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The Color of X-rays. Spectral Computed Tomography Using Energy Sensitive Pixel Detectors
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Summary

> *The retina of the eye is quite insensitive to these rays: the eye placed close to the apparatus sees nothing.*
>
> W. C. Röntgen, 1895.

Professor Röntgen calls these rays “X-rays”, as he says, *for the sake of brevity* and probably to emphasize that, apart from the observation that *bodies behave to the X-rays as turbid media to light*, he knew very little about the nature of this phenomenon. To such an extent that he did not have any trouble in placing his own eyes just in front of what seems to have been a rather powerful radiation source if *Platinum 2 mm thick allows some rays to pass.* Today, we are well aware of the dangers of such an action, and radiation protection teams work hard in order to avoid such occurrences.

Apparently however, professor Röntgen was the first who, unwillingly, attempted to detect X-rays with an energy sensitive pixel detector: the human retina. Of course he could not see anything, because the retina is not at all sensitive to X-rays. The technology required to realize energy sensitive X-ray artificial retinas has become available only 100 years later. These detectors are made by connecting a semiconductor pixel sensor to an energy resolving read-out chip and can be employed to achieve color, i.e. material resolved, X-ray imaging.

The principle of color vision in the retina relies on the presence of three types of “pixels”, the cone receptor cells, each having its sensitivity peak at a different wavelength. The incoming light spectrum is filtered by each receptor and the image is decomposed onto a basis of three colors (red, green and blue, see figure 1a).

Following a different concept, spectroscopic pixel readout chips for semiconductor X-ray detectors are able to separate an incoming radiation spectrum into multiple energy channels, at the level of single pixels. Compared to the retina principle, where three images in different color channels are obtained at the expense of spatial resolution (one out of three receptors are used to form each image), energy sensitive X-ray imaging devices allow for the formation of multiple simultaneous images with no resolution loss (figure 1b).

We are able to see more "colors" in X-rays than in visible light. The question that remains open is: what is color for X-rays?

In a similar way as different types of surfaces exhibit different reflection properties of visible light, different materials are characterized by different X-ray transmission properties. The X-ray spectrum reaching the detector pixel thus bears information on the material traversed by the radiation along its path from the source to the pixel.

Until recently, this information was completely lost, because X-ray detectors were only able to measure one integral value, be it the total deposited energy or, more recently, the total number of photons (the beam intensity). On the contrary, spectroscopic X-ray detectors give the possibility to measure the full energy spectrum, even if just coarsely binned, at single pixel level, which provides a handle to extract more significant knowledge on the material content of the sample than the one encoded in a simple grayscale radiograph.

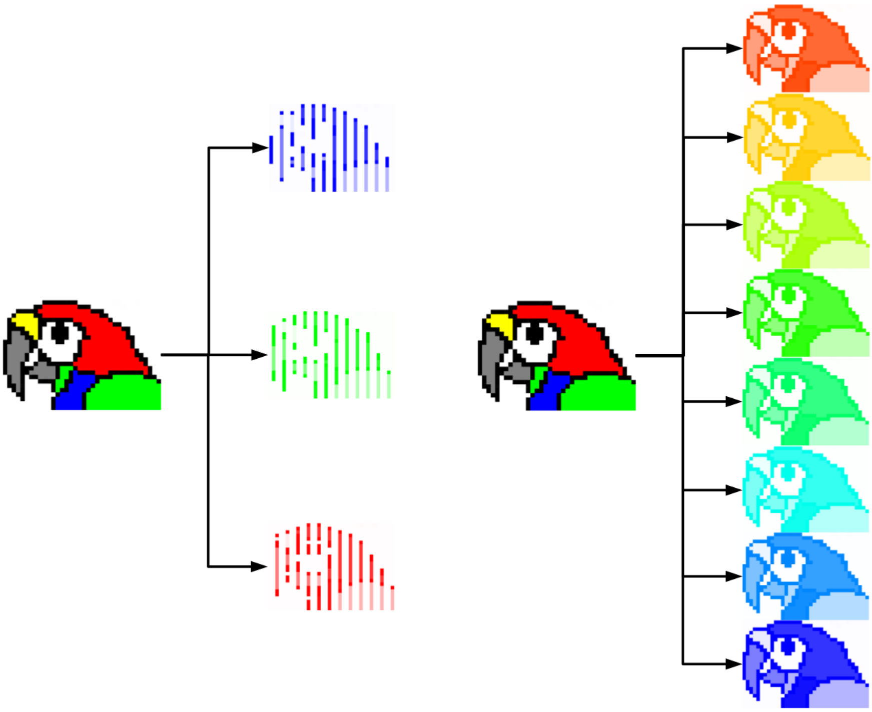
Spectral information can be used to identify different materials and their distribution in the sample. If different colors are assigned to each material, color X-ray imaging is achieved.

The set of 3D X-ray imaging techniques exploiting energy information is called spectral Computed Tomography (CT). Spectral CT is a relatively new field, due to the fact that energy sensitive X-ray imaging detectors only appeared recently.

The main challenge in spectral CT is to answer the following question:

> What is the best way to process spectral information from a set of two-dimensional radiographs and realize color (i.e. material resolved) X-ray three-dimensional imaging?

The aim of this thesis has been to answer this question for a specific set of detectors, i.e. silicon sensors connected to the spectroscopic readout chips of the Medipix family. The work needed to reach this goal not only involves the



(a) **Human retina.** (b) **Medipix3 spectroscopic mode.**

Figure 1: **Image decomposition into color bases.**

implementation of dedicated image reconstruction algorithms capable of handling the spectral information measured by these detectors, but it also requires a precise characterization of the properties of the silicon sensor. This knowledge is necessary in order to implement the detector response in the reconstruction phase.

In the first place, a calibration method is developed, needed in order to define the detector energy scale. As monochromatic reference sources, the method exploits fluorescence X-ray radiation emitted from elements that are excited by the primary beam of an X-ray tube. A fitting procedure is designed to achieve an efficient calibration of single pixels, which is crucial to correct for variations due to inter-pixel mismatches and to reach an equal response of the full detector.

To understand how an incoming X-ray spectrum is distorted due to detector effects, the energy response function of the sensor has to be known. The strategy adopted in this thesis is to reach this result with a fully measurement based approach, in order to avoid biasing errors from the introduction of physics constants and to avoid the need to calculate the electric field configuration, which would require the precise knowledge of the doping profile of the sensor.

The measurement of the detector response function has been performed through a test beam with relativistic charged particles and a synchrotron test beam. Charged particles are used to study the transport properties of the sensor. Exploiting the energy information provided by the pixel readout, the energy deposition as a function of different positions in the pixel volume is determined. This information is used to extract the evolution of the charge profile as a function of the drift distance. The particle beam is thus used as a micro-probe to look at charge diffusion at microscopic level.

This information is exploited to implement a numerical framework for the calculation of the detector energy response function. The synchrotron test beam is needed to determine the values of the parameters of this model by comparing the calculations with measurements. Using monochromatic synchrotron radiation at different energies, the energy response function of the detector is measured directly over a wide spectral range.

The energy response function is used to calculate the detected spectrum, given an input spectrum coming from the transmission of an X-ray beam through an object. This step is crucial for the implementation of a spectral CT reconstruction algorithm suited for data taken with Medipix based silicon detectors.

As a proof of principle, an algorithm is derived by extending a conventional iterative method in order to incorporate spectral information. The algorithm, as formulated at this stage, is only applicable to a limited subset of sample geometries. Nonetheless, the results not only show an example of material resolved X-ray CT, but they also show the benefits arising from spectral CT with respect to conventional CT. The quality of the reconstruction improves as beam hardening artifacts are eliminated, which typically appear if spectral information is not accounted for.

To obtain a more efficient implementation, a statistical reconstruction algorithm is developed, based on a maximum likelihood principle. First results on simulated data show the validity of the method and hint at the necessity to further develop this research line in order to exploit the full potential of the Medipix chip (and similar technologies) in X-ray imaging applications. The algorithm is implemented using tools developed for the statistical treatment of large amount of data from high energy physics, thus giving a demonstration of how fundamental research can be exported to applications in other fields.

Although the results are derived only for a very specific type of detector operated in a specific state (a 300 μm silicon sensor read out by a Medipix chip and operated at 100 V bias) these devices, at these operating conditions, are standard for the majority of the applications. The results, and especially the methods, have thus a more general validity. First applications in several fields, including medical, are not far away. The general belief is that once fully understood and established, spectral CT will surely have a considerable impact in the field of X-ray imaging.

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30 November 2014