Industrial radiography and tomography based on scanning linear scintillator array

L. Franco[1], F. Gómez[1], A. Iglesias[1], F. Vidal[2], R. Ameneiro[2]*
[1]USC, Universidade de Santiago de Compostlal, Spain; [2]AIMEN, Asociación de Investigación Metalúrgica del Noroeste, Spain.
** Corresponding author, email: luciaff@usc.es, tel:. +34 981 563100 ext 13547*

Abstract: We have developed an industrial CT and Digital Radiography system (CT/DR) for NDT at the USC (Spain). A 510 mm long detector array of 640 detection elements with sub-millimetre spacing (0.8 mm), together with a 50kV mini-focus tube have been integrated in a 3-axis positioning system of flexible configuration. Accurate characterization of geometrical parameters and system commissioning has been performed. System calibration algorithm has been implemented to correct for channel response variations. Other artifact sources, like beam hardening and scatter radiation, have been experimentally optimized. System capability to perform CT and DR scans has been demonstrated and several images of phantoms and weldings are shown.

Keywords: Digital radiography, computed tomography, linear array

1 Introduction

Computed tomography, CT, (*tomos*, derived from greek, means slice or section) was born initially as a diagnostic technology in medicine through x-ray visualization. It has been widely developed in medicine, although its application in the industry is becoming more and more important within the non-destructive testing (NDT) field. Its importance comes from the fact that CT gives full 3D and quantitative information of industrial pieces, allowing to detect, locate and to measure defects.

CT is a radiographic technique; it is based on radiation transmission on the object to inspect. The output radiation map that reaches the detector plane is modulated by absorption processes in the object, which depend on density, atomic number and width of the object along radiation incidence. The measured signal is proportional to the radiation intensity traversing the object and reaching the detector.

The logarithm of the ratio between measurements of attenuated and not attenuated (without object) signals represents the line integral of the attenuation coefficients and it is the projection measurement (equation 1). This logarithm is calculated for different angles of incidence (Radon transform) to reconstruct the 2D image of an object. The matrix of projections for all angles of incidence is represented by the object's sinogram. The sinogram is used to reconstruct the image of the object by a filtered back-projection algorithm, based on the Fourier slices theorem.

$$p_i = -\log(\frac{I_i}{I_{i0}}) = \int_{L_i} \mu(x)dx \qquad (1)$$

The reconstruction algorithm varies depending on the CT system geometry, which also defines the CT scan generation. First generation CTs are based on a punctual x-ray source and a single detector element, while second generation CTs have the same geometry but several detector elements. A linear displacement translating both the source and the detector is needed to entirely cover the object. This scan geometry gives parallel projections, with the x-ray source focus and the detector moving in the same direction.

On third generation CTs, the object is completely covered by the beam and the detector array, with linear or arc shaped geometry. In fourth generation CTs, the detection array arc covers 360º (around the object) while the x-ray source rotates during a scan. In both last CT generations, fan beam geometry is defined by the source on the active detector array. This scan sequence is considered for clinical CT (not moving the object-patient), but the object uses to be rotated for industrial CT applications. Cone beam geometry is also implemented for CTs, when 2D detector arrays are used.

Industrial CT systems must comply with several application specific requirements for NDT, related to penetration capacity of the x-ray beam (high energy) on the object to be explored, to the required spatial resolution for detail identification and system geometry (object size and weight). The system herein described was specifically designed to perform CT and digital radiography (DR) NDT studies of metallic pieces with submillimetrical resolution, for welding quality control at the technological centre AIMEN (Spain). We have implemented a third generation CT system, which allows performing three different radiographic studies (scan modes): planar digital radiography (DR), single slice CT and multi-slice CT.

2 System description

The industrial CT/DR system developed at the USC is comprised of the following subsystems (figure 1):

2.1 X-ray source

A 50 kV mini-focus x-ray tube , with 0.1 mm focal spot size and with 2 mA maximum current (100 W, Oxford Instruments, Neptune 5000 series) has been used. It is a tungsten target monopolar tube, with the anode connected to high voltage. A closed circuit of water was installed for tube refrigeration.

2.2 Radiation detector system

The detector consists of a modular linear array of 640 detection elements, covering a length of 512 mm with a 0.8 mm spacing (sensor pitch). The sensor elements are based on gadolinium oxysulfide (gadox) scintillator, due to its high conversion efficiency for low x-ray energies, coupled to linear array of photodiodes. Photodiode signal is read through a multi channel readout VLSI chip (XCHIP on XDAS signal readout board of Electron Tubes, Ltd). Each XDAS readout board integrates 128 readout channels, by multiplexing and analogue-differential transmission to a control board for ADC conversion, and allowing further readout by a fast digital I/O PCI frame-grabber. This detection system implementation allows modular composition of up to 20 readout boards. Presently, 5 XDAS readout modules have been integrated, each with 4 consecutive arrays of 32 detection elements, with a total of 640 readout channels (figure 2). The XDAS readout solution allows replacement of detection elements by other arrays based on different scintillator material, and thereby flexible upgrading of the detection system.

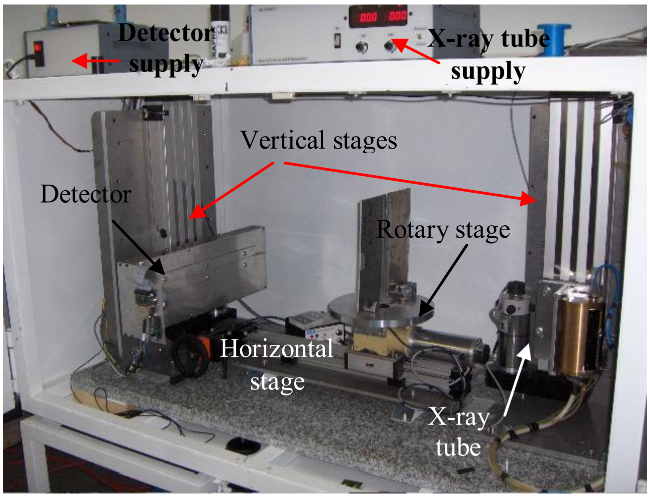

Figure 1. Picture of the CT/DR system prototype developed at the USC.

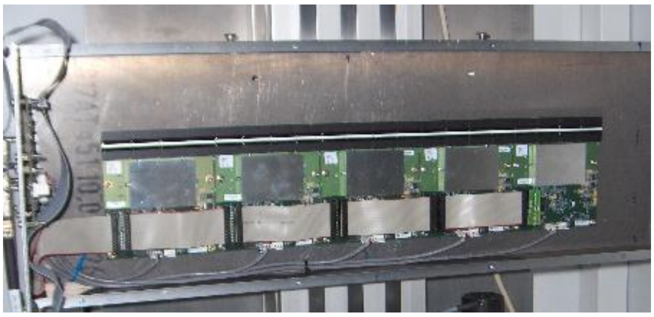

Figure 2. Radiation detector system. A 512 mm long linear array is shown made of 5 readout modules with 8 x 32 detection elements (0.8 mm pitch) per module.

2.3 Positioning system

The positioning system has been implemented as a 3-axis system allowing flexible configuration of system geometry and scan sequence. The mechanical assembly integrates two motorized linear stages (400 mm travel), both vertically positioned, and a motorized horizontal rotary stage (80 kg load capacity).

The rotary stage is mounted on a horizontal linear stage (1000 mm travel), which allows a manual adjustment of the source-to-object distance obtaining different magnification factors. System support structures have been fixed to two 2.5 cm thick granite sheets to reduce vibrations. Level bases and fine step screws on several locations of fixation system allow a precise alignment of the stages.

The x-ray tube and the sensor array are assembled on the two opposite vertical stages for synchronized linear translation, defining a detection line (CT slice). System geometry has been implemented as a third generation CT system, where the field of view fully covers the object width during the acquisition with a fan beam geometry. The object of interest is situated on a 30 cm diameter plate rotated by a motorized rotary stage.

The positioning system control is based on a PID controller (MINIVISION system of Tex Computer, s.r.l.) with the scanning sequences programmed in CNC. Different scanning mode codes (digital radiography, single slice or multislice CT) are run from remote control software (LabVIEW code) on a dedicated computer. This solution allows a very flexible configuration for image acquisition.

2.4 Acquisition and control computer system

Control software has been developed in LabVIEW code and it integrates both the system mechanical positioning and the acquisition of data:

- The acquisition and control code carries out an initialization of the system and allows selection of some parameters related to acquisition (integration time, number of subsamples) and scanning mode, like slice spacing (down to 0.25 mm), number of projections (typically from 360 to 1200), etc.
- The synchronization of signal readout from the detection system (through a PCI framegrabber) with the system positioning sequence is performed by means of trigger signal and acknowlegment signals comunicating the PC with the local PID controller (acquisition end of complete scan or single slice in CT, data saving from framegrabber, etc.).
- X-ray tube parameters (high voltage and current) can be remotely modified by the control software program (through USB connection of high voltage supply).

The flexible acquisition and control system can be adapted to modifications on system elements (radiation source, detector) through an initial calibration of the system parameters.

2.5 Reconstruction and visualization software

Imaging reconstruction is carried out with Matlab (www.mathworks.com) through already implemented algorithms for reconstructing fan beam data. We have developed stand-alone executables in Matlab for individual reconstruction of DR, CT slices and multislices.

For DR and slices, the image is stored in a bmp file to further visualization and image adjustments. The CT files are reconstructed in the Analyze 7.5 format (developed by BIR in the Mayo Clinic), which can be visualized by most visualization software. For example, *AMIDE* (amide.sourceforge.net, a free software developed for medical imaging), allows slices visualization and 3D rendering of the image.

3 System commissioning

Image quality is system dependent, since it is determined by the system geometry, component calibration, and correction of artifacts.

3.1 Characterization of geometrical parameters

System geometry commissioning is of crucial importance for accurate data reconstruction. Main geometrical parameters of the system have been characterized.

Magnification dependence on horizontal stage positioning:
Precise determination of the source-to-object distance and characterization of magnification factor of the image depending on the horizontal stage position is needed for the reconstruction of fan beam projections and image dimensioning. The magnification coefficient is the ration between the measured size for each position and the object actual size. A reference opaque object with known dimensions was scanned (DR) for different positions of the horizontal stage. A linear dependence between the magnification inverse values and the horizontal stage position was obtained (figure 3).

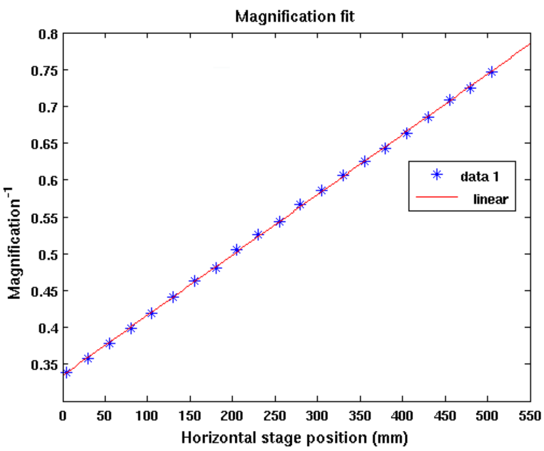

Figure 3. Dependence of magnification factor with horizontal stage position.

Considering that the magnification value at isocentre is 2 and 1 for the detector position, the source-detector distance can be calculated. In our system, the magnification varies from 1.3 to 3, with a source-to-detector distance of 1222.3 mm.

Object rotation axis and alignment with centre of detector array:
The object axis of rotation must be aligned with the centre of the linear array of detection elements, for every position of the horizontal stage (magnification values). A thin metallic object was used for generating point object image CT slices. The centre of the slice sinogram was checked to be the 320th channel for different positions of the horizontal stage for centering of the rotation axis.

Linear array alignment:
Detection plane, defined by detection elements positions during scan, has to be perpendicular to the object-detection axis. Detector array position was visually adjusted with a laser marker. A DR of a large edge-object was acquired for alignment verification, getting edge profiles for each channel, whose half-height point positions showed negligible dispersion.

3.2 Calibration of the detection system

Several image artifacts related to detector response variations between channels (figure 4) can be corrected (although not totally removed) by system calibration.

Detector signal offset, due to electronic noise and photodiode dark current, is a random process that changes with temperature and time (figure 5).

Detector response (gain factor) depends on X-ray beam intensity and can also change with time.

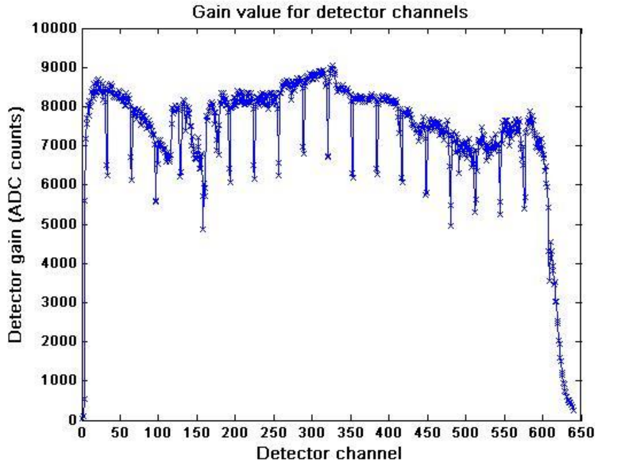

Figure 4. Flat field detector response variations between channels (raw data).

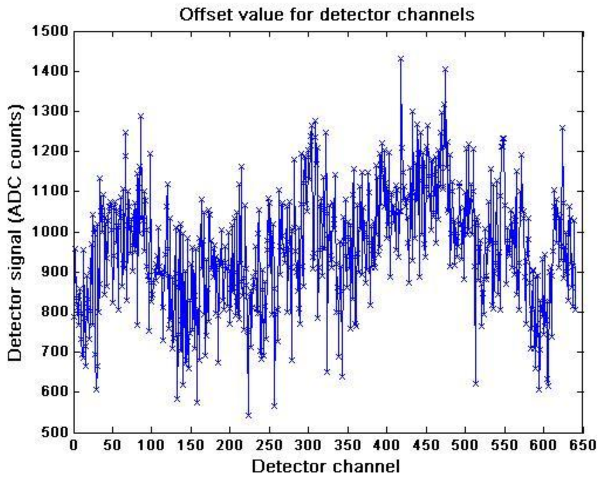

Figure 5. Detector offset variations between channels (raw data).

To individually calibrate all readout channels and correct these effects *air scans*, consisting on measurement series without any object, were performed. Fitting each detection channel response to increasing values of X-ray beam intensity (figure 6), signal correction factors of individual detector gain and offset (slope and origin value, respectively) were obtained. These calibrations, along with the corresponding signal correction, are implemented in the acquisition software to be performed before each scan session. In spite of this previous calibration, signal variations of less than 1% may appear, causing soft artifacts in the image.

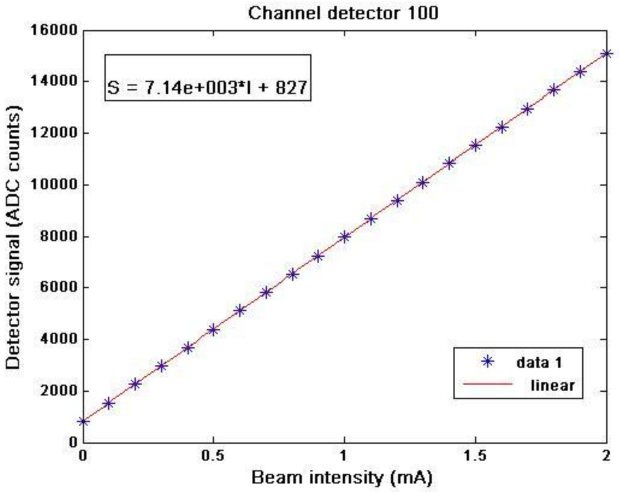

Figure 6. Dependence of detector (element number 100) response with beam intensity.

3.3 Other artifacts

Beam hardening:
When introducing an object to be scanned, differences not only in intensity but also in the energy distribution of the detected x-ray beam (beam energy quality) are found compared to the measurement on air scan calibration conditions. Beam hardening artifacts can appear when the average energy of the beam reaching the inner volume of the object is significantly higher than at the incident beam, since comparatively more low energy than high energy x-ray absorption is produced at the object outer volume. This causes a diminution of image intensity in the central zones on CT slices of the object, related to differences in the reconstructed attenuation coefficients and its dependence with x-ray energy. Beam hardening artifacts can be minimized by introducing a filter at the x-ray beam source, so the filter itself absorbs the lowest energy radiation. A 0.1 mm thin copper foil was included in our system for this purpose (see figure 7).

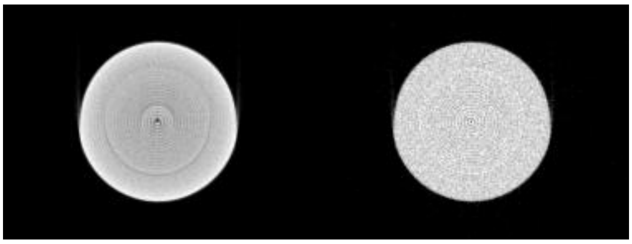

Figure 7. Beam hardening effect on a slice of a plastic cylinder (left) and filter correction (right).

Scattered radiation:
X-ray beam photons which are not attenuated or transmitted are scattered in the object (or system components), mainly through incoherent (Compton) scattering, changing its primary energy and trajectory. Scattered radiation reaching the detector contributes to detector signals and reduces image SNR. Scatter also depends in source-to-object distance; the scatter contribution to the detected signal diminishes with increasing magnification. Non uniform scatter on the detection plane can cause image artifacts like shades or streaks. Scattered radiation effects can be reduced, and related artifacts can be minimized, by collimating the incoming radiation in the detector elements, and by introducing a thin filter to absorb part of the low energy scattered x-rays. A 0.8 mm collimation slit (between lead plates) and a 0.07 mm thick copper sheet filter were included at the detection line of our CT/DR system for this purpose.

4 Results

The capability of the system to perform CT and DR scans has been demonstrated by acquiring and generating images of several samples under different scanning conditions.

Only raw images are represented, since no reconstruction filter has been implemented yet.

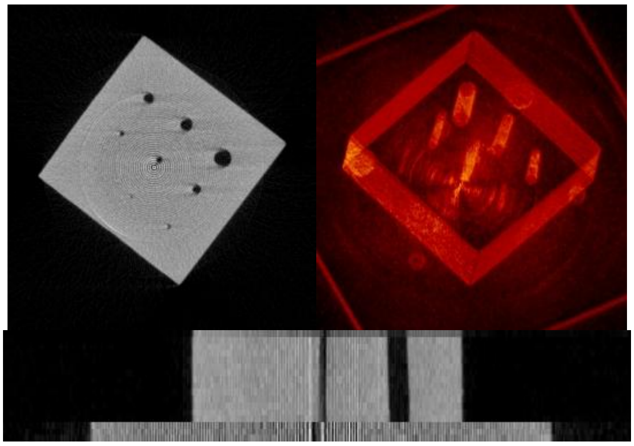

Figure 8a. (up, left) CT slice of a PMMA phantom extracted from the 3D data set (up, right) and frontal view (down).

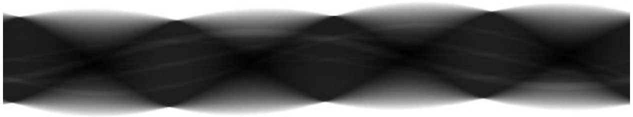

Figure 8b. Sinogram of the PMMA phantom.

Figure 8 shows a CT slice of a PMMA phantom with several holes (5, 3, 2.5, 1, 0.75, 0.55, 0.25 mm diameter).

In our system, CT and DR scans show submilimetric resolution clear images, although several artifacts can still be observed. Details of aproximately 0.5 mm size can be detected in CT slices, and even smaller in DR images.

Figure 9 shows a DR (0.25 mm step vertical scan) of a printed circuit board with a BGA encapsulated chip. Small density variations in circuit layout and BGA boundings are clearly observed.

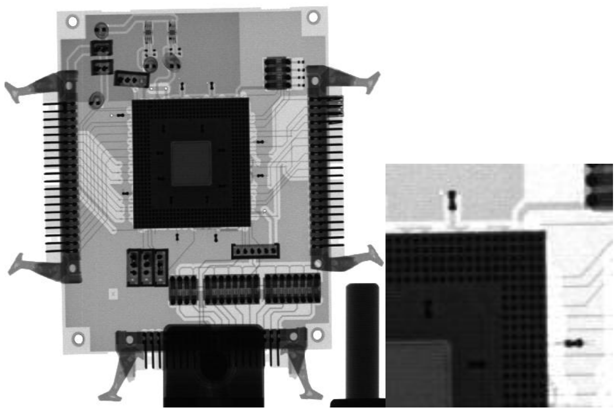

Figure 9. Digital radiography and detail of a printed circuit board with a FPGA chip.

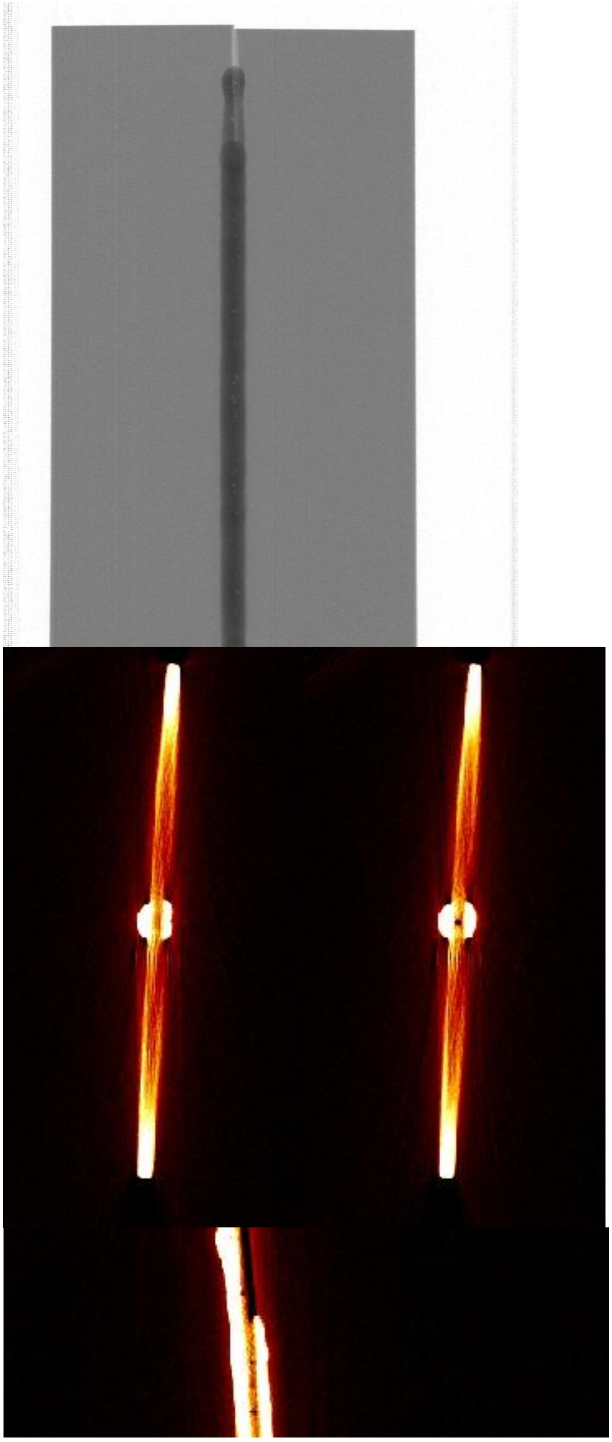

Figure 10a. Radiograph of a MIG weld on two aluminium plates (up). Details on two slices of the weld extracted from the 3D data set and a frontal view (down).

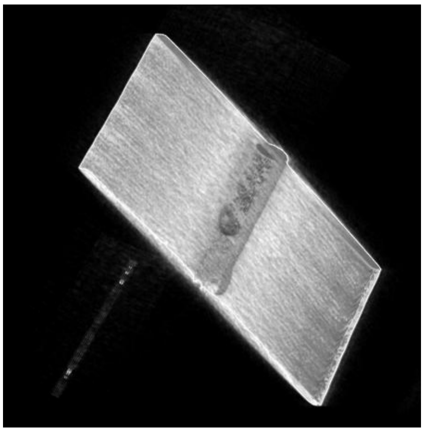

Figure 10b. 3D rendering of the welded plates.

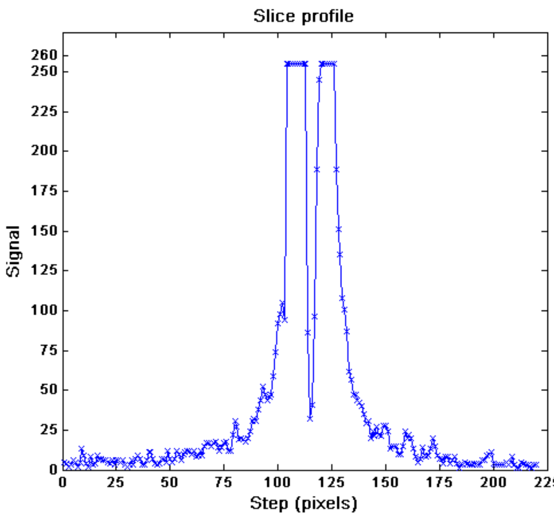

Figure 10c. Slice profile, showing the signal difference for the welding pore.

Several DR and CT scan images have been obtained of different welding structures on metal plates. Figure 10a and 10b show a multi-slice CT of a weld on two 6 mm thick aluminium plates where well defined pores could be identified. Figure 10c shows a profile of the previous slice with the pore.

5 Conclusions and future work

We have developed a CT system for industrial tomography with applications for NDT. Acquisition modes of digital radiography, CT slice and multislice have been implemented in our system.

Data acquisition and mechanical assembly are integrated and controlled by a software developed in LabVIEW. Reconstruction is implemented in Matlab and image data is stored in known formats for its visualization.

Further work is focused on the system imaging capabilities. System performance in terms of spatial frequency (point-spread function and MTF) must be analyzed. Raw data filtering (before reconstruction) has to be studied, through studies with reference samples, in order to minimize imaging artifacts .

A CT system for NDT of large pieces (up to 80 cm x 100 cm) is under development based on this prototype with a linear array of one meter length (1280 readout channels) and a 225 kV x-ray tube.. The flexible configuration is also built (variable magnification, vertical motion of x-ray source – detector) and the same code is implemented.

This system is a demonstration prototype for inspection of light, low density pieces. Another industrial CT is under development for large pieces (up to 80 cm x 100 cm) with a linear array of one meter length (1280 readout channels) and a 225 kV x-ray tube. This system is being built at AIMEN (Spain) for NDT of metallic pieces, specially oriented to welding quality assurance.

References

[1] J. Hsieh, *Computed tomography. Principles, Design, Artifacts and Recent Advances*, SPIE Press, 2003.

[2] C. Kak and M. Slaney, *Principles of Computed Tomographic Imaging*, IEEE Press, 1999.

[3] D. J. Krus, W. P. Novak and L. Perna, "Precision linear and two-dimensional scintillation crystal arrays for x-ray and gamma ray imaging applications", *The SPIE International Symposium on Optical Science, Engineering and Instrumentation* , 1999 (SPIE Vol. 3768).

[4] *Specification and acceptance testing of computed tomography scanners,* APPM Report Nº 39.