alignment. Once aligned the units, the scan is automatically performed by remote control of motion. X-ray tube and detector simultaneously move and stop at the planned position for image acquisition. X-ray shot and digital acquisition follow; then, the subsequent position is reached. After the alignment procedure, a shift of 15 pixels has been revealed in the images taken at the furthest positions of the scanner. The scan is tailored to fit each painting, and digital images are automatically stitched at the end of the scan, after their correction.

3 Digital processing

All the acquired images are corrected for the noise due to dark currents in the sensor and for non-uniformity due to beam and to detector. An image (I) of the X-ray irradiated sample is corrected as follows. An image (D) is acquired with no X-ray beam, so collecting only dark currents in the detector pixels. An image (W) is acquired with the same X-ray settings of I but with no sample, thus taking care of the tube emission lack of uniformity. The corrected image (C) is obtained by the following algorithm:

$$C = \frac{I - D}{W - D}$$

A 1×1 m^2 painting requires 196 shots and about 3-h scan. The stitching is a matter of few minutes and is obtained by means of the software PTGui10 by New House Internet Services BV, the Netherlands.

The slight misalignment of 15 pixels of the detector and tube units has no effect on the stitching, which is based of details on the images themselves, but may result in inaccurate correction. However, the unevenness of the tube emission is smooth: we measured 1.7% in grey-level scale, the residual lack of uniformity due to that misalignment.

The resolution of the system of 4.5 lp/mm has been measured by means of a resolution target.

4 Data examples and discussion

The scan system has been tested on a painting of the sixteenth century representing Giacomo Masino (Fig. 3). According to the dimensions of the painting (62 × 80 cm),

Fig. 4 Radiography of the portrait of Giacomo Masino

99 radiographic images had to be acquired to obtain the final image, at 24 kVp, 19 mAs and filtering with 0.5 mm of Al. Such a process took 1.5 h.

Thanks to a 20% overlap among images, the stitching result was good and allowed to obtain no artefact in the final image (Fig. 4). The radiography reveals an underneath painting of a clergy member, enhancing decorative details of the dress in the middle of the canvas and the hands.

On a white canvas, a radiographic test was also performed. The aim was to verify whether a good final image could be obtained even without a drawing to be followed as a reference in the stitching phase. In addition, it was relevant to identify other potential effects due to the misalignment, not yet enhanced in the previous case. In such a situation, only the wires of the weave could properly serve as a guide in the image reconstruction. The stitching operation was successful, suggesting that the presence of a drawing is not necessary to get a good result, even in the presence of a slight misalignment. Nevertheless, an excellent overlap among the acquisitions is requested.

Overall, the new scanner device proved to get good results. The difficulties in the alignment, necessary before every new in situ acquisition, are due to the mechanical separation of the X-ray tube and the detector.

5 Conclusion

The scanner for in situ radiographies of painting can be suitable for works of art of any size. The device proved to give very good results, carrying out digital radiographies also in museums and restoration laboratories.

Nowadays, tests are ongoing, in order to create a software able to manage the automatic scan of paintings. It should control the movement, the X-ray emission and the digital acquisition of the images. In this way, the times for acquisition would significantly decrease.

Acknowledgements The authors gratefully acknowledge the contribution of Luca Landi and Stefano Squerzanti, of the Mechanics Service of the Dept. of Physics and Earth Sciences and INFN-Ferrara, for the invaluable help in the construction of the device. This project has been supported by INFN National Network on Cultural Heritage (CHNet) and by the 5th Scientific Commission of INFN.

References

1. A. Gilardoni, R. Ascani Orsini, S. Taccani, X-rays in art. Gilardoni S.p.a., Lecco (1977)
2. F. Albertin, E. Peccenini, F. Petrucci, La diagnostica per immagini dell'icona di Noale. Progetto Restauro **65**, 20–26 (2013)
3. F. Albertin, M. Gambaccini, F. Petrucci, M. Gargano, N. Ludwig, M. Milazzo, F. Pedrielli, S. Chiozzi, F. Evangelisti, Nuove applicazioni della radiografia digitale alla diagnostica dei dipinti. Proc.of Elettroottica 2008, B.3-38. AEIT, Milan (2008)
4. F. Albertin, L. Boselli, S. Chiozzi, E. Peccenini, V. Pellicori, F. Petrucci, G. Poldi, F. Tisato, La radiografia e le diagnostiche fisiche del dipinto Madonna con Bambino tra san Rocco e san Sebastiano di Giovanni da Mel. Progetto Restauro **65**, 40–48 (2013)
5. A. Re, F. Albertin, C. Bortolin, R. Brancaccio, P. Buscaglia, J. Corsi, G. Cotto, G. Dughera, E. Durisi, W. Ferrarese, M. Gambaccini, A. Giovagnoli, N. Grassi, A. Lo Giudice, P. Mereu, G. Mila, M. Nervo, N. Pastrone, F. Petrucci, F. Prino, L. Ramello, M. Ravera, C. Ricci, A. Romero, R. Sacchi, A. Staiano, L. Visca, L. Zamprotta, Results of the Italian neu_ART project, IOP Conf. Ser.: Materials Science and Engineering, **37**, 012007 (2012)