Construction and Operation of the MARS-CT Scanner

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Abstract

The aim of this project is to build a spectroscopic CT scanner capable of taking multiple energy CT images of small animal and pathology specimens. The current prototype scanner uses a conventional x-ray tube and a Medipix2 x-ray detector (developed by the European Organisation for Nuclear Research - CERN) that is capable of photon counting and energy discrimination. The scanner is referred to as the Medipix All Resolution System-CT (MARS-CT). We designed and constructed the gantry and control electronics so that the detector and x-ray tube could be rotated around an object of up to 100 mm diameter. Software was written to control the scanner and reconstruct the spectroscopic projection data into a 3D volume, using cone beam filtered back projection. The scanner successfully takes 3D images at 43 µm resolution. The use is able to define the energy ranges known as energy bins. The scanner's stability, accuracy and image quality was proven and tested. We successfully scanned a range of small objects including mice.

1 Introduction

Interest in dual energy computed tomography (Dual energy CT, or DECT) has grown in recent years following the development of commercial systems for clinical use. These systems work by having either two x-ray tubes or a single x-ray tube operated at two voltages. The aim of our work was to construct an x-ray CT scanner capable of acquiring a 3D dataset in multiple energy bins. It provides spatial and energy resolution at the same time so is referred to as Medipix All Resolution System CT (MARS-CT).

Spectroscopic x-ray detectors such as CERN's Medipix detectors offer the possibility of energy-selective biomedical x-ray imaging. The MARS-CT scanner is part of a new generation of CT scanners using this new type of x-ray detector. These count individual x-ray photons within specified energy windows. This allows for CT images of objects to be obtained with spectral information [1]. The current prototype scanner, MARS-CT, is being operated and tested at the Bioengineering Laboratory in the Department of Radiology at Christchurch Hospital. Groups within the Medipix collaboration as well as suppliers of medical x-ray systems are working on reconstructing the material composition from radiographs [2].

2 Scanner Components and Operation

The MARS-CT system is a desktop x-ray CT scanner consisting of a micro focus x-ray tube aligned with an x-ray detector. This is placed in a rotating gantry controlled by a motor system. It enables us to image small (up to 100 mm diameter and 200 mm length) animals and biological samples. The scanner was designed to take full advantage of the high spatial and energy resolution that Medipix2 offers (55 µm square pixels). Energy resolution is limited by the detector material and low energy charge-sharing effects.

The scanner was built to prove both the detector's abilities and the scanner design; it had to be safe, robust, architecturally flexible, transportable and affordable. Figures 1, 2, 5 and 7 show a MARS-CT scanner design, a photograph of the completed MARS-CT gantry, the MARS-CT scanner and a top view of the loaded specimen, respectively.

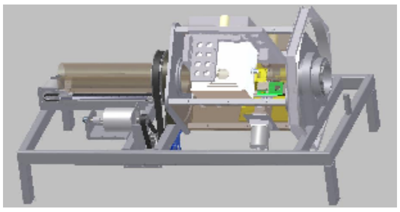

Figure 1: MARS-CT scanner design

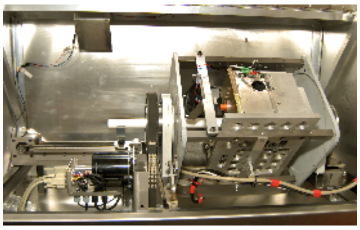

Figure 2: Completed MARS-CT gantry

2.1 Medipix2 Detector and the Detection Principle of x-rays

Advances in CMOS technology have opened up new possibilities in particle detection and imaging. In recent years, particle physics experiments have been transformed by the introduction of application-specific integrated circuits (ASIC) particularly for tracking detectors. Pixel detectors have become key components in tracking systems, especially in high multiplicity environments where excellent spatial resolution is combined with extremely high signal to noise ratios. This allows physicists to find evidence of rare particle tracks in very complicated events [3]. The Medipix2 chip demonstrated that the photon counting approach provides images with excellent dynamic range which are practically free of non-photonic noise [4, 5]. Figure 3 shows a schematic diagram of the Medipix2 detector..

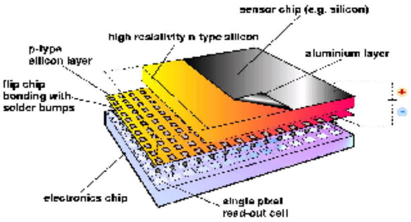

Figure 3: Schematic diagram of Medipix2

An incident x-ray photon generates a cloud of electron-hole pairs in the semiconductor sensor layer of the detector. These charge pairs are measured by the underlying ASIC layer. The electronics of each pixel counts the photons incident on the sensor, but can also be set to only count photons that fall within a certain energy range. Each Medipix2 pixel is 55 μm^2, giving a spatial resolution comparable to mammographic film; the film with the smallest grain size in regular use in medical imaging. Each Medipix2 pixel acts as an individual spectral detector. The logic circuits for each pixel (approximately 1300 transistors) can analyse incoming events at near megahertz rates, comparing the charge of the electron-hole cloud with preset levels. This results in a resolution of about 2keV across the range of 8 – 140keV.

In summary, the Medipix2 detector is a hybrid ionising particle detector designed to provide energy selective images at high spatial and temporal resolutions. These position sensitive detectors have been successfully used in spectroscopic radiation measurements [4]. One of the main tasks performed in the MARS-CT project was the creation of a THL equalisation mask for the detector. Threshold equalisation is a procedure which exploits 3-bits (4-bits for the Timepix chip) THL/THH adjustment to make the overall threshold as homogenous as possible. It finds the distribution of thresholds for each adjustment value, and selects an adjustment for each pixel. This ensures that its threshold is as close as possible to the average of means of the threshold distributions.

The Medipix2 chip (Figure 4) consists of 256 x 256 identical elements (resulting in a detection area of 1.98 cm^2, which represents 87% of the entire chip area). Each works in single photon counting mode for positive or negative input charge signals. In Medipix3, a future version, each group of four pixels will be capable of simultaneously reading eight energy windows allowing for true spectroscopic CT without multiple x-ray exposures. In addition, Medipix3 will have significantly improved energy resolution.

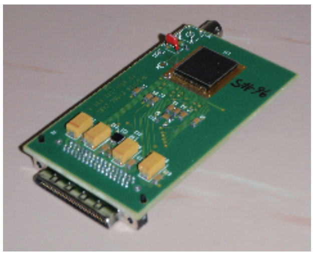

Figure 4: Medipix2 detector

2.2 MUROS Readout System

The Medipix2 re-Usable Readout System, version 2, (Muros2) board is an interface between a board carrying a maximum of four Medipix2 chips and a National Instruments DIO-653X board. The Muros2 has been developed at the National Institute for Nuclear Physics and High Energy Physics (NIKHEF) as a successor to the Muros1 board, (designed for Medipix1) [5]. The Muros2 board supports serial communication with the Medipix2 chip.

2.3 Gantry and Housing

The scanner is built around a stable steel frame made of 50 x 25 mm^2 welded box-section steel. This is designed to keep any twisting or vibration to a minimum. The scanner gantry is constructed from two solid steel endplates attached to each other by four steel rods to form a strong and rigid rotating unit. The endplates rotate on large diameter bearings, leaving a 106 mm hole for sample tubes to pass through. This gives a maximum sample size of 100 mm. One side of the gantry is formed by a solid steel base plate, which provides support for the x-ray tube and the detector. All sides are covered by stainless steel panels, one of which has a primary 3 mm lead barrier for radiation shielding.

The scanner is housed in a lead shielded box (Figure 5) which consists of 1.8 mm lead sandwiched between 0.5 mm aluminium and 0.5 mm stainless steel. The box has interlocked access on sample doors, and shielded ports for cable entry and ventilation. A warning light on the scanner box is illuminated when x-rays are being produced. There is no measurable radiation outside the box. Cables going to the rotating gantry are arranged to accommodate a half twist as they leave the scanner through a port in line with the centre of rotation.

The micro focus tube and high voltage generator are assembled on one side of the gantry. The x-ray tube is also attached to the base plate and can be moved in or out to give the most efficient position ensuring complete coverage of the sample object. A fan has been mounted to cool the x-ray tube and allow continuous operation at full current. On the opposing side, a Medipix2 detector is positioned. It is mounted on a plate that allows fine angular adjustment to ensure the detector pixels are aligned with the vertical axis. Since the detectors are small (either a single detector chip at 14 x 14 mm^2, or a quad detector assembly at 28 x 28 mm^2) they may need to be translated vertically to create a complete projection radiograph. The mounting plate is connected to a screw drive which accurately translates the detector to each imaging position. The screw drive is supported by the steel base plate and can be translated perpendicular to the access of rotation to accommodate different sample sizes, which range from 25 to 80 mm.

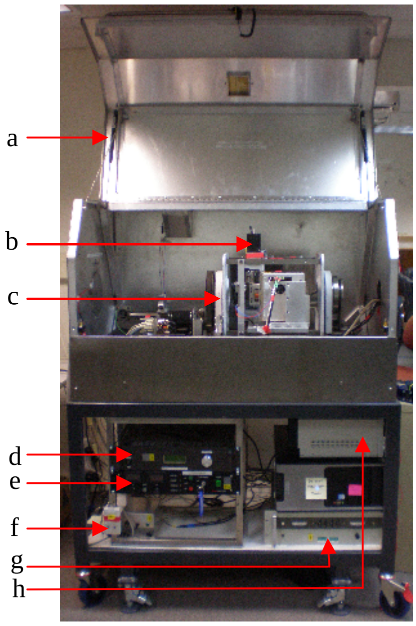

Figure 5: MARS-CT scanner with its main components labelled (a) lead shielded box, (b) stepper motor, (c) gantry, (d) motor controller, (e) x-ray controller, (f) fan switch, (g) power supply and (h) MUROS power

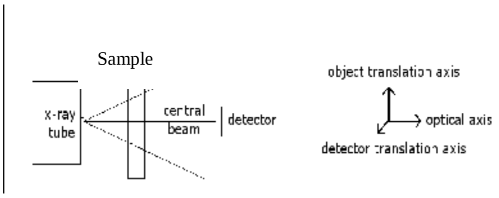

Figure 6: The scanner axes

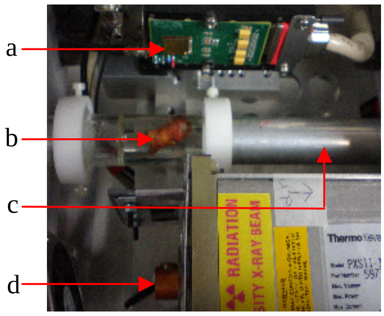

Figure 7: The MARS-CT gantry with its main components labelled (a) Medipix2 detector, (b) sample (in this case a human atheroma plaque fixed in Perspex), (c) sample holder and (d) micro focus x-ray tube

2.4 X-ray tube

A Thermo Scientific Kevex PXS11-150-75 is the x-ray source for the MARS-CT scanner. It is a portable x-ray source with 75 kV and 11.25 W. It has constant potential and mini-focus for use in high resolution radiography and real time imaging applications. The 40 µm spot size delivers high resolution direct x-ray magnified images over the entire range of operation. In spite of its high performance, the Kevex PXS11 uses a filament cathode, thereby eliminating the need for bias or focus supplies which are necessary for dispenser cathode type x-ray tubes.

The Kevex PXS11 combines the x-ray tube, high voltage power supply and control circuitry in one compact package that is powered from a 28 VDC source. The specifications of this micro focus x-ray tube include: a 8.9 mm Focus-to-Object Distance (FOD) which enables high magnification; a high flux output of 70 R/min at 11.25 W; an operating voltage range of 40–75 kV ± 1%, which enables use with a wide range of materials; an integrated source-tube power supply and control circuitry; an internal cooling fan. The x-ray tube weight is approximately 4 kg.

2.5 Operation of the MARS-CT scanner usingMedipix2

The operation of the x-ray tube, the stepper motors and the Medipix2 detector is controlled by Matlab on a dedicated PC. Serial interfaces are used for the x-ray tube and stepper motors. The Medipix2 detector is read using Pixelman software [6] via a custom designed Pixelman-Matlab interface. The user defines a number of parameters before scanning. These include the number of rotational steps, the number of sensor positions (to enlarge the field of view), the threshold settings and corresponding acquisition times. In order to simplify cable management on the gantry, the scanner is designed to complete one revolution and then return to the starting position.

The detector and x-ray source are mounted on the gantry with the sample between. An image is taken called a frame and then gantry rotated, rotating the detector and source around the sample. At the next stop the next projection frame is taken. This process is repeated around the entire sample. The number of stops and therefore projection frames taken is determined by the user. For larger samples the detector can be moved linearly up and/or down and the process repeated. This creates more than one frame at each rotation stop. The frames are stitched together to form the projection images. The linear movement of the detector allows larger samples to be imaged. A small overlap of a few pixels maintained in the movement to help check alignment and to ensure consistent exposures. All scanner control and image triggering is performed via Matlab routines. Table 1 shows an example of typical scan parameters for four energy bins.

Table 1: Scan parameters for mouse with four energy bins

THH	1023	1023	1023	1023
THL	714	680	577	520
Energy (keV)	12	17	33	42
Time (s)	0.3	0.3	1.5	3.0

3 Image Recovery, Processing and Visualisation

Images obtained from the multi-energy MARS-CT scanner were processed by being back projected in to a 3D volume data set using Octopus version 8.2 [7]. Octopus is a commercial tomography reconstruction software for cone beam CT, spiral CT, or parallel beam CT. The Feldkamp, Davis and Kress [8] cone-beam computed tomography (CBCT) FDK algorithm was used to reconstruct the images. The software allows the user to change a number of settings concerning the pre-processing and filtering. Pre-processing steps are included in the package such as ring filtering, normalisation, beam hardening correction and axis tilt correction.

In addition, the CBCT reconstruction algorithm was also implemented in Matlab to reconstruct images from the projections. The T-FDK approach was chosen, which includes two steps of rebinning the projection data and performing a filtered backprojection. Additional pre-processing of the raw projection data was required due to the special scanner geometry. The point source emits a cone shaped beam, which is detected by the two-dimensional Medipix detector. The detector rotates simultaneously around the centre of rotation, which ideally is in the centre of the object.

The projections $P_{\alpha}(\gamma, \Phi)$ obtained with a cone beam can be characterised by the rotation angle α, the fan-angle γ and the cone angle Φ. In this work, two steps of rebinning were used. In the first step, $P_{\alpha}(\gamma, \Phi)$ is converted into $P_{\beta}(\mu, \Phi)$. This is called row-wise rebinning, where one row at a time is taken. This implies a fixed value of the cone angle Φ. This row represents fan-beam geometry and can therefore be converted into parallel-beam geometry. Each set of rotation angle, α, and fan angle, γ, is converted into the corresponding pair of rotation angle β and distance μ of parallel-beam data.

The 3D reconstructed images can be used for visualisation purposes to produce a more comprehensive model of the object. A research program for volumetric visualisation, called MARSExplorer, is being developed for the interactive exploration of the spectroscopic data as volumetric objects. This will allow for better diagnosis and interpretation of medical and biological data. MARSExplorer provides multiple views to allow for comparison of energy bins side by side or multiple views of the same energy bin. Each view can combine energy bins with simple techniques including finding the average, difference, and maximum and minimum voxels between two energy bins. Also, three energy bins can be assigned to the three primary colours to directly compare brightness levels of the voxels and contrast the differences with the resulting colour (colour combination mode).

MARSExplorer provides a basic set of volumetric tools for navigating through the energy bins. These tools include slicing the volume, controlling the transparency and thresholding the luminance range. The tools are mapped to slider bars to allow for fast and interactive control over the volume. The algorithm for direct volumetric rendering is based on the volume rendering integral. Furthermore, a Maximum Intensity Projection algorithm and an iso-surface algorithm are integrated into MARSExplorer. Also included is a volumetric PACS viewer, which allows the direct view of any slice of the energy bin in any orientation.

The performance of MARSExplorer is dependent on the hardware of the desktop PC. With a PC containing a GEForce 8800 GT graphics card with 512Mb video RAM, up to 1800 slices of 512 x 512 pixels (16 bit, tiff images) can be stored on the graphics card. The frame rate peaks at 60fps depending on the number of iterations chosen, for the volume rendering integral. The standard settings for direct volume rendering with four views results are 30 fps.

The tools for navigating through the volumes include slicing, transparency, threshold and iteration controls as well as pan, rotate and scale tools. Most of these tools are currently mapped to the keyboard, but widgets are being developed so that the program interface is more interactive, for example the slider bars which control the slicing. While artefacts are still visible the volume is clear. Continual improvements are being made to the programme moving it from its basic form to incorporate more complex rendering algorithms. An additional program called osgMARSImage was created to remove air material from the CT slices. The 3D visualizations are accurate representations of the scanned objects.

4 Results and Discussion

To date several objects have been scanned. These include test phantoms and mice. We were able to successfully obtain multi-energy CT images with a spatial resolution of 43μm. Example images are shown in Figures 8 and 9. The cross section of a mouse abdomen and volume rendering of a mouse skull and paws, respectively, are shown.

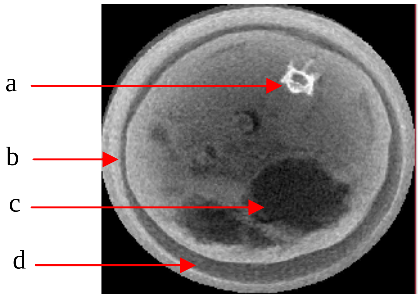

Figure 8: Cross section of a mouse abdomen with its main components labelled (a) spine, (b) support tube, (c) stomach and (d) air

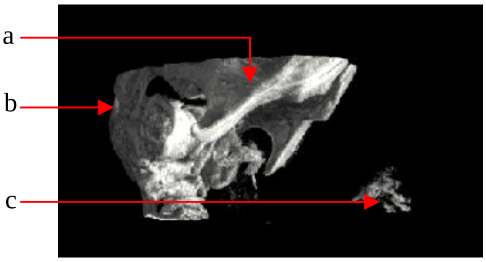

Figure 9: Volume rendering of a mouse with its main components labelled (a) jaw, (b) skull base and (c) paws

5 Conclusions

Combining the broad energy spectrum of an x-ray tube with an energy resolving detector enables us to acquire data in chosen energy bins. This approach is different to that of dual-energy-CT, where two tubes or a modification of the energy spectrum of a single tube is used. Key benefits of MARS-CT over dual-energy systems are the use of a single x-ray tube and projection data with no overlapping energies. These are consequences of the ability of the Medipix family of detectors being able to resolve the energy of each incident photon. The user can specify the energy windows. The energy windows can be optimised for imaging specific materials.

6 Future Work

The MARS-CT scanner is able to provide 3D spectroscopic x-ray images of small animal and pathology specimens. Image processing and display techniques are being developed for best utilising this novel energy information. A variety of clinical applications have been investigated, and further experiments will be carried out using pathology specimens and mouse models of diseases. In particular, we are concentrating on applications in vascular and breast cancer imaging. Work on spectroscopic material reconstruction is ongoing [3]. The anticipated benefits from using spectroscopic pixel detectors for medical imaging include reduction of image artefacts, better contrast imaging and improved soft tissue contrast. Initial work with the Medipix2 detector found that it is reliable and easy to use. MARS-CT is designed to incorporate future versions of Medipix, such as Medipix3 which has better energy resolution and up to eight simultaneous thresholds.

Acknowledgements

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