Course Project

MEDICAL CT SCANNER SYSTEM DESIGN

ME 337: Mechanical Systems Design

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1 Introduction

A Computed Tomography (CT) scanner is an advanced medical imaging device that utilises rotating X-ray sources and detectors to record cross-sectional images of the human body. This project explores the mechanical system design of a medical CT scanner using a structured systems engineering approach inspired by NASA's Systems Engineering Handbook. The project encompasses the entire design process, from the definition of stakeholder requirements to the CAD modelling and animation of the proposed solution.

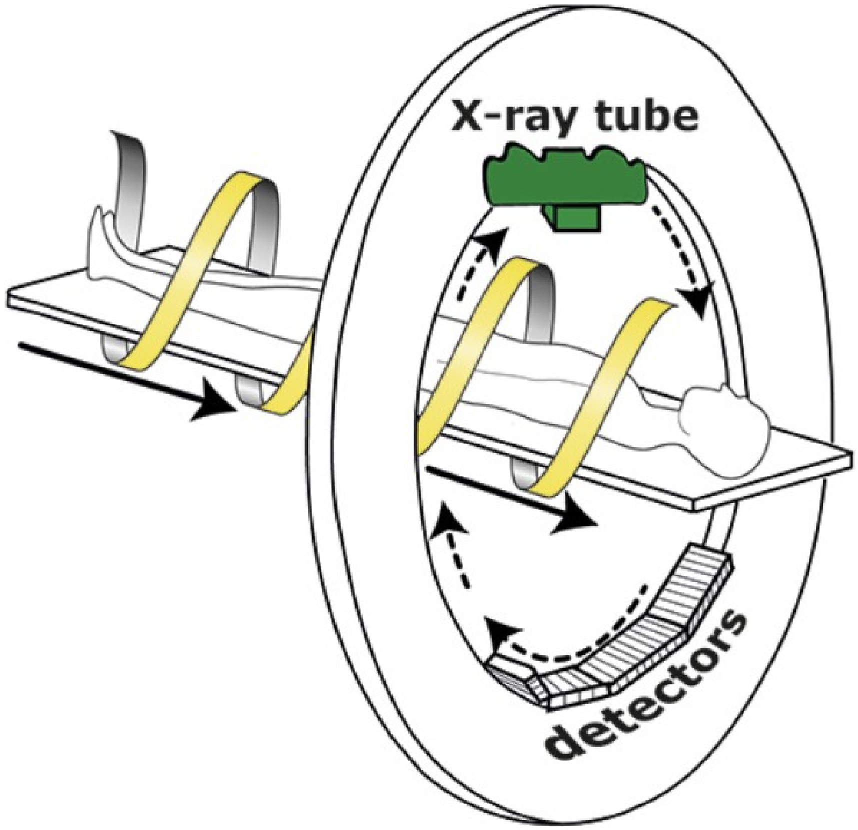


Figure 1: Computed Tomography (CT) Scanner [1]

2 Background and Principles

CT scanners work by rotating an X-ray source and detector around a patient to generate cross-sectional images of internal body structures. The primary components include the gantry, patient table, detectors, and control systems. Designing such a machine requires precision, speed, and ergonomic integration.

2.1 X-ray Projection and Attenuation

In computed tomography (CT), the fundamental process involves measuring the transmission of X-rays through a patient's body from many different angles. This is achieved using a rotating X-ray tube and an array of detectors that capture data from approximately 1000 angles and hundreds of detector rows aligned along the axis of rotation.

The values in a CT image correspond to the average linear attenuation coefficient μ (in m^{-1}) of the tissue in each voxel. The attenuation is governed by Beer's Law:

$$I(x) = I_0 e^{-\mu x} \tag{1}$$

where:

- I_0 is the intensity of the unattenuated X-ray beam,
- $I(x)$ is the intensity after passing through material of thickness x,
- μ is the linear attenuation coefficient, which depends on the tissue's density, composition, and the X-ray photon energy.

For heterogeneous materials, the attenuation is represented by an integral:

$$I(d) = I_0 e^{-\int_0^d \mu(x)\,dx} \tag{2}$$

This attenuation data from various angles is reconstructed into a 2D matrix of pixels, each representing the attenuation of a small volume element (voxel).

2.2 Hounsfield Units

To standardize CT values, the linear attenuation coefficients are converted to Hounsfield Units (HU) using the formula:

$$HU = 1000 \times \frac{\mu_{\text{material}} - \mu_{\text{water}}}{\mu_{\text{water}}} \tag{3}$$

Where:

- μ_{material} is the attenuation coefficient of the tissue,
- μ_{water} is the coefficient for water at room temperature.

This scale sets water at 0 HU and air at -1000 HU. For example, compact bone may have values around +1000 HU, and fat typically shows around -90 HU.

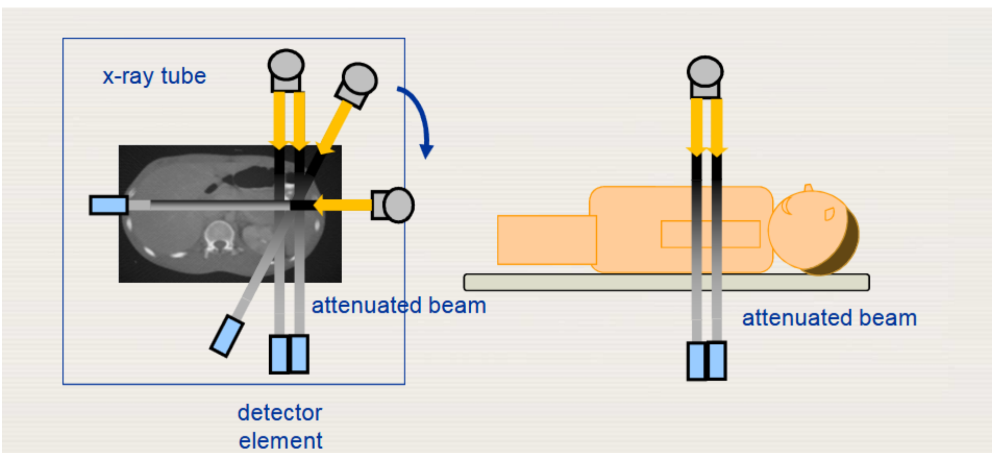


Figure 2: Illustration of X-ray tube, attenuated beams, and detector elements in a CT scanner.

2.3 Display and Calibration

CT images are displayed using a grayscale defined by:

- **Window Level (WL)**: the midpoint HU value shown as mid-gray,
- **Window Width (WW)**: the HU range between black and white.

Clinical accuracy of HU values can be affected by factors like scanner calibration, reconstruction algorithms, field of view, and beam hardening. Over time and between different scanners, HU values can drift, necessitating careful calibration—especially in multicenter studies.

A minimum of 12-bit depth is recommended to represent HU values from −1024 to +3071, while 14-bit depth allows extended ranges up to +15359 HU, which is useful for imaging high-density implants.

3 CT Imaging System

- **Overview and Gantry**
  The gantry houses essential components: X-ray tube, detector arrays, high-voltage generator, collimators, cooling systems, and beam-shaping filters. These are mounted on a rotating platform enabling a full **360° rotation**. Slip rings supply power and enable data transmission via contact brushes or wireless means.

- **Patient Table and Positioning**
  The patient lies on a motorised table that moves longitudinally through the gantry. Scans can be head-first or feet-first, in supine or prone positions. Laser positioning lights ensure precise pre-scan alignment. The table's position is recorded for accurate image reconstruction.

- **X-ray Tube and Beam Shaping**
  The X-ray tube features a rotating **tungsten anode**, operating at **70–140 kv**. It emits either a fan beam or cone beam, shaped by bow-tie filters to ensure uniform intensity and minimise peripheral dose. These filters also reduce beam hardening effects and improve calibration accuracy.

- **Detector System**
  Modern detectors use solid-state scintillators (800–1000 elements per arc, up to 320 rows longitudinally). They convert X-ray photons to visible light, detected by photodiodes, and convert them to electrical signals. Anti-scatter grids and thin septa enhance signal quality by reducing noise and crosstalk.

- **Resolution Enhancements**
  CT spatial resolution depends on detector size, spacing, and angular sampling. Quarter detector shift increases sampling density, while flying focal spot techniques dynamically move the X-ray source to improve resolution. These methods enable resolutions of 0.6–0.9 mm.

- **Multi-Detector Row CT**
  MDCT systems with multiple active detector rows allow simultaneous slice acquisition, improving scan speed and z-axis coverage. Configurations like **4×1 mm**, 16-row, 64-row, and up to 320-row enable single-rotation imaging of entire organs (e.g., brain, heart), yielding high-resolution volumetric data.

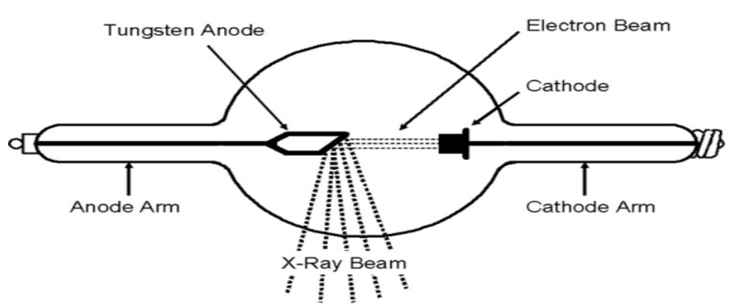


Figure 3: X-ray tube and beam shaping in CT Imaging

4 Image Reconstruction and Processing

- **Basic Principles**
  CT image formation involves collecting X-ray projections from multiple angles, where each projection provides a transmission profile. These profiles are mathematically reconstructed into a two-dimensional image.

The key concept is that the logarithm of the ratio of incident to transmitted intensity, $\ln(I_0/I(d))$, is linearly related to the integrated attenuation coefficient along the path. Simple backprojection, which evenly distributes projections over the image, results in blurred images. Therefore, a more sophisticated approach called *filtered backprojection* is used, which enhances image clarity.

- **Reconstruction Techniques**

  1. Filtered Backprojection (FBP) is the most commonly used method and relies on transforming projection data into Radon space, filtering them, and backprojecting the filtered data to create an image.

  2. Algebraic Reconstruction Techniques (ART) solve a system of equations formed from projection data. While conceptually useful, they are computationally intensive and sensitive to noise—making them impractical for routine clinical use.

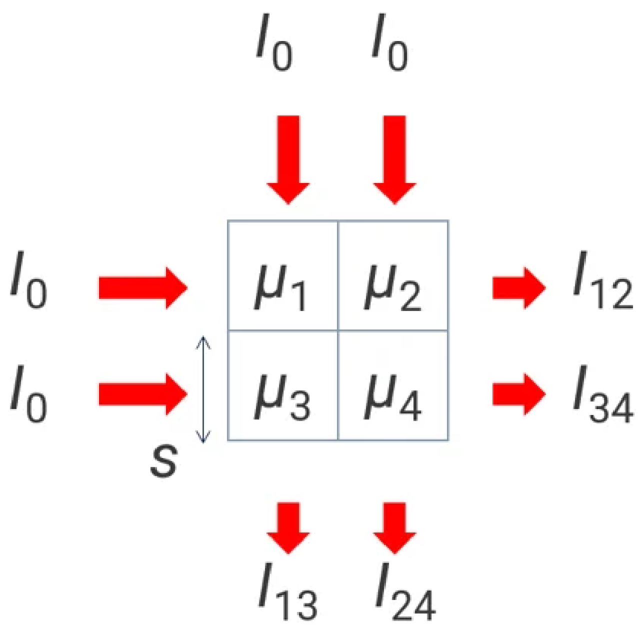


Figure 4: Algebric Reconstruction

  3. Iterative Reconstruction (IR) involves refining an initial estimate by comparing it with measured data. Though computationally demanding, IR is useful for low-dose CT, and can reduce noise and artifacts like streaks.

- **Spatial Domains**

  Three domains are involved in CT reconstruction:

  - **Object Space**: Represents the actual anatomy (attenuation values).
  - **Radon Space (Sinogram)**: Contains projection data from multiple angles.
  - **Fourier Space**: Frequency domain derived via 2D Fourier transforms.

  Using the Central Slice Theorem, the 1D Fourier transform of a projection corresponds to a slice through Fourier space. By combining many such slices, we can reconstruct the full image through inverse transformation.

5 CT Acquisition Methods

- **Scan Projection Radiograph (SPR)**
  SPR captures a low-dose preliminary image to assess anatomy and adjust scan parameters. It also provides input for automatic exposure control by adapting tube current to patient size and attenuation.

- **Axial Scanning (Step-and-Shoot)**
  In axial CT, the patient remains stationary while the X-ray tube completes a 360° rotation. The table then moves incrementally for the next acquisition. This method offers high-quality slices but is time-consuming.

- **Helical (Spiral) Scanning**
  Helical (or spiral) scanning involves the continuous rotation of the X-ray tube combined with steady table movement, resulting in a spiral trajectory of data acquisition. This method enables faster scans, minimizes motion artifacts, and provides continuous volumetric data suitable for 3D reconstructions. A key parameter in helical scanning is the pitch factor, defined as the ratio of table travel per full rotation to the beam width, which influences both image quality and patient dose.

- **Multidetector CT (MDCT)**
  Modern CT systems employ multiple rows of detectors—ranging from 4 to as many as 320—allowing the simultaneous capture of multiple slices. This multidetector CT (MDCT) configuration improves coverage along the body's length (z-axis), enhances temporal resolution, and yields higher image quality.

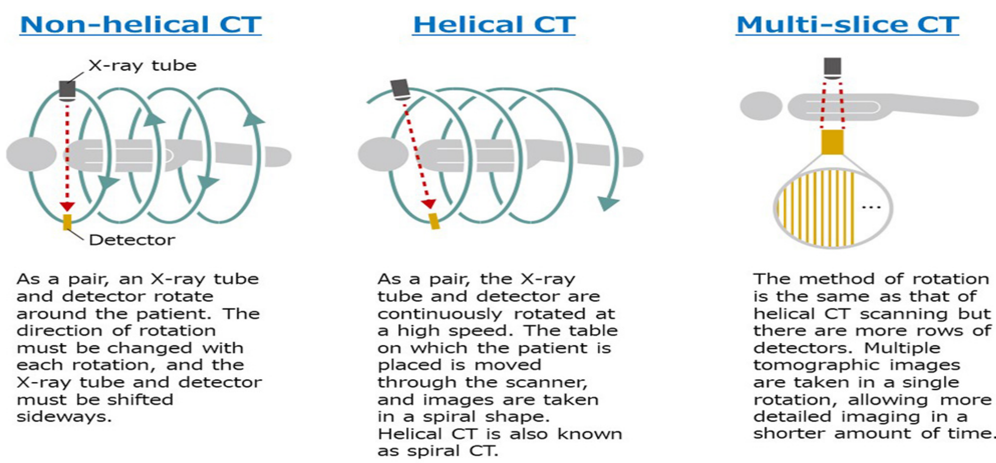


Figure 5: CT Aquisition Methods

6 CT Image Quality

- **Key Image Quality Metrics**
  - Spatial Resolution - defines the ability to distinguish small objects and is quantified by the Point Spread Function (PSF) or Slice Sensitivity Profile (SSP), often measured as Full Width at Half Maximum (FWHM).
  - Low-Contrast Resolution - is assessed using phantoms with subtle differences in HU values. It determines the system's capability to visualize faint structures.
  - Noise and Homogeneity - impact diagnostic accuracy. Uniform regions are evaluated to check consistency in HU values.

  - Temporal Resolution - measures how well motion can be captured. It depends on the rotation time of the gantry and reconstruction algorithms. Cardiac CT often uses half-scan reconstructions or dual-source CT to improve temporal resolution.

- **Clinical Observer Performance**
  Although phantoms help quantify quality, clinical image quality depends on diagnostic tasks. For example, detecting a tumor might require higher contrast resolution than bone imaging.

- **Acquisition and Reconstruction Effects**
  Parameters like tube voltage, current, rotation time, slice thickness, and reconstruction filter significantly affect image quality. Trade-offs often exist between spatial resolution, noise, and scan time.

- **Advanced Image Visualization**
  Advanced image visualization in CT includes several reformatting techniques to enhance diagnostic interpretation. These include multiplanar reformats (MPR) that provide axial, coronal, and sagittal views; 3D rendering techniques such as volume rendering and surface shading; Maximum and Minimum Intensity Projections (MIP/MinIP) to highlight high or low-density structures; and curved planar reformats, commonly used for visualizing structures like coronary arteries.

7 Design Objectives

The primary objective of this project is to design a mechanical system for a CT scanner that balances imaging performance, reliability, and patient comfort. Specific goals include:

- Designing a compact and rigid gantry to support high-speed rotation.
- Integrating an ergonomic and motorized patient handling table.
- Ensuring compatibility with selected X-ray tube and detector systems.
- Facilitating ease of assembly and maintenance.
- Minimizing mechanical vibrations to preserve image quality.

8 Design Methodology

8.1 Conceptual Design

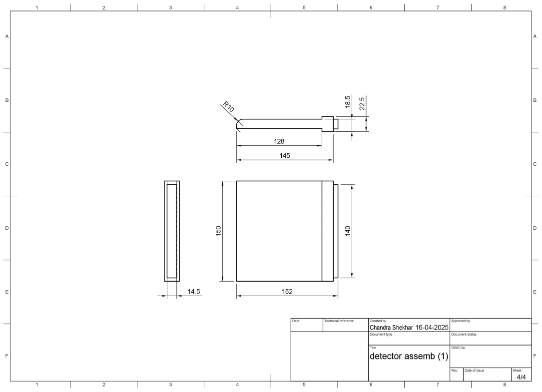
The need for mechanical precision, safety, and integration with electronic imaging subsystems drove the conceptual design. Key conceptual elements included:

- A rotating gantry with internal mounting provisions for X-ray tube and detector.
- A slip ring mechanism to support continuous data and power transmission.
- A telescopic patient table with linear actuators for smooth motion control.
- Modular subassemblies for ease of transport and maintenance.

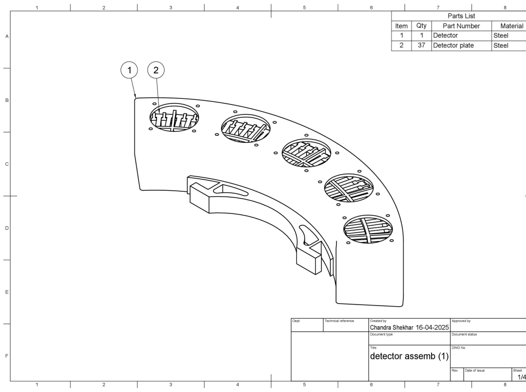
8.2 Component Selection and Calculations

X-ray Tube: Philips 800 MRC

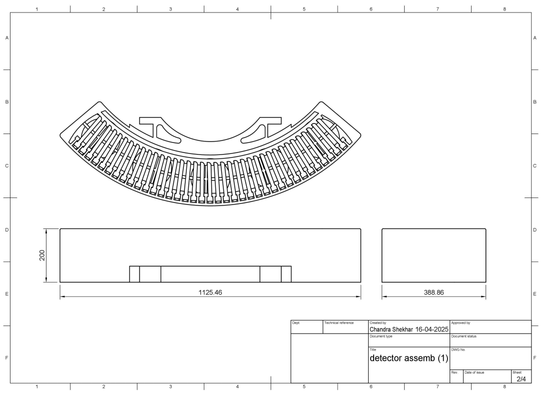
- **Power Output:** 80 kW
- **Focal Spot Size:** Small (0.7 mm), Large (1.2 mm) – suitable for high-resolution imaging
- **Cooling Method:** Liquid-cooled – ideal for sustained use in clinical settings



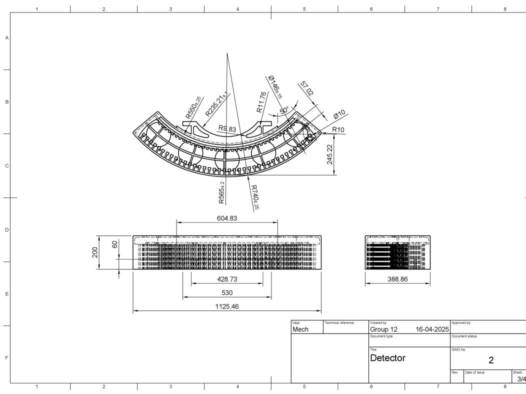
(a) Detector



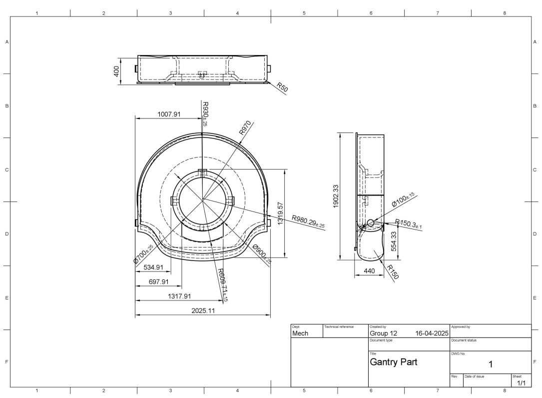
(b) Detector



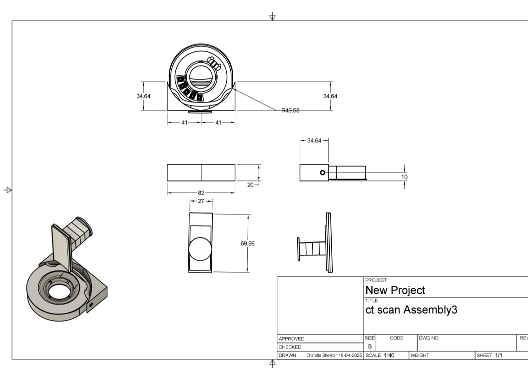
(c) Detector



(d) Detector



(a) Gantry



(b) CT Scanner Assembly

Figure 7: Overview of CT Scanner Components and Visualization Techniques

- **Reason for Selection:** Offers high image quality, reliability under continuous scanning, and integration compatibility with commercial CT setups.

Siemens *straton* X-ray tube	**GE Performix VCT Z-ray tube**	**Philips 800 MRC X-Ray Tube**
voltage range : 80–140 kVp **power output :** 50–120 kW	**voltage range :** 80–140 kVp **power output :** 40–100 kW	**voltage range :** 80–140 kVp **power output :** 30–90 kW
Focal spot : 0.7 mm	**Focal spot :** 0.6 mm High heat capacity (8 MHU) – long duration	**Focal spot :** 0.5 mm Dual-energy scanning for better tissue contrast

Detector: Philips NanoPanel Prism

- **Pixel Size:** 0.5 mm × 0.5 mm
- **Data Acquisition Rate:** High-speed – supports multi-slice imaging
- **Noise Performance:** Low electronic noise – enhances contrast resolution
- **Reason for Selection:** Ensures high-resolution image acquisition with real-time capability. Compact footprint fits well within gantry constraints.

Specification	**GE Healthcare - Gemstone Detector**	**Siemens Healthineers - Stellar Detector**	**Philips Healthcare - NanoPanel Prism Detector**
Material	Garnet-based scintillator (GOS)	Integrated photodiode & scintillator	Yttrium-based scintillators
Applications	High-definition, spectral CT	Low-dose imaging, high spatial resolution	Spectral and conventional CT imaging
Key Features	High temporal resolution, fast response times	Reduced electronic noise, enhanced signal quality	High-efficiency, multi-energy imaging
Quantum Detection Efficiency (QDE)	High	High	Very High
Noise Performance	Low noise levels	Low noise due to reduced electronic interference	Low noise, improved signal-to-noise ratio
Dynamic Range	Wide	Wide	Very Wide
Temporal Resolution	High	Moderate to High	High
Typical Use Case	Spectral imaging, Cardiac Imaging	Low-dose imaging, General Purpose Imaging	Multi-energy Imaging, High-resolution Imaging

8.3 CAD Modeling

The entire system was modeled using SolidWorks. CAD models include:

- The full gantry assembly with mounts for tube and detector.
- Rotational bearing supports with motor coupling.
- The patient table with actuator and linear guide integration.

- Casing and support frame to enclose and stabilize the scanner.

The CT scanner system was designed using CAD tools, focusing on modular components such as the bed, detector assembly, gantry, and complete scan assembly. Below are concise descriptions of each component and relevant modelling details.

CT Scanner Bed

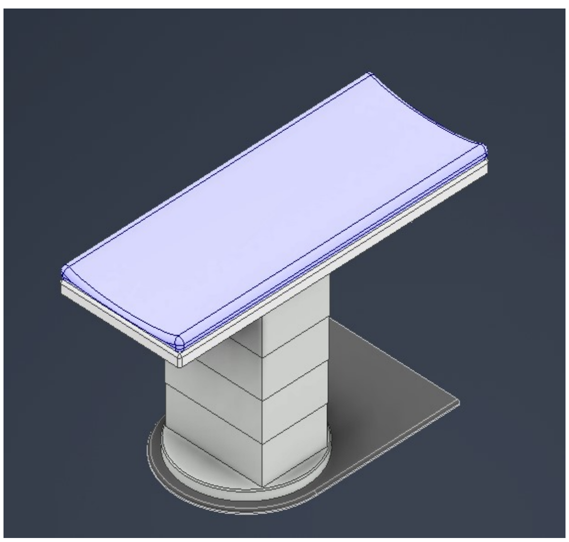
The bed supports and positions the patient during the scan. It features a rectangular structure with inclined surfaces and rounded corners. Key modelling operations include:

- **Extrusion** of the main base profile.
- **Fillet** operations for edge rounding.
- **Cut features** for surface shaping and support clearance.

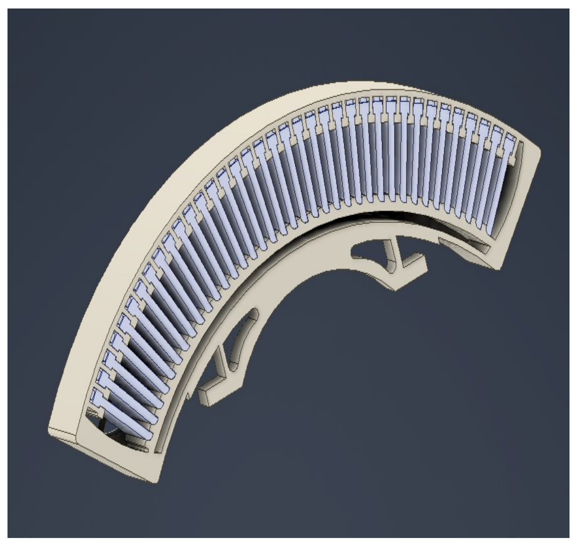
Detector Assembly

This comprises a central detector body and an array of 37 steel detector plates. Precision is critical due to sensor alignment. Modelling steps include:

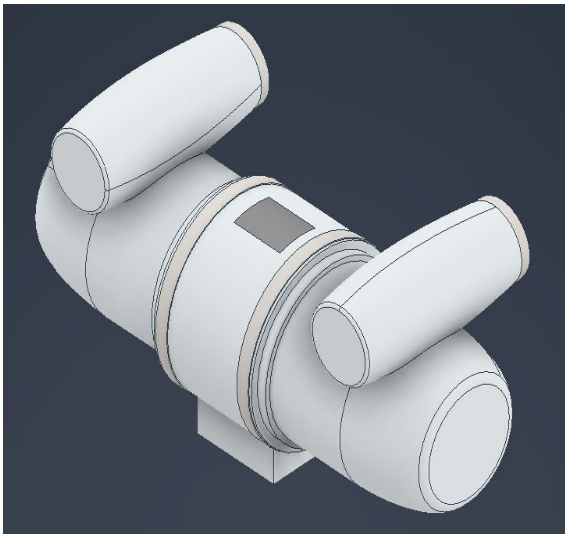
- **Patterning** of plates using linear arrays.
- **Radial and circular features** using revolve and sketch tools.
- **Cut-extrude and hole features** for mounting and wiring paths.



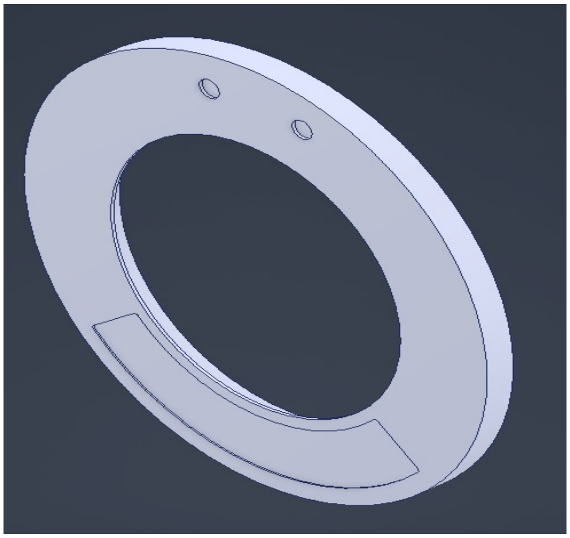
(a) Patient Table



(b) Detector



(a) X-Ray Tube



(b) Gantry Plate

Figure 9: CT Scanner Components

CT Scan Assembly

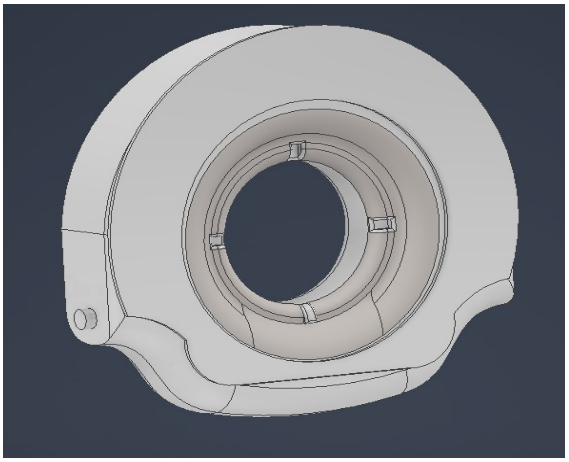
This is the overall layout integrating all major parts. It is created in an assembly workspace with precise positioning:

- **Assembly constraints** and **mates** to align bed, gantry, and detector.
- Use of **reference planes and axes** for spatial organization.

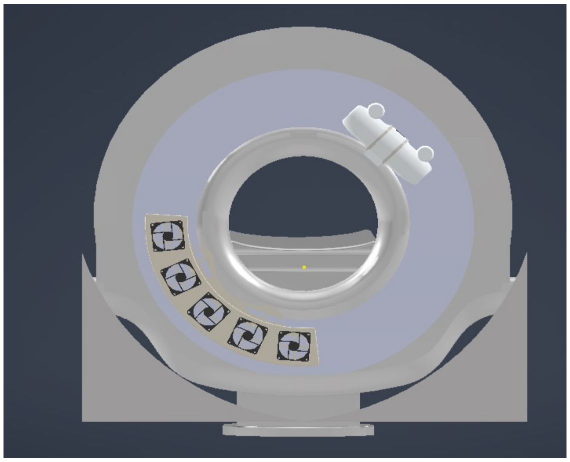
Gantry

The gantry holds the rotating X-ray source and detectors. It is a large, circular frame with complex curves and multiple radii. CAD features include:

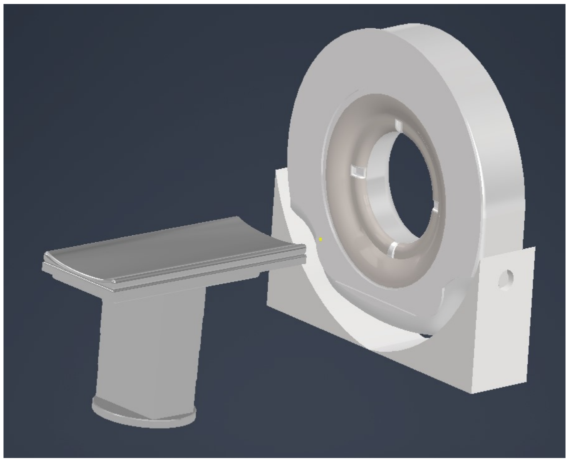
- **Revolve** to form the main ring structure.
- **Fillets** and **cut-outs** for component fitting.
- **Circular patterns** for symmetric hole placement.



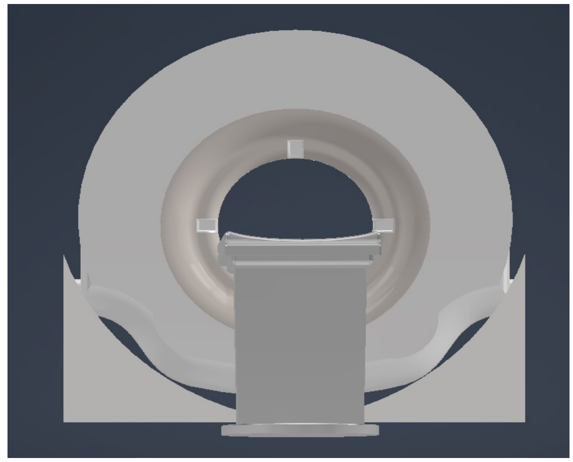
(a) Gantry



(b) cT Scanner



(a) Assembly Side View



(b) Assembly Front View

Figure 11: CT Scanner Assembly Views

9 Results

The designed CT scanner integrates key components to achieve high-performance imaging. The gantry supports high-speed rotation, while the motorized table ensures patient comfort and precise positioning. Components like the Philips 800 MRC X-ray tube and NanoPanel Prism detector provide compatibility and high-resolution imaging. CAD models enable modular assembly, and preliminary testing with phantoms confirms compliance with safety and quality standards.

10 Performance Evaluation from Literature

SE Phase	**Phase Requirements**	**Accomplishment for Medical CT Scanner**
Pre-Phase A	Identify feasibility, define mission needs, and analyse technology gaps	Analyze clinical imaging requirements, assess patient safety standards, review existing CT technologies, and identify gaps in resolution, speed, and radiation dose control
Phase A	Define mission objectives, perform trade studies, and identify critical technologies	Define key performance metrics (e.g., spatial resolution, scan speed), perform cost vs. performance trade-offs, and identify technologies such as detectors, X-ray tubes, etc.
Phase B	Develop system requirements, conduct preliminary design, and test key subsystems	Develop subsystem specifications (e.g., gantry speed, image processing algorithms), perform risk assessments, and prototype image reconstruction modules and detector arrays
Phase C	Complete detailed design, fabricate system components, and validate subsystem performance	Design and manufacture components (e.g., rotating gantry, slip ring, detector system), and validate via phantom scans and subsystem testing

SE Phase	Phase Requirements	Accomplishment for Medical CT Scanner
Phase D	Integrate system components, conduct full-scale system testing, and validate against requirements	Assemble complete CT scanner, perform system-level testing with human-equivalent phantoms, validate image quality and safety compliance
Phase E	Maintain system operations, monitor performance, and ensure longevity	Deploy in clinical setting, monitor for image quality degradation, update software, conduct regular maintenance and calibration routines
Phase F	Decommission system, analyze mission data and document lessons learned	Retire systems as per end-of-life protocols, archive patient and system data as per regulations, and document operational insights for future system improvements

11 Challenges Faced

- Achieving a compact gantry design while maintaining structural integrity.
- Managing thermal dissipation from the X-ray tube without compromising design compactness.
- Ensuring alignment between the tube and detector during rotation.
- Limited commercial data on exact load ratings for some custom parts, requiring assumptions and iterative calculations.
- Animation constraints due to software limitations in simulating dynamic mechanical systems.

12 Conclusion

The CT scanner design demonstrates robust integration of mechanical and imaging systems, enabling efficient, high-quality scans. Challenges in alignment, thermal management, and compactness were addressed effectively. Further validation in clinical settings is recommended to optimize performance and reliability.

13 References

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