Development of a translation stage for in situ noninvasive analysis and high-resolution imaging

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Abstract Noninvasive imaging techniques and analytical instrumentation for cultural heritage object studies have undergone a tremendous development over the last years. Many new miniature and/or handheld systems have been developed and optimized. Nonetheless, these instruments are usually used with a tripod or a manual position system. This is very time consuming when performing point analysis or 2D scanning of a surface. The Centre Européen d'Archéométrie has built a translation system made of pluggable rails of 1 m long with a maximum length and height of 3 m. Three motors embedded in the system allow the platform to be moved along these axis, toward and backward from the sample. The rails hold a displacement system, providing a continuous movement. Any position can be reached with a reproducibility of 0.1 mm. The displacements are controlled by an Ethernet connection through a laptop computer running a multiplatform custom-made software written in JAVA. This software allows a complete control over the positioning using a simple, unique, and concise interface. Automatic scanning can be performed over a large surface of 3 m on 3 m. The Ethernet wires provide also the power for the different motors and, if necessary, the detection head. The platform has been originally designed for a XRF detection head (with its full power alimentation) but now can accommodate many different systems like IR reflectography, digital camera, hyperspectral camera, and Raman probes. The positioning system can be modified to combine the acquisition software of the imaging or analytical techniques and the positioning software.

1 Introduction

Spectroscopy devices as X-ray fluorescence (XRF), Raman or FT-IR applied on field are generally depicted as handheld, mobile or transportable [1]. Commercial or handheld devices instruments are usually used directly by holding the device close or in contact with the sample. In this situation, the acquisition time needs to be adapted because the user must not move during the acquisition, which is not always easy. Also, works of art often require no contact between the sample and the instrument. Thus, spectroscopy instruments are commonly fixed on a tripod structure. The excitation source and the detector are placed on a platform which is adapted to a tripod for fieldwork analysis. These tripods are largely used in cultural heritage survey. This kind of instruments are easily moved and provide in situ XRF spot analysis but the displacement between two points of analysis makes it very time consuming and sometimes not adapted to large works of art.

More complex instruments structures mounted on tripods offer further degrees of liberty such as rotational and angular movement providing additional possibilities to better adapt to curved surface analysis [2]. To the extent of our knowledge, our custom-made mobile translation XRF instrument was the first of its kind that has been published [3]. It has the particularity to be remote controlled and it is able to cover a large area (3 m × 3 m) by means of plugged rails. A new version of this system is fully described in the next section. Comparing to the 2008 version it has been considerably modified to optimize the translation stability, the ease of use and connectivity.

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Since the development of the first version of our system, other similar spectrometers have been described. For example, a custom-made portable XRF spectrometer has been developed in Florence at the LABEC laboratory of Istituto Nazionale di Fisica Nucleare (INFN) [4]. This mobile EDXRF spectrometer has the particularity of possessing two spots in the spectrometer where it is possible to place two X-ray tubes out of a choice of three, each made with different anode materials (molybdenum, titanium and tungsten) that can be used depending on the specific application. The different tubes offer the maximum sensitivity for different element ranges and the equipment is particularly well adapted to the detection of low-Z elements. The support is also composed of two translation stages in the plane parallel to the sample surface covering (50 × 180 cm) and accurate positioning on the sample is obtained by the superposition of two laser spots indicating the point of analysis. All displacements are monitored by a camera embedded in the XRF spectrometer head. Mobile instruments also offer the possibility to perform XRF line scans or elemental mapping. Commercial μ-XRF Bruker Artax spectrometer is available since the beginning of 2000s and by means of a flexible tripod support driven by motors allows spot analysis and elemental scanning of square centimeters areas [5, 6]. Even if the acquisition time over a large area takes generally hours or even days to be completed, this instrument provides highly detailed elemental distribution over areas of interest.

Macro-XRF mapping possibility has been implemented in our instrument since 2009 [7, 8]. Large elemental 2D-scans areas can be performed. However, such analysis requires a minimum time of few seconds for each point and the whole mapping can also take hours or days. Since then, several other custom-made instruments capable of large XRF mapping have been created. The mobile XRF equipment of the AXI2L Research group (Department of Chemistry in University of Antwerp) benefits from having four SDD detectors to record fluorescence radiation from a large solid angle and a powerful X-ray tube (from 10 to 50 W) providing intense primary radiation, both allowing a very short analysis time. Together, these characteristics with an acquisition time of one second or less, allow the instrument to perform large scans of ten square centimeters in few hours with a lateral resolution of 100 to 500 μm [9, 10]. Numerous examples of elemental characterization of hidden paintings have been brought to light with this instrument.

Other translation systems have been developed for imaging of cultural heritage like in the European projects VASARI [11], CRISATEL [11, 12] and PRISMS [13]. Besides those projects, prototypes in several European universities appeared, such as the UBI [14] and UM [15] systems. Recently, for imaging purposes Bertani presented a new panoramic system for IR reflectography [16] an author that already had developed such a system (at the camera sensor level) for reflectography [17], an idea taken later by a British company that sells today the Osiris IR reflectography camera. Today, many photographers and researchers are documenting cultural heritage already using simple systems, such as the common photographic panoramic tripod heads [18].

2 Moving translation system

The device structure can be described as follows. The whole system is modular, and both arms are formed by many plugable Rose–Krieger profiles rails of 1 m long each to reach three meters horizontally and vertically. These rails hold displacement system providing a 100 μm displacement steps repeatability and allow moving continuously. The detection head is fixed on a movable platform which can be moved forward and backward. The whole head assembly could also be rotated to look up or down and therefore allows measurements on curved surfaces (Fig. 1).

The platform is fixed on a vertical column along which it can be moved up and down. This vertical column is fixed on a cart which can move along a horizontal rail. Four independent motors embedded in the system allow X, Y, Z and θ movements. By means of these movements, the detector can be focused precisely over the whole surface.

A micro-camera fitted on the head is used for precise positioning of the detection head. The camera looks at reduce area (5 × 5 cm) and presents the observed region on the computer screen for a prepositioning of the head in front of the region of interest. The distance between the detection head and the object surface is measured by a laser
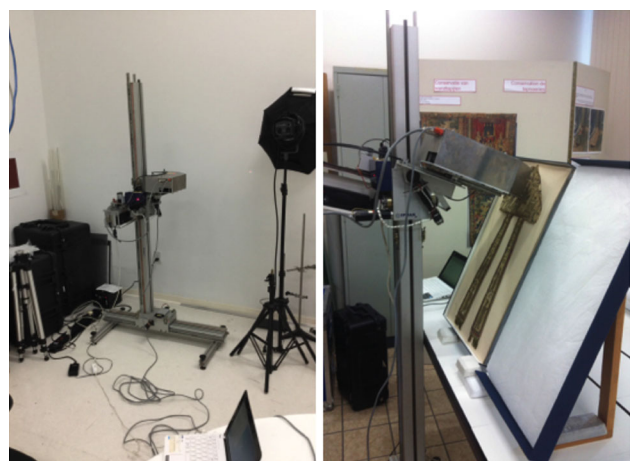

Fig. 1 Custom-made translation stage with plugable rails. The system is shown with the XRF detection head

distance sensor from Baumer (OADM 12U6460/S35A) with a resolution up to 2 μm. There is a feedback coming from this sensor allowing this distance to be kept constant thanks to the Z motorization. If the spectrometer is getting too close to the sample, a sound is generated and alerts the user. If the distance is changing rapidly or that the signal is lost, the system is automatically going backwards to prevent any damage to the object.

All displacements are computer (or smartphone) controlled through a custom-made graphic interface. The connection is made via a WiFi interface, and data are passing through two microcontrollers embedded in the system. This proprietary software, which has been specifically written in JAVA for this application, is multiplatform, very easy to use, and allows full control of the four motors (X, Y, Z and θ) (Fig. 2). Automation is also possible for all displacements via this program. During displacement, values obtained from touch-sensitive devices situated on the support are continuously transmitted to the controller. This allows precise monitoring of position of all the moving parts over a large surface (3 m × 3 m). This remote controlled system makes the positioning very easy to manage and drastically reduce the time between two acquisitions. The power needed for the motors and the detection head is provided by Ethernet cables, meaning that there is only one wire coming out of the system.

This system has already been used to perform high-resolution photography, infrared reflectography, XRF and Raman spectroscopy and can be easily adapted to any detection system by simply positioning the camera or the spectrometer on the plate. Hyperspectral imaging camera could be easily implemented as the speed can be adjusted. Some case studies will be presented in the following section.
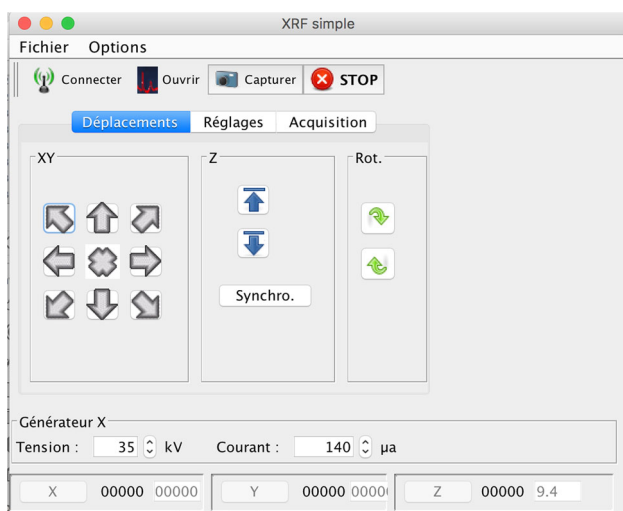
3 Case studies

3.1 High-resolution photography

High-resolution photography is easily implemented with this translation stage. The principle is to use it to move regularly a camera mounted on the detection head. In our case, we have used a Nikon D3000 camera (10.2 Mpixel sensor) equipped with a macro-objective Nikon 105MM AF-S VR F/2.8G IF-ED MC. The system is placed at 40 cm of the surface to capture (this gives pictures of around 4 cm wide). Distance is kept constant with the laser sensor which is switched off when the picture is taken. Automatic displacement and photographic acquisition are performed thanks to the software. Translation is done in order to have a superposition of two adjacent pictures of 20 % minimum. The resulting pictures are then used to build a mosaic with the help of a specific software.

We present here the result of this scanning for a painting from Thomas Puteanus, *Eliezer gets Bethuel the hand of Rebecca for Isaac* (Musée des Beaux-Arts de Liège, Belgium, Inv. 730, 52.5 cm × 32. 5 cm). The final image for this painting is 29,000 × 18,000 pixels (520 MPixels). With this resolution, we can have a full view of the painting and zoom anywhere to see details such as brush strokes or cracks (see Fig. 3).

3.2 Infrared reflectography

Another example is to use the translation system to perform infrared reflectography. This imaging technique is using an infrared camera in the range 1000–2100 nm and is generally a suitable method to visualize underdrawings and retouchings on a painting. In this study, we have used
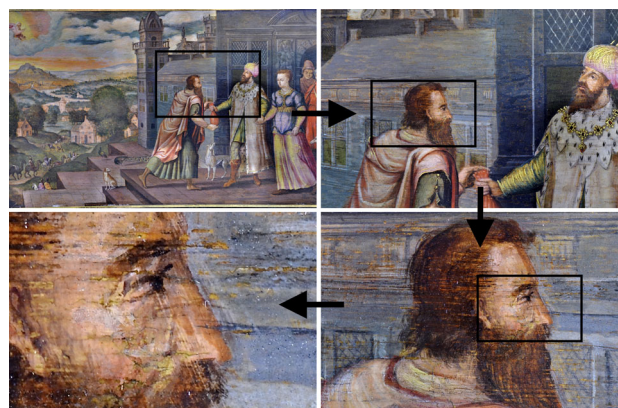

Fig. 2 Custom-made software written in JAVA. Software can be used to go to a specific position or do automatic scanning. Software is easily adapted to any acquisition system

Fig. 3 High-resolution visible photography acquired by the automatic translation system of Thomas Puteanus' painting *Eliezer gets Bethuel the hand of Rebecca for Isaac* (Musée des Beaux-Arts de Liège, Belgium, Inv. 730, 52.5 cm × 32. 5 cm) . Final image is 29,000 × 18,000 pixels

Fig. 4 Infrared reflectography acquired by the automatic translation system of Thomas Puteanus' painting *Eliezer gets Bethuel the hand of Rebecca for Isaac* (Musée des Beaux-Arts de Liège, Belgium, Inv. 730, 52.5 cm × 32. 5 cm). Final image is 7000 × 4500 pixels

exactly the same setup as for the high-resolution photography, replacing the camera by an infrared vidicon camera C2741-03 from Hamamatsu. As shown in Fig. 4, the final image is less resolved than in the visible range due to the characteristics of the camera (analogic camera with a 600 TV line resolution). The first step is then to digitize the signal coming from the camera. This has been implemented in the custom-made software. The obtained image of the same painting is 7000 × 4500 pixels (30 MPixels).

3.3 XRF mapping

Macro-2D elemental mapping is achievable from now on with our XRF mobile instrument. This was possible through the conception of miniaturized electronics for data acquisition and the adaptation of the translation stage. MA-XRF scans performed with our mobile system have been applied in previous in situ analysis for the mapping of paintings [7, 8], showing that this technique can bring additional information complementary to X-ray radiography and infrared reflectography. Elemental mapping and intensity distribution bring additional information over spot analysis. Pigment characterization, as in every elemental analysis, remains the principal objective since it contributes to the definition of the artist's pallet and his painting technique. XRF mapping also helps to better understand the painting layers by comparing characteristic elements of apparent pigments with obtained intensity distributions over the scanned area. Moreover, precise localization of restoration areas can be achieved. Even in small number of cases, differentiation between superficial restorations, like repainted areas, and deeper restorations where inner layers have been changed, can be made. Finally, scans with portable instruments can reveal underlying painting.

In situ mapping reduces physical risks of the work of art under investigation since no displacement to larger facilities
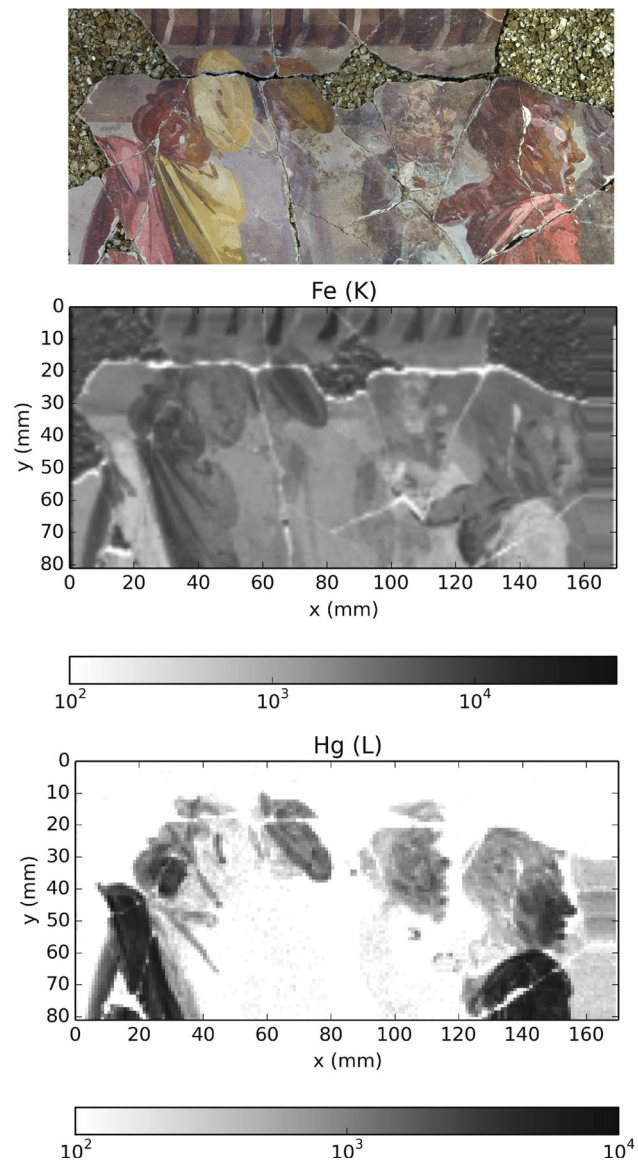

Fig. 5 XRF mapping of a Roman wall-painting fragment: iron and mercury distributions are shown

has to be done. The elemental distribution of chemical elements locates the precise areas of restoration and retouching. The major drawback of our previous system [3] is the very long acquisition time. For a 10 cm × 10 cm scan with a 1-mm step distance and with an acquisition time of 10 s and an average translation time of 2 s per spectrum, the total acquisition time is more than 32 h. With this new system, we have been able to reduce the total acquisition time by a factor of 10. First, we have installed a X-ray detector with a bigger detection surface (Amptek SDD123 detector) and optimize the distance between the detection head and the analyzed surface (from 23 to 9 mm). Secondly, instead of doing a step-by-step acquisition, the detection head is moving slowly with a speed of 1 mm/s. The data are recorded in a buffer and

written on the computer disk at the end of the line. The example shown in Fig. 5 is a XRF mapping of a Roman wall-painting fragment. The distribution of the iron and mercury signal is shown. Iron is associated with iron oxides pigments, and mercury is coming from cinnabar, a red pigment. The images have been obtained using the PyMCA software [19]. Similar images have acquired for other elements (Cu, Zn, Ca, K, Pb, Sr, ...).

4 Conclusion

The modular system of plugged Rose–Krieger profiles may appear heavy and sometimes quite difficult to adapt to the field. The apparatus is brought on-site in a large rigid case of ($60 \times 45 \times 120$ cm) weighting about 80 kg when filled. Nevertheless, once on-site and installed, the advantage lies in the low-time-consuming positioning when moving from a point of analysis to another thanks to the displacement control. The remote control evolved from a small handheld PDA Palm exchanging displacement information with microcontrollers through Bluetooth connection to a WiFi connection control via a software. The positioning is helped by means of a laser visualized through CCD camera embedded in the system. Data acquisition is managed via software through an Ethernet connection. These developments on a new positioning system have allowed to perform high-resolution imaging, infrared reflectography, and 2D elemental mappings with our equipment.

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