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Development and Validation of an X-ray Imaging Detector for Digital Radiography at Low Resolution

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ABSTRACT

Digital X-ray detectors are required in different sciences and applications, however many high quality devices are expensive although high-resolution images are not always required. We present an easy way to build a detector capable of forming X-ray digital images and video with a very large area (18×18 cm^2). The detector is formed by three main components: scintillator, optics lenses and CCD sensor. Basically, the device converts the X-rays into visible light which is then collected by the CCD sensor. The scintillator is Gadox type, from Carestream®, 18×18 cm^2, regular type, lambda 547 nm. The optics lenses are generic, with manual focus and widely visual field. The CCD sensor has a size of 1/3″, 752×582 pixels, monochrome, 20 FPS, 12 bits ADC and pixel size of 3.8 µm. With the built detector and an X-ray source, we formed an X-ray imaging detection system to generate digital radiographs of biological or inert objects-examples are given-, as well as real-time X-ray video. Additionally, the spatial resolution limit was measured in terms of Modulation Transfer Function by the method of opaque edge from a lead sheet with a result of 1.1 Lp/mm. Finally using a filter, the focal spot of the X-ray source is measured, resulting in a diameter of 0.9 mm (FWHM).

1. Introduction

The use of X-rays to form images of objects interiors is known since 1885 by the discoveries of the German physicist Wilhelm Röntgen [1]. Since then, its use continues to this day with very important applications in commerce, transport, industry, medicine, research, art, security, etc. [2]. Therefore, X-ray image forming systems are essential due to the high importance applications. In general, a complete imaging system essentially requires three elements: (a) a source of information carrier-photons, waves, particles, etc.- that interact with (b) an object or sample to be displayed, and (c) an X-ray detector which is a device capable of detecting the carriers of the information-X-rays-, and it reconstructs the data generating an image that a user can interpret.

Digital radiography systems allow us to observe the internal structure of certain objects. They use detectors that can be classified them as those that directly detect X-rays and convert them into electric charge, and those who indirectly detect X-rays. The former is based on semiconductor materials such as amorphous selenium (a-Se) or Cadmium telluride (Cd-Te) with the advantage that no intensifying screens or intermediate steps are required to collect and convert the incident photons. The indirect detectors may use a scintillator to first transform the incoming X-ray into visible light; this light is collected by means of photodetector device which in turn converts this information to electric current in order to generate a digital radiograph. There are several variants of this experimental arrangements, for example: (i) the scintillator optically coupled to photomultiplier, (ii) the scintillator optically coupled to array of a-Si photodiodes and/or phototransistor, (iii) image intensifier which isa photomultiplier coated with a scintillator optically coupled to CCD (charge coupled device), (iv) crystals optically coupled to a CCD line array with fiber optic face-plateand (v) scintillator with optical lens coupled to a CCD [3, 4]. Current digital detectors have high performance in terms of high resolution, high quantum efficiency, low noise, etc. However, they are affordable for many users and many times those high-quality characteristics are not necessarily required.

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The information carriers are the X-rays. An X-ray source (for example an X-ray tube) produces a cone-shaped beam that reaches the sample that you want to visualize. X-rays interact with the object through a process such as photoelectric effect, Rayleigh and/or Compton dispersion. These physical processes are implicitly included in the so-called mass attenuation coefficient of the various materials that constitute the sample [7-9, 10].

Although there are several mechanisms to produce X-rays, it is the X-ray tube the conventional source used in digital radiography. An X-ray tube is a device for generating X-rays by deaccelerating high energy electrons (more than 5keV) through metal target collision from which the X-rays are emitted. This X-rays production principle is called bremsstrahlung and it generates a continuous emission spectrum. Overlapped to the continuous spectrum there are characteristic peaks that normally appear which are the result non-elastic interaction with electrons with in the atom target: enough energy electrons can ionize the atom causing a hole which is filled by another electron of a higher shell causing the release of a photon. If the phenomenon occurs in the layers close to the nucleus, the released photon will be in the X-rays spectral range [7, 9, 10].

Basically, an X-ray tube is composed of (Fig.1): A filament that is heated by a low-voltage electric current causing electron release by thermionic emission. A glass cover to keep the device in vacuum conditions. An anode that transforms the electron energy into X-rays. A case with a window transparent to X-rays, for the outgoing of the X-rays. When an electrical current flow through the filament, electrons are released by thermionic emission. They are then sped up by a potential difference in the order of tens or hundreds of kilovolts applied between the filament and the anode. When striking in the anode, the high-sped electrons lose their energy in the form of heat and electromagnetic radiation.

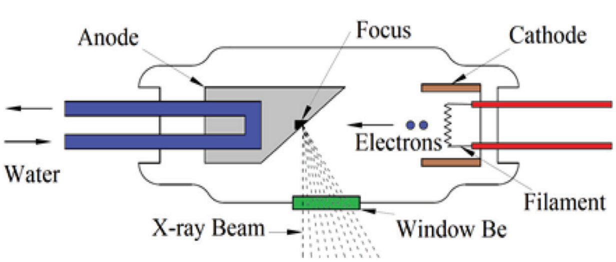


Figure 1: X-ray tube diagram. The electrons produced in the filament are accelerated to impact the anode, producing continuous bremsstrahlung and the characteristic X-rays. The spectrum and the focal spot are two aspects that describe an X-ray source.

In this work we report the design, construction and characterization of an indirect type X-ray detector, that allows obtaining X-ray digital images of conventional objects. Some experimental arrangements similar to this work are shown in [5, 6]. After building our detector we validate its functionality by obtaining digital radiographic images of various objects. Afterward we characterize the detector using the Modulation Transfer Function (MTF) by the opaque edge technique. [11, 12]. Subsequently using a methodology like the one shown in [13, 14], we carry out a study of the X-ray source to know its focal spot. This is an important physical parameter because it allows us to know the gloom or unsharpness of our imaging system. Finally, we give a discussion and conclusions of this work.

2. Materials and Methods

A complete description of the design and characterization of the detectorit's given below, including the X-ray source, scintillator, optic lens, CCD sensor and image acquisition software. The general scheme of the imaging system is illustrated, and its operation discussed. Generated images are shown, the system resolution measured and the geometry of the focal spot for the X-ray tube is generated.

2.1 Detector Design

The objective of this work is to design a detector composed of a scintillator, optics and a CCD sensor. An X-ray source illuminates the object to be displayed, and just after in front of the sample, the scintillator is placed which converts X-rays into visible light to be collected by the CCD sensor (Fig 2). The collected data is interpreted and sent to a computer to view and/or store the radiography. The whole arrangement is on the "x" axis: R_1 represents the source-sample distance, R_2 is the sample-scintillator distance, R_3 is the scintillator-Lens distance, and R_4 is the lens-CCD distance. The scintillator, the lens and the CCD sensor are inside a box transparent to X-rays but opaque to visible light in order system can be used under any lighting condition. The system is portable and fits in any laboratory table.

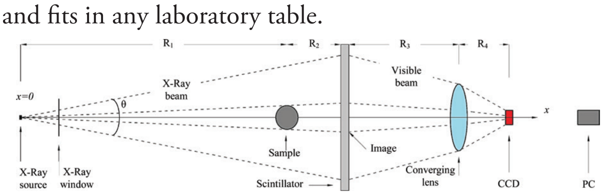


Figure 2: Experimental arrangement for X-ray imaging detector. An X-ray source emits a cone-shaped beam that strikes a sample, then the X-rays interact with a scintillator and visible light is emitted that is focused by optical lenses on a CCD sensor. The signal is digitized and sent to a PC to be displayed or stored.

2.2 X-Ray Source

The X-ray source (Fig. 3) used was a medical X-ray source, dental type, generic brand. It uses a Toshiba® X-ray tube, model not specified. The operating voltage and current are fixed at

60kV and 12mA. It has a tungsten anode with a beam cone angle of 24° and a nominal focal spot size of 0.6mm. The control unit allows to control emission times from 0.1 to 9.0 seconds. It has no cooling system so it cannot be operated for long periods.

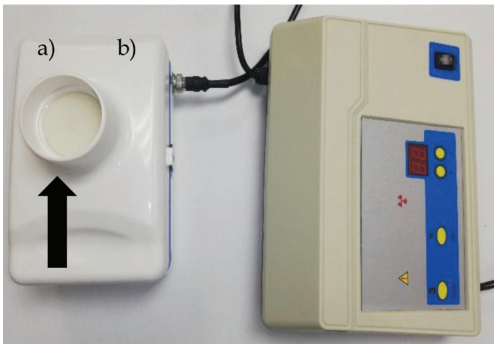


Figure 3: Medical X-ray source. An X-ray used for the built system. a) the window where the X-rays emerge in the form of a 24° angle cone is shown. b) unit control.

2.3 Scintillator

A scintillator is a material (phosphor) that exhibits scintillation, i.e., the property of luminescence when it is excited by ionizing radiation: after an X-ray photon is absorbed, ultraviolet or visible light arises in the scintillator. Wide band-gap materials are employed to transform X-rays in ultraviolet/visible photons. Consistent phenomenological descriptions of the scintillation conversion process, efficiency criteria, etc. were developed in the seventies and further refined later. Scintillation conversion is a relatively complicated issue, which can be divided into three consecutive subprocess conversion, transport and luminescence. Full details can be found at [4]. Within the scintillator materials we used Gadolinium oxysulfide (Gd_2O_2S), also called Gadox, which is an inorganic compound, a mixed oxide-sulfide of gadolinium. The crystal structure of Gadox has trigonal symmetry (space group number 164). Each gadolinium ion is coordinated by four oxygen atoms and three sulfur atoms in a non-inversion symmetric arrangement. The Gadox structure is a sulfur layer with double layers of gadolinium and oxygen in between [15]. Fig. 4 shown a Gadox screen employed.

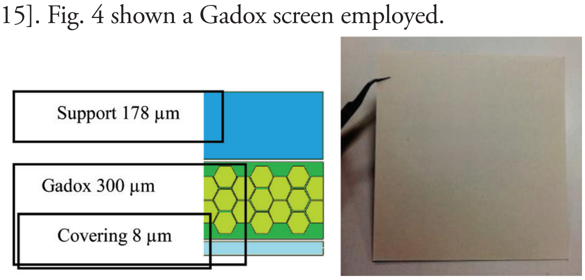


Figure 4: Scintillator. Gadox type scintillator used, here the conversion of X-rays to visible light happens. a) Scheme of the internal structure of the Gadox screen. b) Actual Gadox screen used in the detector, 18×18 cm^2.

2.4 CCD Sensor, Optic Lens and Acquisition Software

Technical details from CCD sensor, optic lens and acquisition software are shown in Table 1.

Table 1: CCD Sensor (Generic brand).

Image Sensor	**1/3" Monochrome CCD,**
Resolution	0.5 MP, 752 (H) x 582 (V) pixels
Pixel size	3.8 µm
Output	USB 2.0
Frame rate	20 FPS
Scan Type	Progressive Scan
Outer Dimensions	48mm x 48mm x 50mm
Photo format	JPEG/BMP/PNG/RAW
Color	Monocrhome
Minimum illumination	0.1 Lux
Noise	≥48 dB
Power supply	DC 12V
Lens Mount	C-mount
Frame grabber	ADC 12 bits
Software used	AMCap®
Optical Lens	Generic, f = 2, Length 8 cm
CCD sensor and lens used:	

2.5 Imaging System Resolution

To measure the limit of the spatial resolution of the system, a 1mm thick lead sheet is constructed from a straight edge, with approximative dimensions of 2cm×2cm. With this device placed in front of the detector an image is generated. The characterization process according to the methodology shown in [11,12] was agreed.

2.6 Focal Spot Size

In order to estimate the size of the focal spot, we constructed a pinhole using a lead film in which a 0.2 mm circular hole was made. Using the geometry shown in Fig. 5-a), the projection of the focal spot in the detector was generated.

In order to obtain thepinhole image of the sharpest focal spot possible, corrections were made by dark and flat field consideration. Focal spot is a very important parameter for any imaging system, because having a finite size, there will be a twilight effect on the edges of the object to be visualized, or in practical terms, image blur. A focal spot as small as possible but very bright is desired. The effect of the penumbra or unsharpness is an effect that is accentuated when magnified images are generated, see Fig. 5-b). In this work all the generated images have one magnification, that is, $R_2 = 0$, as the objects are attached to the scintillator.The above methodology is based on [13, 14] references.

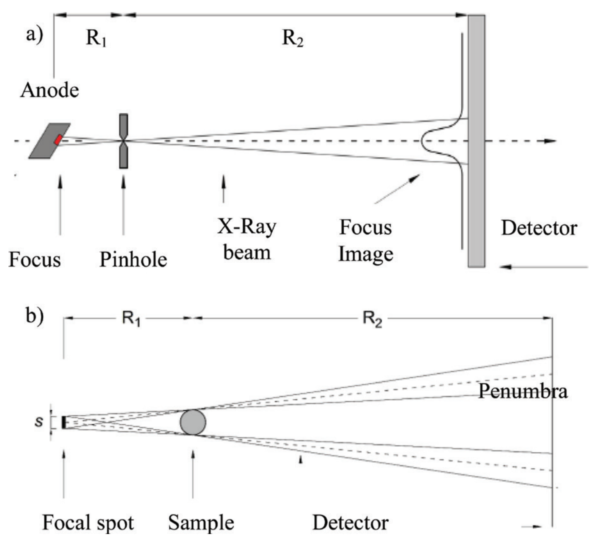


Figure 5: Set Up to know the focal spot size. a) Experimental arrangement using a radiological pinhole, 0.2 mm diameter. b) Scheme of the penumbra effect due to focal spot size.

3. Results and Discussion

Building an X-ray image detector to form a digital radiographic image acquisition system is interesting, it is a project that involves knowledge in physics, materials, instrumentation and data processing. The first practical result of this work is to have a functional system (Fig. 6 and 7) for acquiring digital X-ray images. In Fig. 8 we show radiological images of biological and inert objects validating the goal of building a digital X-ray image detector. Even that the quality of the images from our system is lower respect commercial systems, there are applications in which a high spatial resolution is not required, and with the advantage of having built this system with a budget of approximately 800 USD. Additionally, the system can deliver real-time X-Ray video, limited to 9 seconds which is the maximum continuous operation of our X-ray source; obviously this X-ray source can be replaced by one with better technical characteristics extending our device performance.

3.1 Digital X-ray Detector

The first result is to have a digital X-ray image detector. The detector consists of a plastic box with the Gadox scintillator material placed at one end, and at the opposite side, a lens attached to a CCD sensor. The sample to be displayed is placed in front of the scintillator. This detector can be used with virtually any X-ray source, see Fig. 6.

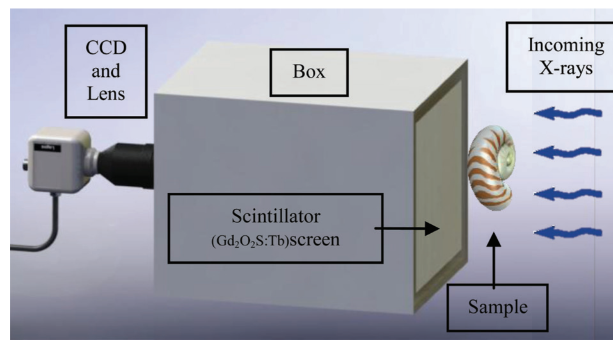


Figure 6: X-ray Detector. Built-in detector scheme and its use. The scintillator is inside the box that is opaque to external visible light.

The arrangement of the complete imaging system is shown in Fig. 7, from right to left the X-ray control unit of the X-ray source, the X-ray source, the sample to be radiographed, the X-ray detector, the optical lens, CCD sensor, frame grabber and computer to storage and display the images. The geometric parameters from Fig. 2 used were $R_1 = 20$cm, $R_2 = 0.1$ cm, $R_3 = 15$ cm and $R_4 = 5$ cm. This is a total optical path length of 45 cm. Using the AmpCap® software, the system can generate images with exposure times (and integration times in CCD sensor) of 0.1 to 9.0 seconds.

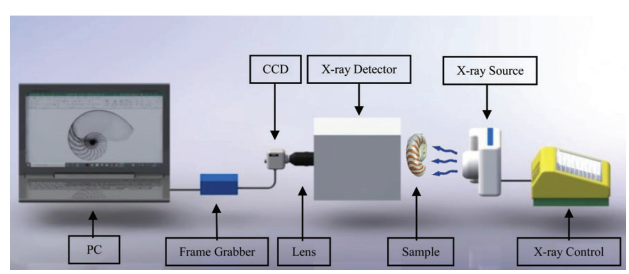
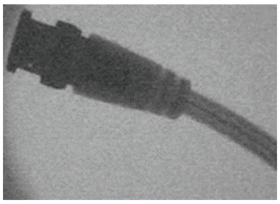


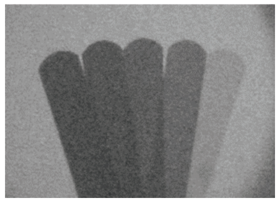
Figure 7: X-ray imaging system. This system is portable, digital, and low cost. The images are generated immediately.

3.2 Acquired Images

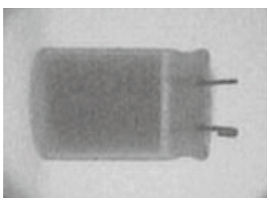
Digital X-ray images of various objects found in our laboratory were generated with an exposure time of 0.2 seconds and the standard operating parameters of the used X-ray source. The obtained images (Fig. 9) are raw with no image digital processing so its quality can be improved. Our detector has a sensitive area of 18cm×18cm, however, the X-ray beam would have to be removed to cover this entire surface, decreasing the intensity of X-rays and generating lower quality images. No dose readings were obtained due to lack of measuring equipment. See Fig. 8.



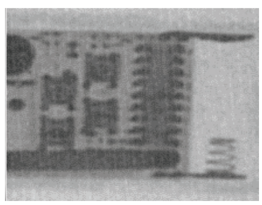
a) **Coaxial cable** Effective view: 57 mm × 41 mm



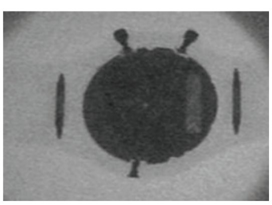
b) **Steel metal plates** Effective view: 69 mm × 50 mm



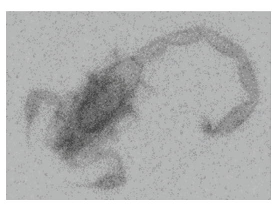
c) **Capacitor** Effective view: 19 mm × 13 mm



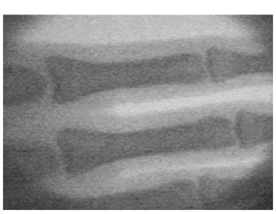
d) **Circuit board** Effective view: 39 mm × 28 mm



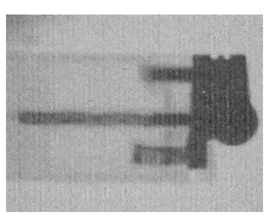
e) **Small watch** Effective view: 44 mm × 32 mm



f) **Scorpion** Effective view: 30 mm × 22 mm



g) **Fingers** Effective view: 75 mm × 52 mm

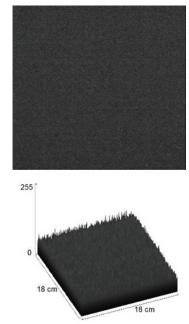


h) **Lighter** Effective view: 48 mm × 35 mm

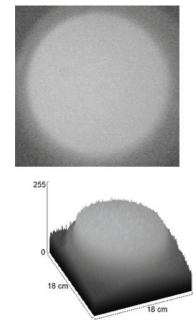
Figure 8: Sample X-ray images. X-ray tube voltage: 60 kV, Geometrical magnification rate: ×1.0.

3.3. Spatial Resolution

This detector is part of a system designed for non-destructive inspection. Our detector makes X-ray imaging as easy as handling an ordinary CCD camera. This detector has a resolution of 1.1 Lp/mm (The resolution limit is 10% of the MTF, see Fig 10-g). The experimental procedure for performing this measurement is shown in Fig.10.



a) **Dark field image** Effective view: 180 mm × 180 mm

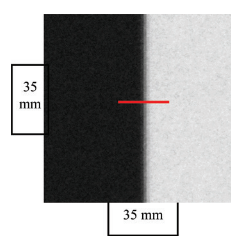


b) **Flat field image** Effective view: 180 mm × 180 mm

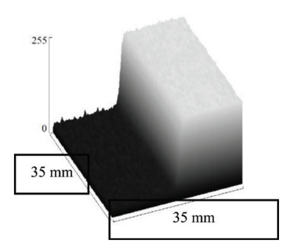
Figure 9: Sample X-ray images. X-ray tube voltage: 60 kV, (*Source* detector distance: 400 mm).

3.4 Focal Spotgeometry

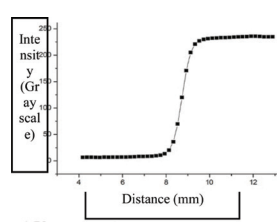
The last result of this work consisted of measuring the focal spot of the X-ray source with the detector constructed, using the experimental arrangement in Fig. 5 a) and the result is shown in Fig. 11-a). After a dark and flat field removal processing, median filtering, and applying a color scale, the images of Fig. 11-b) and 11-c), clearly show the focal spot generated with a pinhole size of 0.9 mm (FWHM). Image processing was performed using ImageJ® software.



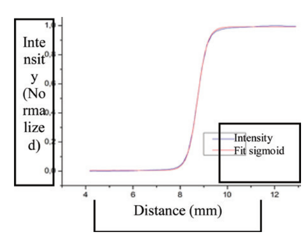
a) **Edge image.** An edge image block extracted from a radiograph of the edge test device. Red line is an intensity profile used.



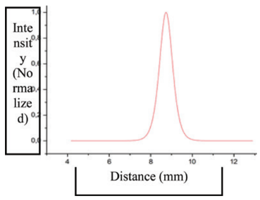
b) **Edge image as surface.** 8-bit grayscale image as surface (256 gray levels). Effective view: 35 mm × 35 mm



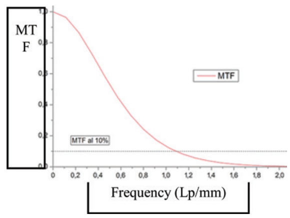
c) **Plot profile.** Graph of plot profile data.



e) **Fit and normalized.** The data is normalized and adjusted to a sigmoid function.



f) Derivative. The adjusted sigmoid function is derived, and the line spread function are obtained (LSF).



g) MTF. The magnitude of the Fourier transform is calculated and normalized to obtain the MTF. The resolution limit is 10% of the MTF.

Figure 10: Spatial resolution. The spatial resolution is in terms of Modulation Transfer Function (MTF), in a) to g) is shown the specific procedure.

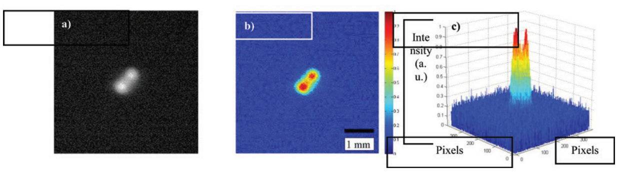


Figure 11: Focal spot geometry. a) Shows the image generated in the detector, b) and c) shows more clearly the focal spot size anf form, its shape is slightly elongated and its dimension is 0.9mm at FWHM.

Conclusions

We have designed, constructed, validated and characterized, a low-cost X-Ray system for digital imaging radiography with general purpose applications where no high resolution is needed. We have obtained digital radiographies of miscellaneous objects to validate the concept of the constructed system. The maximum potential area of the radiographies is 18 by 18 cm with the proper X-ray source and the exposition times can be controlled from 0.1 to 9.0 seconds. The obtained images are digitalized in an 8-bit gray scale of 752×582 pixels with the possibility of generating real time video radiography at 20 FPS.

The characterized resolution was measured using the MTF resulting in 1.1 Lp/mm. With this device we have measured the focal spot of the used source resulting in 0.9 mm (FWHM). Even though this is no high-resolution system, the compensations are a low cost (800 USD aprox.), compact device and as future work we plan to characterize the optimal X-ray dose for the best images and incorporate an rotatory platform to extend the functionality as a small tomography device.

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