Realization of an instrument for X-ray radiography and tomography dedicated to objects of historical and artistic interest within the neu_ART regional project

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Objectives of the neu_ART project

1. Development and construction of a X-ray scanner to perform digital radiographies of paintings (canvas and wooden panels up to 3 x 2.5 m²)

2. Development and construction of a X-ray tomography apparatus to analyze large objects (up to 2 m wide and 2.5 m high)
   in collaboration with Bologna University (F. Casali, M.P Morigi, M. Bettuzzi)

3. Development and construction of an apparatus to perform K-edge radiographies
   in collaboration with Ferrara University (F. Petrucci e M. Gambaccini)

4. Feasibility study to use compact fusion neutron source (D-D; D-T) to perform neutron radiographies and tomographies
Project and design of a custom CT scanner

Evaluation of dimensions of artworks restored at CCR

Centro Conservazione e Restauro
La Venaria Reale

Painted canvas and wooden panel

Wooden statues and furniture

3 m × 2.5 m

2 m × 2.5 m

cm

cm

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The shielded area
The scanner

- horizontal axis to move the X-ray detector
- X-ray linear detector
- vertical axis to move the X-ray source
- Rotary stage (160 cm diameter)
X-ray source and detector

X-ray source
General Electric
Eresco 42MF4
Tube voltage: 5 - 200 kV
Tube current: 0.5 - 10 mA
Max power: 900 W
Focal spot size: 3 mm
Cone beam: 60° (h) x 40° (v)
Anode: tungsten
Window: Beryllium (0.8 mm)

X-ray Line Sensor Camera
Hamamatsu
C9750-20TCN
Pixel size: 200 x 200 μm²
Pixel number: 2560
Sensitive area: 512 x 0.2 mm²
Scintillator: Gd
Max scan speed: 20 m/min
Output: 12 bit (4096 grey levels)
Characterization of the scanner

Motorized mechanical system with high precision
350 cm (horizontal) x 200 cm (vertical)
Deviation lower than pixel dimension (200 μm)

Dynamic Calibrator
Agilent Technologies
5529A
Characterization of the scanner

**Dynamic range**

Effective grey levels: \((172 \pm 12)\)

Effective dynamic range: \((44.8 \pm 0.9)\) dB

Characterization of the scanner

Spatial resolution

10% MTF: $(2.5 \pm 0.1)$ lp/mm

Sharp-edge

MTF from Edge Spread Function
**Standard image correction**

To take into account:
- characteristic of the detector (different response of each pixel and dark current)
- inhomogeneity of the beam (cone)

- **Dark image**: X-ray off
- **White image**: X-ray on, no object
- **Raw radiography**: X-ray on, object

**Corrected radiography**
From the Racconigi Castle (CN) – Italy

“FILIPPO II DI SAVOIA” (1443 – 1497)

Dimensions: 200 cm x 110 cm

Radiographic parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray tube voltage</td>
<td>90 kV</td>
</tr>
<tr>
<td>X-ray tube current</td>
<td>10 mA</td>
</tr>
<tr>
<td>Scanning speed</td>
<td>1 m/min</td>
</tr>
<tr>
<td>Object-Detector Distance</td>
<td>20 cm</td>
</tr>
<tr>
<td>Source-Detector Distance</td>
<td>294.3 cm</td>
</tr>
<tr>
<td>Source-Object Distance</td>
<td>274.5 cm</td>
</tr>
<tr>
<td>Magnification</td>
<td>1.07 ×</td>
</tr>
<tr>
<td>Penumbra</td>
<td>≈ 0.2 mm</td>
</tr>
<tr>
<td># of radiographic scan</td>
<td>5</td>
</tr>
</tbody>
</table>

Digital radiography

Portraits of the Savoy Family
Portraits of the Savoy Family

From the Racconigi Castle (CN) – Italy

“FILIPPO II DI SAVOIA” (1443 – 1497)

inscription - underpainting - seam

Digital radiography
Portraits of the Savoy Family

From the Racconigi Castle (CN) – Italy

“BONA DI BERRY” (1365 – 1435)

Digital radiography
Digital radiography

Portraits of the Savoy Family

From the Racconigi Castle (CN) – Italy

“AMEDEO VII” (1360 – 1391)

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Portraits of the Savoy Family

From the Racconigi Castle (CN) – Italy

“FILIBERTO II” (1480 - 1504)
Fake Etruscan “Bronzes”

Soprintendenza per i Beni Archeologici del Piemonte e del Museo Antichità Egizie

Bronze thickness:
from 2 to 10 mm

Operative conditions:
200 kV - 4,5 mA - 0,5 m/min

Digital radiography

Lantern

Mirror

Statue

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Fake Etruscan “Bronzes”

Mirror

- Increased readability
- State of conservation, critical points

Digital radiography
Fake Etruscan “Bronzes”

Statue: executive technique, state of conservation, critical points
CT reconstruction performed with a non-commercial software-utility developed by Dan Schneberk of Lawrence Livermore National Laboratory (USA), fan beam geometry and filtered back-projection algorithm.
Fan-beam geometry

- Distances:
  - Source-Detector: 2,95 m
  - Source-Object: 2,14 m
  - Object-Detector: 0,81 m
- Pixel size: 0,8 mm
- Magnification: 1,38 x
- Voxel size: 0,58 mm

X-ray beam

- Tube voltage: 180 kV
- Current: 5 mA
- Focal spot size: 3 mm
- Scan speed: 5 m/min
Test on some pieces of wood

Sample prepared by the wooden artworks laboratory of the CCR “La Venaria Reale”

Radiograph

CT reconstruction: horizontal section

CT reconstruction 3D rendering

Poplar wood

Oak wood
Earth block with hidden objects

From an archaeological excavation near L’Aquila (Italy)
Soprintendenza per i Beni Archeologici dell’Abruzzo

Computed tomography

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Computed tomography

Earth block with hidden objects

CT reconstruction: horizontal sections
Earth block with hidden objects

Computed tomography

CT reconstruction: 3D rendering
Earth block with hidden objects

Computed tomography

CT reconstruction: 3D rendering
Wooden decorative column

From the “Etruscan Room”, Racconigi Castle (CN) – Italy

Wooden column decorated with wooden inlays (XIX century)
Dimensions: 143 cm high; diameter: 35 cm
Wooden decorative column

Computed tomography

The plinth is empty
Wooden decorative column

A nail in the main body of the column (not visible from outside)

Original nails

Modern screws
Wooden decorative column

Holes of xylophagous insects

Decorative ring divided in two part and made in a different kind of wood

Wooden decorative column

Computed tomography

Wooden decorative column

Wooden decorative column

Wooden decorative column
“Doppio Corpo” by Pietro Piffetti

- Pietro Piffetti: one of the most famous European cabinetmakers of XVIII century (Savoy court)

- “Doppio corpo”: part of the collections of Quirinale Palace in Rome

- Made of exotic woods, polychrome ivories, nacre, tortoiseshell

- Dimensions: 312 × 128 × 62 cm³

**Why a tomography?**

- Building technique
- Conservative conditions
- Previous interventions
“Doppio Corpo” by Pietro Piffetti

- **Size:** 129 x 59 x 312 cm³
- **Horizontal sections:** 13
- **Radiographs/sections:** 720
- **Total radiographs:** 9360
- **Resolution:** 10500x2560 pixel²
- **Pixel size:** 200 μm
- **Scanned area:** 2.1 x 0.5 m²
- **Output:** 12 bit
- **Image size:** 51,3 MB
- **Disk space:** 437 GB
- **Mean time for a section:** 10 hours
- **Total time:** 5.6 days
“Doppio Corpo” by Pietro Piffetti

Computed tomography

Radiographs of the 13 horizontal sections
“Doppio Corpo” by Pietro Piffetti

Computed tomography

Previous interventions

Radiograph: screws are different and more recent than the ones employed by Pietro Piffetti in other artworks

Radiograph: screws are different and more recent than the ones employed by Pietro Piffetti in other artworks.
Computed tomography

“Doppio Corpo” by Pietro Piffetti

Radiograph:
row of small nails (not visible either from the outside or from the inside) to repair a longitudinal fractures of the wood behind the ivory plate in the door, to fix a crevice

Previous interventions

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"Doppio Corpo" by Pietro Piffetti

Computed tomography

Building technique

Radiograph

CT reconstruction: horizontal section

three triangular spacers in the external side

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CT reconstruction: horizontal section

**Layer 1:** ivory veneer (half cm thick)

**Layer 2:** thin wooden layer (one cm thick)

**Layer 3:** wooden support
Computed tomography

“Doppio Corpo” by Pietro Piffetti

Building technique

Radiograph

CT reconstruction:

different kinds of joints

tonguings

cogs

cog and groove

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“Doppio Corpo” by Pietro Piffetti

Computed tomography

CT reconstruction: horizontal section
secret drawers and openings

Building technique
"Doppio Corpo" by Pietro Piffetti

Computed tomography

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Building technique
- cavity and brighter blocks
  (probably walnut wood)

Conservative conditions
- holes of xylophagous insects
- different wooden blocks highlighted

CT reconstruction: horizontal section
“Doppio Corpo” by Pietro Piffetti

Computed tomography

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CT reconstruction: 3D rendering

Radiograph

Building technique

composed by many parts pasted together
“Doppio Corpo” by Pietro Piffetti

Building technique

Computed tomography

CT reconstruction: 3D rendering

different wooden blocks highlighted

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**Description of the method**

Takes advantage of the sharp rise of X-ray absorption coefficient of the investigated element.

Two monochromatic images, with energy bracketing K-edge, are acquired. With an algorithm processing an elemental mapping is obtained.
Description of the method

- **K-edge radiography**

**Mass attenuation coefficients**

\[ \mu/\rho \text{ (cm}^2/\text{g)} \]

- **Zn K-edge = 9.65 KeV**
- **As K-edge = 11.80 KeV**
- **Direct beam**
- **Transmitted beam**

**Energy (KeV)**

- **Calcium carbonate**
- **Litopone (BaSO₄+ZnS)**
- **Titanium white**
- **Zinc white**

**Description of the method**

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Experimental setup

- Detector
- Sample
- Mosaic crystal
- X-ray tube
- Double collimator
- Quasi-monochromatic beam
- Isocentric goniometers

K-edge radiography

SSD: Silicon Strip Detector
512 Si-strips: 1 cm thick
Pixel size: 300×100 μm²

Single photon counting mode
Efficiency: (81±4)% at 9 keV
(88.3±1.4)% at 26.7 keV

Experimental setup
Experimental setup

- Sampleholder and motors
- Mosaic crystal
- Collimators
- Goniometer for the crystal and for the X-ray tube
- Detector
- Sample
- X-ray tube
- K-edge radiography
Experimental setup

- **Mosaic crystal (graphite)**
- **SSD detector**
- **Amptek Si-PIN XR-100CR**
- **Goniometer for the X-ray tube**
- **Goniometer for the crystal**
- **Collimators**
- **X-ray tubes Metaltronica (Mo and W)**

**K-edge radiography**

**Experimental setup**

- **X-ray tubes** Metaltronica (Mo and W)
- **Collimators**
- **Goniometer for the X-ray tube**
- **Goniometer for the crystal**

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**Experimental setup**

Grafite $d = 3.365 \text{ Å}$

- Beam
- Microcristals

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**Test on canvas #1**

**Azurite** \((2\text{CuCO}_3 \cdot \text{Cu(OH)}_2)\)  
**Smaltino** (potassium glass containing cobalt)

**Cu imaging**  
K-edge: 8.97 keV

**Co imaging**  
K-edge: 7.7 keV

**Cu imaging**  
**Co imaging**  

Co and Cu content profiles on  
Azurite & Smaltino  
--- Cu  
--- Co

(K-edge radiography)

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**Test on canvas #2**

Single **Cadmium Red** (CdS) pigment layer (diagonal) on a double (on the left) and single (on the right) **Naples Yellow** (Pb\(_2\)Sb\(_2\)O\(_7\)) layers pigments (vertical)

- **Sb imaging** (K-edge: 30.49 keV)
- **Cd imaging** (K-edge: 26.71 keV)
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