Industrial X-ray Computed Tomography: A Comprehensive Technical Report on Principles, Technologies, and Future Directions for Scientific R&D and Non-Destructive Evaluation

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October 15, 2025

Section 1: Genesis and Evolution of Computed Tomography

Computed Tomography (CT) has evolved from a theoretical mathematical concept into an indispensable tool for industrial non-destructive evaluation (NDE) and scientific research. Its history is a compelling narrative of convergent scientific disciplines, engineering innovation, and the continuous adaptation of a technology from its medical origins to meet the rigorous demands of industrial quality assurance and materials science. This section traces the foundational principles, key milestones, and pivotal figures that have shaped the trajectory of CT.

1.1 Foundational Principles: From Röntgen's Discovery to the Radon Transform

The conceptual origin of all radiographic imaging dates to 1895 with Wilhelm Conrad Röntgen's discovery of X-rays, a form of penetrating electromagnetic radiation.[1] This groundbreaking discovery, which earned Röntgen the first Nobel Prize in Physics in 1901, immediately enabled the visualization of internal structures within opaque objects, revolutionizing both medical diagnostics and industrial inspection.[4] However, the resulting image, a radiograph, was a two-dimensional projection—a shadowgram where all structures along the X-ray path are superimposed, fundamentally lacking depth information.[1]

To address this limitation, early 20th-century innovators developed methods of conventional tomography. Pioneers such as André Bocage conceived of mechanical systems that moved the X-ray source and the photographic plate in a synchronized manner during exposure.[1] This motion was designed to blur out structures above and below a specific focal plane, leaving a single cross-section in relative focus. While a conceptual step forward, these early tomographic techniques were limited by mechanical complexity, long exposure times, high radiation doses, and the production of inherently blurry images that lacked the clarity to distinguish between materials with similar densities, such as different soft tissues.[7]

The true mathematical foundation for modern computed tomography was established long before the technology was feasible. In 1917, the Austrian mathematician Johann Radon published a seminal paper on integral transforms. In this work, he mathematically proved that a two-dimensional or three-dimensional object can be perfectly reconstructed from an infinite set of its projections taken from all possible angles.[1] This principle, now known as the Radon transform, provided the theoretical solution to the reconstruction problem but remained a mathematical curiosity for decades, awaiting the computational power necessary to implement it in practice.

1.2 The Medical Revolution: Hounsfield, Cormack, and the First CT Scanners

The practical realization of computed tomography emerged from the independent work of two key figures in the mid-20th century. In the 1950s and 1960s, South African-American physicist Allan McLeod Cormack, without knowledge of Radon's work, independently developed the mathematical theories for tomographic reconstruction.[1] He went on to provide the first experimental demonstration of the principle, using a gamma-ray source to scan a phantom made of wood and aluminum and successfully calculating their distinct attenuation coefficients from the projection data. His foundational results were published in 1963 and 1964 but initially generated little interest from the scientific community.[10]

Contemporaneously, British electrical engineer Sir Godfrey Newbold Hounsfield, working at the Central Research Laboratories of EMI (Electrical and Musical Industries), began to explore pattern recognition and image reconstruction.[1] Hounsfield's work was uniquely positioned by his experience with Britain's first commercially available all-transistor computer, the EMIDEC 1100, which gave him a deep appreciation for the potential of digital computing.[1] Unaware of Cormack's publications, Hounsfield conceived of a practical system to reconstruct a 3D object as a series of 2D slices, an idea famously sparked during a country walk.[8] The development of this ambitious project was supported by EMI, a company whose research budget was notably bolstered by the immense commercial success of its music division, particularly The Beatles.[8]

Hounsfield's initial prototype used a gamma-ray source and took nine days to acquire 28,000 measurements from a test object, requiring over two hours of processing time on a mainframe computer.[1] After finding a crucial collaborator in neuroradiologist Dr. James Ambrose, Hounsfield's team built the first clinical prototype. On October 1, 1971, at Atkinson Morley Hospital in London, they performed the first successful CT scan on a human patient, clearly revealing a cystic brain tumor on the resulting 80x80 pixel image.[8] The groundbreaking results were publicly announced in 1972, sparking a revolution in medical imaging.[13]

The first commercial head scanner, the EMI Mark I, was rapidly adopted, with the first units installed in the United States in 1973.[8] This was followed by the development of the first whole-body scanner in 1974 by Dr. Robert Ledley at Georgetown University.[10] The subsequent years saw rapid technological advancements through successive "generations" of scanner geometries, moving from the slow translate-rotate pencil-beam systems to faster fan-beam and eventually modern rotate-rotate systems.[1] For their parallel and pivotal contributions to the development of computer-assisted tomography, Hounsfield and Cormack were jointly awarded the 1979 Nobel Prize in Physiology or Medicine.[12] This convergence of mature mathematical theory, the advent of practical computing power, and engineering ingenuity marked the birth of modern CT.

1.3 The Industrial Pivot: Transitioning from Medical Diagnosis to Non-Destructive Testing (NDT) and Metrology

While CT was transforming medicine, its potential for industrial applications was also being recognized. The transition to NDT began in earnest in the 1980s, driven by the need for a method that could inspect the internal structure of complex components without destruction.[3] This represented a significant evolution in the field of NDT, which had progressed from the radiography established after Röntgen's discovery to techniques like ultrasonic testing (UT), magnetic particle testing (MT), and liquid penetrant testing (PT) throughout the 20th century.[5]

Early industrial CT applications focused on qualitative flaw detection, such as identifying pores, voids, and cracks in metal castings and other technical objects.[18] A significant driver for adoption came from the electronics industry, where CT was used for completeness checks and flaw detection in printed circuit boards (PCBs) and surface mount technology (SMT) assemblies.[18]

However, a fundamental divergence in requirements separated the medical and industrial domains. While medical CT prioritized scan speed and radiation dose reduction for qualitative diagnosis, industrial applications began to demand high accuracy, superior resolution, and metrological traceability for quantitative validation.[18] This shift from simply "seeing" inside an object to "measuring" it with certified accuracy required a new class of CT systems.

A critical breakthrough occurred in the early 2000s when the "3D-accuracy and traceability problem" was solved through the development of new calibration methodologies, often using conventional coordinate measuring machines (CMMs) to establish a traceable reference frame.[18] This milestone paved the way for CT metrology. The culmination of this effort was in 2005, when the German company Werth Messtechnik presented the first CMM with a fully integrated X-ray sensor.[18] This event cemented CT's role as what many consider the third revolutionary development in coordinate metrology, following tactile CMMs in the 1970s and optical 3D scanners in the 1980s.[18] This innovation spurred a wave of development from other metrology system vendors, firmly establishing CT as a cornerstone of modern industrial quality control.

1.4 The Modern Landscape: Key Applications in R&D and NDE

Today, industrial CT is an indispensable, multi-faceted technology used across a wide spectrum of industries for quality control, failure analysis, assembly analysis, reverse engineering, and materials R&D.[18] Its unique ability to provide a complete, non-destructive 3D representation of both internal and external geometries makes it invaluable for complex and high-value components.

- **Aerospace:** In this safety-critical sector, CT is used for NDE of turbine blades, engine parts, and airframe structures to detect subtle defects like porosity, micro-cracks, inclusions, and foreign object debris (FOD).[26] It is also essential for inspecting composite materials for delamination and fiber orientation, and for validating additively manufactured components.
- **Automotive:** The automotive industry employs CT for a wide range of tasks, from inspecting engine components and transmission parts for casting defects to ensuring the quality of complex assemblies like electronic connectors and headlights.[24] With the rise of electric vehicles (EVs), CT has become crucial for inspecting the internal structure of battery cells and modules for defects in welding, electrode alignment, and contamination.[30]
- **Electronics:** For the electronics industry, CT provides unparalleled insight into the quality of PCBs, solder joints (especially in ball grid arrays), wire bonds, and encapsulated microchips. It can non-destructively detect defects such as broken wires, voids in solder, and delamination that are impossible to find with other methods.[24]
- **Additive Manufacturing (AM):** CT is not just an inspection tool for AM; it is a fundamental enabler. Traditional metrology tools like CMMs can only measure external surfaces, but the primary advantage of AM is the ability to create parts with complex internal geometries, such as lattice structures or conformal cooling channels.[18] CT is the only technology capable of non-destructively measuring these internal features and detecting process-specific defects like lack-of-fusion porosity or trapped powder, thereby validating the integrity of the printed part.[18] The reliability of AM for critical applications is thus inextricably linked to the capabilities of industrial CT.
- **Emerging Fields:** The application of CT continues to expand. In the food industry, it is used to detect contaminants like glass, metal, or stone in packaged goods.[18] In security, CT scanners are deployed at airports and border crossings for the automated detection of explosives and other threats

in luggage.[34] In materials science, it is a vital research tool for the 3D characterization of foams, composites, geological samples, and biological structures.[33]

Section 2: The Physics of X-ray Computed Tomography

The capacity of X-ray computed tomography to reveal the internal structure of an object is rooted in the fundamental principles of physics governing the generation of X-rays and their subsequent interaction with matter. A comprehensive understanding of these principles is essential for interpreting CT data, comprehending the origins of image artifacts, and appreciating the capabilities and limitations of the technology.

2.1 Generation of X-rays: Bremsstrahlung and Characteristic Radiation

The production of X-rays in a standard industrial or medical X-ray tube is a process of energy conversion, where the kinetic energy of accelerated electrons is transformed into electromagnetic radiation. This process requires three essential components: a source of electrons, a means to accelerate them to high velocities, and a target material to abruptly decelerate them.[40]

The process begins at the cathode, where a tungsten filament is heated by an electrical current. This heating causes electrons to be liberated from the filament's surface through a process known as thermionic emission, forming an electron cloud.[41] A very high voltage potential, typically measured in kilovolt peak (kVp), is applied between the negatively charged cathode and a positively charged anode. This strong electric field accelerates the electrons across a vacuum gap, causing them to strike the anode target at extremely high speeds.[40] The magnitude of this accelerating voltage (kVp) determines the maximum kinetic energy of the electrons and, consequently, the maximum energy of the X-ray photons that can be produced.[40] The quantity of electrons flowing from cathode to anode per unit time, known as the tube current (measured in milliamperes, mA), controls the number of electron-target interactions and thus the overall intensity or flux of the resulting X-ray beam.[40]

Upon impact with the anode, which is typically made of a high-atomic-number (high-Z) material like tungsten to maximize X-ray production efficiency, the vast majority of the electrons' kinetic energy—over 99%—is converted into heat.[41] This immense thermal load necessitates sophisticated cooling mechanisms, such as rotating the anode at high speeds to distribute the heat over a larger surface area.[41] The small fraction of remaining energy, approximately 1%, is converted into X-ray photons through two distinct physical mechanisms.[42]

- **Bremsstrahlung (Braking Radiation):** This is the dominant mechanism, responsible for approximately 80-90% of the X-ray output in a typical diagnostic or industrial tube.[43] Bremsstrahlung occurs when a high-speed incident electron passes close to the positively charged nucleus of a target atom. The strong electrostatic attraction deflects the electron from its original path and causes it to decelerate, or "brake." According to the law of conservation of energy, the kinetic energy lost by the electron during this deceleration is emitted as an X-ray photon. The energy of the emitted photon can range from near zero up to the full kinetic energy of the incident electron, depending on how closely the electron approached the nucleus and how much it was decelerated. This process results in a continuous spectrum of X-ray energies, which is a defining characteristic of tube-based X-ray sources.[41]
- **Characteristic Radiation:** This secondary mechanism produces X-rays at discrete energy levels. It occurs when an incident electron has sufficient kinetic energy to collide with and eject an electron from one of the inner orbital shells (e.g., the K or L shell) of a target atom, creating a vacancy. This leaves the atom in an unstable, ionized state. To return to a stable state, an electron from a higher-energy outer shell (e.g., L or M shell) "drops down" to fill the inner-shell vacancy. The difference in binding energy between the two shells is released as an X-ray photon with a precise, discrete energy. Because the binding energies of electron shells are unique to each element, the emitted photons have energies that are "characteristic" of the anode material (e.g., tungsten). These appear as sharp peaks superimposed on the continuous Bremsstrahlung spectrum.[41]

2.2 X-ray Interaction with Matter: A Detailed Analysis

As the polychromatic X-ray beam generated by the tube passes through the object under inspection, its photons interact with the atoms of the material. These interactions cause photons to be either absorbed or scattered, reducing the intensity of the beam—a process known as attenuation.[44] The degree of attenuation depends on the energy of the photons and the density and atomic number of the material being traversed. The spatial variation in this attenuation is what creates the contrast in a radiographic projection and, ultimately, in a reconstructed CT image.[42] For the energy ranges used in industrial CT, three primary interaction mechanisms are of significance.

2.2.1 The Photoelectric Effect: Basis for Contrast

The photoelectric effect is an absorption process that is fundamental to generating contrast between different materials in a CT image. In this interaction, an incident X-ray photon collides with a tightly bound, inner-shell electron (typically K- or L-shell) of an atom. The photon transfers its entire energy to the electron, which is then ejected from the atom as a photoelectron. The incident photon is completely absorbed and ceases to exist.[44] The kinetic energy of the ejected photoelectron is equal to the incident photon's energy minus the binding energy of the electron's shell.

The probability of a photoelectric interaction is highly dependent on two factors:

1. **Atomic Number (Z):** The probability is approximately proportional to the cube of the atomic number of the absorbing material ($P_{PE} \propto Z^3$).[2]
2. **Photon Energy (E):** The probability is approximately inversely proportional to the cube of the photon's energy ($P_{PE} \propto 1/E^3$).[44]

This strong dependence on atomic number is the primary reason CT is so effective at material differentiation. A small difference in the average atomic number between two materials (e.g., a metallic inclusion in a polymer matrix) will result in a large difference in their X-ray attenuation via the photoelectric effect, creating strong image contrast.[2] This interaction is most dominant at lower X-ray energies (typically below 100 keV in soft materials) and in materials with high atomic numbers.[2]

2.2.2 Compton Scattering: Source of Noise and Artifacts

Compton scattering, also known as incoherent scattering, is the predominant interaction mechanism at the higher energies typical of industrial NDE and in materials with low atomic numbers.[44] In this process, an incident photon interacts with a loosely bound, outer-shell electron of an atom. The photon transfers a portion of its energy to the electron, which is ejected from the atom (the Compton electron), and the photon itself is deflected, or scattered, from its original path with reduced energy.[44]

The probability of Compton scattering is primarily dependent on the physical density and electron density of the material and decreases slowly with increasing photon energy (roughly proportional to $1/E$).[44] Critically, it is almost independent of the atomic number of the material.[44]

While Compton interactions contribute to the overall attenuation of the beam, the scattered photons are a significant detriment to image quality. If these scattered photons reach the detector, they do not carry accurate spatial information about their origin and contribute to a general background fog or haze. This reduces image contrast, increases noise, and can introduce severe artifacts, particularly cupping artifacts.[44] This creates a fundamental challenge in high-energy NDE: the very energies required to penetrate dense objects are those at which the image-degrading Compton effect is the dominant mode of interaction. This necessitates the use of physical anti-scatter grids or post-patient collimators and sophisticated software-based scatter correction algorithms to maintain image integrity.[50]

2.2.3 Pair Production: Relevance in High-Energy Regimes

Pair production is an interaction that only occurs at very high photon energies. If a photon with an energy exceeding 1.02 MeV passes close to the strong electric field of an atomic nucleus, the photon's energy can be spontaneously converted into mass in the form of an electron-positron pair.[44] The 1.02 MeV threshold represents the combined rest-mass energy of the two particles (2×0.511 MeV). The incident photon is annihilated in the process.

The probability of pair production increases with photon energy above the 1.02 MeV threshold and is also proportional to the atomic number of the material.[44] This interaction is therefore irrelevant for conventional microfocus and low-energy CT systems. However, it becomes a significant component of total attenuation for the high-energy systems used to inspect very large and dense components, such as linear accelerators (Linacs) operating in the 6-9 MeV range.[44]

2.3 Attenuation and the Beer-Lambert Law: The Mathematical Basis of Projection Imaging

The aggregate effect of these interactions is the attenuation of the X-ray beam. For a simple, monoenergetic beam passing through a homogeneous material, this attenuation is described by the Beer-Lambert law:

$$I = I_0 e^{-\mu x}$$

where I is the intensity of the beam after passing through the material, I_0 is the initial beam intensity, x is the thickness of the material, and μ is the linear attenuation coefficient of the material for that specific photon energy.[51] The linear attenuation coefficient μ is a fundamental property of a material that encapsulates the combined probabilities of all interaction types at a given energy.

In computed tomography, the object is heterogeneous, meaning μ varies with position (x, y). The detector measures the total attenuation along a straight line (ray) through the object. The logarithm of the intensity ratio is thus the line integral of the attenuation coefficient along that path, s:

$$p = \ln\left(\frac{I_0}{I}\right) = \int_s \mu(x, y) ds$$

A single 2D projection image acquired at a given angle θ is a collection of these line integral values (p) for all rays passing through the object at that angle. The complete set of projections acquired over a full rotation (typically 0-360 degrees) is organized into a 2D data array known as a **sinogram**.[51] The sinogram is not an intuitive image of the object; rather, it is a representation of the object in the Radon domain. Each point in the object traces a sinusoidal path in the sinogram, hence the name. This sinogram serves as the raw input data for the reconstruction algorithms described in Section 4. The structured nature of this data is critical, as artifacts that appear complex in the final reconstructed image often manifest as simple, identifiable patterns in the sinogram. For instance, a consistently miscalibrated detector element creates a straight line in the sinogram, which transforms into a ring artifact in the image. This makes the sinogram the ideal domain for applying many artifact correction algorithms before the computationally intensive reconstruction process begins.[52]

The use of Bremsstrahlung-based sources introduces a significant complication. The polychromatic nature of the beam means that the Beer-Lambert law in its simple form does not hold. As the beam passes through the object, lower-energy photons are more readily absorbed (primarily via the photoelectric effect, with its strong $1/E^3$ dependence), causing the average energy of the remaining photons to increase. This phenomenon, known as **beam hardening**, means the effective attenuation coefficient changes as the beam penetrates deeper. Standard reconstruction algorithms assume a monoenergetic beam and fail to account for this non-linear effect, leading to characteristic artifacts such as cupping and dark streaks between dense objects.[56] This physical reality necessitates the complex correction algorithms discussed in Section 5.

Section 3: Anatomy of an Industrial CT System

An industrial CT system is a complex integration of high-precision mechanical, electronic, and optical components designed to acquire high-fidelity X-ray projection data for 3D reconstruction. While sharing the same physical principles as their medical counterparts, industrial systems are architecturally distinct, optimized for accuracy, flexibility, and the diverse range of materials and geometries encountered in manufacturing and research.

3.1 Core Components: Gantry, Manipulator, Detectors, and Shielding

The primary components of an industrial CT scanner are housed within a radiation-shielded cabinet or a purpose-built concrete bunker to ensure operator safety.[23] The internal architecture reflects a key difference from medical systems: in most industrial CT configurations, the X-ray source and detector remain stationary while the object is precisely rotated and manipulated.[23] This "rotate-the-object" design provides superior mechanical stability and allows for flexible geometric magnification by adjusting the relative distances between the source, object, and detector. This flexibility is crucial for optimizing resolution for parts of varying sizes, a capability not present in fixed-geometry medical scanners where the gantry must rotate around a stationary patient.[10]

- **Manipulator:** The manipulator is the heart of the system's mechanical precision. It is a multi-axis stage responsible for holding, rotating, and translating the test object with extremely high accuracy and repeatability. For metrology-grade systems, these manipulators are often constructed from materials with high thermal and mechanical stability, such as granite, and may incorporate air bearings to ensure smooth, vibration-free rotation.[58] The precision of the manipulator directly impacts the spatial resolution and accuracy of the final 3D model.

- **X-ray Tube and Generator:** The X-ray source and its associated high-voltage generator produce the X-ray beam. The choice of source is the most critical factor defining the system's capabilities and is discussed in detail in the following section.[17]
- **Collimators and Filters:** A set of components are used to shape and condition the X-ray beam.
  - **Pre-patient collimators**, located near the X-ray source, are typically adjustable apertures that shape the beam into the desired geometry (e.g., a cone for volumetric scanning) and can help define the slice thickness in some geometries.[50]
  - **Filters**, thin plates of materials like aluminum, copper, or brass placed in the beam path, are used to preferentially absorb low-energy X-rays. This "pre-hardens" the beam, reducing the severity of beam hardening artifacts in the reconstructed image.[50]
  - **Post-patient collimators** or anti-scatter grids may be placed just before the detector to block photons that have been scattered by the object, thereby improving image contrast and reducing noise.[50]
- **Detectors:** The detector is responsible for converting the pattern of transmitted X-ray photons into a digital image. Modern industrial CT systems predominantly use digital detector arrays (DDAs), also known as flat-panel detectors.[63] The most common type is the **indirect-detection solid-state detector**. This design consists of a scintillator layer (e.g., Cesium Iodide, CsI, or Gadolinium Oxysulfide, GOS) that converts incident X-ray photons into visible light. This light is then captured by an array of photodiodes, typically made of amorphous silicon (a-Si), which generates an electrical signal proportional to the light intensity. This signal is then digitized to form the 2D projection image.[50] The choice of scintillator material and detector pixel size are key determinants of the system's resolution and efficiency. Older systems sometimes used gas-filled ionization detectors, but these have been largely superseded due to their lower efficiency and resolution.[50]

3.2 The X-ray Source Spectrum: A Technical Comparison

The selection of an X-ray source dictates the fundamental trade-off between penetrating power (energy) and achievable spatial resolution (focal spot size). No single source is optimal for all applications, leading to a spectrum of specialized CT systems tailored for different NDE tasks. This inverse relationship between power and precision is a central theme in CT system design; sources capable of generating the high-energy photons needed to penetrate dense materials inherently have larger focal spots due to the immense thermal and electrical forces involved, while the sources that achieve the smallest focal spots for ultra-high resolution do so by operating at lower power levels.

3.2.1 Low-Energy and Microfocus/Nanofocus Sources

- **Characteristics:** These sources operate at accelerating voltages typically ranging from 130 kV to 450 kV. Their defining feature is the ability to generate an extremely small electron beam focal spot on the anode target, ranging from tens of micrometers (microfocus) down to less than one micrometer (nanofocus).[39]
- **Advantages:** According to the principles of projection radiography, the geometric unsharpness in an image is minimized as the source focal spot size decreases. This allows for high geometric magnification (by placing the object close to the source) while maintaining sharp image features. Consequently, these sources enable extremely high spatial resolution, making them the standard for detailed inspection of small or fine-featured components.[64]
- **Limitations:** The power that can be concentrated onto a tiny focal spot is limited by the melting point of the anode material. This inherent power limitation restricts the energy and flux of the X-ray beam, thus limiting its ability to penetrate large or high-density objects.[39]
- **Applications:** These sources are ideal for high-resolution NDE and metrology in electronics (inspecting solder joints, bond wires), medical devices, injection-molded plastics, light metal castings (e.g., aluminum), and materials science research on composites and biological samples.[24]

3.2.2 High-Energy Systems: Betatrons

- **Operating Principle:** The betatron is a cyclic particle accelerator. It uses a time-varying magnetic field to both confine electrons to a circular orbit within a toroidal vacuum chamber and induce an electric field that accelerates them to very high energies over many revolutions.[69] Once at maximum energy, the electron beam is deflected to strike a target, producing a high-energy X-ray beam.[69]
- **Characteristics:** Betatrons can generate X-rays in the mega-electron-volt (MeV) range, typically from 2 MeV to 30 MeV, with very small focal spots. However, their primary drawback is a very low photon flux, or radiation output, compared to other high-energy sources.[65]
- **Advantages:** They offer a relatively compact design for producing very high-energy X-rays, enabling penetration of extremely thick materials.
- **Limitations:** The low flux results in prohibitively long exposure times for CT, where thousands of projections are required. This has largely relegated their use to specialized radiographic applications rather than mainstream industrial CT.[65]
- **Applications:** Primarily used for 2D radiography of very thick-walled steel components, such as large castings and forgings, where penetration is the primary concern and long exposure times are acceptable.[69]

3.2.3 High-Energy Systems: Linear Accelerators (Linacs)

- **Operating Principle:** A Linac uses high-frequency microwave fields to accelerate electrons in a straight line down a specialized evacuated structure called an accelerating waveguide. The electrons "ride" the electromagnetic wave, gaining energy continuously until they reach relativistic speeds. At the end of the waveguide, they strike a target to produce a forward-directed, high-energy X-ray beam.[65]
- **Characteristics:** Linacs are the workhorses of high-energy industrial CT. They typically operate in the 1 MeV to 9 MeV range (and higher), producing an extremely high radiation output (high flux) from a relatively small focal spot (typically 0.5 mm to 2 mm).[58]
- **Advantages:** The very high photon flux allows for rapid scanning of large, highly attenuating objects that are impenetrable to microfocus sources. This makes Linac-based CT suitable for high-throughput inspection in production environments.[58]
- **Limitations:** Linacs are large, heavy, and expensive systems that require significant radiation shielding, often in the form of thick concrete bunkers.[58] Their focal spots are significantly larger than those of microfocus sources, limiting their ultimate spatial resolution.
- **Applications:** Essential for the NDE of large, dense components in the aerospace (e.g., large turbine blades, rocket motors), energy (e.g., valves, pressure vessels), and defense industries. They are the only viable option for performing CT on large metallic castings and assemblies.[74]

Source Type	Operating Principle	Typical Energy Range	Typical Focal Spot Size	Relative Photon Flux	Primary NDE Applications
Microfocus/ Nanofocus	Stationary target, small e-beam spot	< 450 kV	< 1 µm - 50 µm	Low	High-resolution inspection of electronics, polymers, light alloys
Betatron	Cyclic electron acceleration via magnetic induction	2 - 30 MeV	< 1 mm	Very Low	Radiography of very thick sections; limited use in CT
Linear	Linear	1 - 9+ MeV	0.5 - 2 mm	Very High	High-speed

Accelerator (Linac)	electron acceleration via microwave fields				CT of large, dense components like engine blocks and turbine blades

3.3 Data Acquisition: From Rotational Scanning to the Sinogram

The data acquisition process in a typical cone-beam industrial CT system is a precisely choreographed sequence. The object to be inspected is mounted on the manipulator stage, positioned between the X-ray source and the detector.[60] The system then acquires a series of hundreds or thousands of 2D digital radiographs as the object is incrementally rotated through a full 360 degrees.[59] Each radiograph is a projection that captures the X-ray attenuation pattern at a specific angular view. This sequence of 2D projection images is then computationally organized to form the sinogram, which serves as the raw dataset for the tomographic reconstruction algorithms that will ultimately generate the 3D volumetric model of the object.[51]

Section 4: The Science of Image Reconstruction

Image reconstruction is the computational core of computed tomography, a process that transforms the abstract collection of projection data stored in the sinogram into a tangible, three-dimensional volumetric representation of the scanned object. The evolution of reconstruction algorithms—from rapid analytical methods to robust iterative techniques and now to intelligent deep learning frameworks—reflects a continuous drive for greater image fidelity, reduced artifacts, and improved computational efficiency. This progression can be understood as an increasing sophistication in how "prior knowledge" about the physical world and the nature of the object is incorporated into the mathematical process.

4.1 Analytical Reconstruction: The Filtered Back-Projection (FBP) Algorithm

For several decades following the invention of CT, Filtered Back-Projection (FBP) was the universally adopted standard for image reconstruction, primarily due to its high computational speed and straightforward implementation.[77] FBP is an analytical algorithm, meaning it is a direct mathematical solution to the inverse Radon transform. Its theoretical basis is the Fourier Slice Theorem, which states that the one-dimensional Fourier transform of a projection at a given angle is mathematically equivalent to a radial slice through the two-dimensional Fourier transform of the object itself, taken at the same angle.[20]

The FBP algorithm consists of two main steps [77]:

1. **Filtering:** Simple back-projection, where projections are smeared back across the image grid, inherently produces a blurred image because it over-represents low-frequency information. To counteract this, each projection is first convolved with a high-pass filter kernel. In the frequency domain, this is equivalent to multiplying the Fourier transform of the projection by a "ramp filter," $|\omega|$, which amplifies high-frequency components (edges and details) and suppresses low-frequency components.[77] This filtering step is the critical operation that allows FBP to produce sharp images.
2. **Back-Projection:** The filtered projections are then systematically "back-projected" onto the image grid. For each pixel in the final image, its value is calculated by summing the contributions from each of the filtered projections at the corresponding ray path. This process is repeated for all pixels and all projection angles to build the final cross-sectional image.[77]

The primary advantage of FBP is its speed; it is a non-iterative, direct calculation that can reconstruct large datasets in seconds.[77] However, its major limitation is its sensitivity to data imperfections. FBP implicitly assumes a perfect, noise-free, and densely sampled dataset. In practical scenarios, particularly with low radiation dose (high quantum noise) or a limited number of projections (sparse-view), the filtering step amplifies this noise, resulting in images with significant streak artifacts and poor low-contrast resolution.[77] It incorporates almost no prior knowledge about the object or the statistical nature of the data acquisition process.

4.2 Iterative Reconstruction Methods: Superiority in Noisy and Incomplete Data

Iterative Reconstruction (IR) methods were developed to overcome the inherent limitations of FBP by adopting a fundamentally different approach. Instead of a direct analytical solution, IR treats reconstruction as an optimization problem: it seeks to find the image that, when forward-projected, best matches the actual measured projection data, while also satisfying certain constraints or prior assumptions about the image.[78] These methods incorporate simple but powerful physical priors, such as the statistical nature of photon detection or the general smoothness of objects.

The general process for iterative reconstruction is as follows [84]:

1. An initial image estimate is created (e.g., a uniform gray image or a low-quality FBP reconstruction).
2. A "forward projection" is computed from this current image estimate, simulating the X-ray acquisition process to generate a calculated sinogram.
3. The calculated sinogram is compared to the actual measured sinogram to determine the error or discrepancy.
4. A correction term based on this error is calculated and used to update the image estimate.
5. Steps 2 through 4 are repeated (iterated) until the difference between the calculated and measured sinograms falls below a predefined convergence threshold.

Several families of iterative algorithms exist:

- **Algebraic Reconstruction Technique (ART):** One of the earliest iterative methods, ART updates the image on a ray-by-ray basis, adjusting pixel values along a single projection line to match the measured value before moving to the next ray.[85] Variants include Simultaneous ART (SART) and Multiplicative ART (MART).[81]
- **Maximum Likelihood Expectation Maximization (MLEM):** This is a powerful statistical approach that incorporates a Poisson noise model, which accurately reflects the quantum statistics of photon detection. MLEM seeks the image that has the highest probability, or likelihood, of producing the measured projection data. It is known for producing high-quality images with excellent noise properties but suffers from very slow convergence.[81]
- **Ordered Subsets Expectation Maximization (OSEM):** To address the slow speed of MLEM, OSEM was developed. Instead of using all projections for each update, it groups the projections into a number of "ordered subsets" and performs an MLEM-like update after processing each subset. This dramatically accelerates convergence, making statistical reconstruction practical for many applications.[81]

The main advantage of IR is its superior handling of noisy and incomplete data. By modeling the physics and statistics of the acquisition process, IR algorithms can produce images with significantly lower noise and fewer artifacts compared to FBP, making them indispensable for low-dose medical imaging and sparse-view industrial applications.[78] Their primary disadvantage is the high computational cost, which can lead to reconstruction times of minutes to hours.[78] Furthermore, some IR algorithms, especially those with strong regularization, can produce images with an unnatural, "waxy" or "blotchy" texture that may obscure fine details.[79]

4.3 The Deep Learning Revolution: AI-Based Reconstruction (DLR)

Deep Learning Reconstruction (DLR) represents the current state-of-the-art in CT image formation, leveraging the power of artificial intelligence, specifically deep convolutional neural networks (CNNs), to perform the reconstruction task.[79] This approach marks a paradigm shift from generic mathematical models to highly specialized, data-driven models. DLR incorporates extremely complex prior knowledge by learning the characteristic features of objects and artifacts from a vast training dataset.

The DLR process typically involves training a CNN on a large number of paired datasets, where one set consists of low-quality data (e.g., noisy sinograms from low-dose or sparse-view scans, or artifact-laden images reconstructed with FBP) and the other consists of corresponding high-quality, "ground truth" images.[88] Through this training process, the network learns the intricate, non-linear mapping required to transform the low-quality input into a high-quality output, effectively learning to denoise, remove artifacts, and restore structural details.[88]

DLR can be implemented in several ways [53]:

- **Image-Domain Denoising:** A CNN is used as a post-processing step to clean up an image already reconstructed with FBP or IR.
- **Sinogram-Domain Denoising/Inpainting:** The network operates on the raw sinogram data to remove noise or fill in missing views before a traditional reconstruction algorithm is applied.
- **End-to-End Reconstruction:** The most advanced approach, where the network learns the entire reconstruction process, taking a sinogram as input and directly outputting the final image, completely replacing FBP or IR.

DLR offers significant advantages. It can achieve noise reduction superior to that of IR while preserving a more natural image texture, avoiding the "plastic" appearance of some iterative methods.[79] It is also computationally much faster than full model-based IR, making it suitable for high-throughput environments.[79] This combination allows for substantial reductions in radiation dose or scan time while maintaining or even enhancing diagnostic image quality.[79] The main limitations are its reliance on large, high-quality, and representative training datasets, and the "black box" nature of deep neural networks, which can make their performance on out-of-distribution data difficult to predict.[79]

4.4 Advanced Scanning and Reconstruction Geometries

Beyond the core algorithms, specific scanning geometries and reconstruction techniques are employed to optimize data acquisition for different object shapes and application needs.

- **Helical (Spiral) CT:** In this mode, the object is translated along the axis of rotation at a constant speed while the projections are continuously acquired. This traces a helical path around the object, allowing for the rapid acquisition of a large volumetric dataset without the start-stop motion of conventional "step-and-shoot" scanning. It is the standard method for scanning long objects or for applications where speed is critical.[1]

- **Half-Scan:** For cone-beam CT, the projection data acquired over 180 degrees plus the angular width of the cone beam contains all the necessary information for reconstruction. Using a half-scan acquisition can reduce scan time by nearly half, which is beneficial for dynamic studies or reducing motion artifacts, though it requires specialized reconstruction algorithms to handle the data redundancy correctly.[19]
- **Matrix and Sub-Pixel Scanning:** These are advanced techniques designed to improve the effective spatial resolution beyond the physical limit of the detector's pixel size. By physically shifting the object or detector by a fraction of a pixel's width during acquisition (sub-pixel scanning), additional sampling information can be captured. This oversampled data can then be used in reconstruction to generate an image on a finer grid (matrix), yielding a higher-resolution result.

The choice of reconstruction algorithm is ultimately a trade-off between the competing demands of image quality, computational speed, and robustness to data imperfections. While FBP remains useful for quick, high-quality scans, IR is the standard for artifact-sensitive applications, and DLR is emerging as the optimal solution that promises to deliver both high quality and high speed.

Algorithm Class	Core Principle	Computational Cost	Noise/Artifact Handling	Suitability for Sparse/Low-Dose Data	Key Limitation
Filtered Back-Projection (FBP)	Analytical inversion via Fourier Slice Theorem	Low (seconds)	Poor; amplifies noise	Not suitable	Image quality degradation with imperfect data
Iterative Reconstruction (IR)	Iterative optimization to match measured data	High (minutes to hours)	Excellent; models noise statistics	Highly suitable	Long reconstruction time; potential for unnatural texture
Deep Learning Reconstruction (DLR)	Learned mapping via Convolutional Neural Network	Medium (seconds to minutes, after training)	State-of-the-art; learns to remove noise and artifacts	Very highly suitable	Requires large, high-quality training dataset; 'black box'

					nature

Section 5: Ensuring Data Integrity: Artifacts and Correction Algorithms

A reconstructed CT volume is not a perfect representation of the object; it is an estimate derived from physical measurements that are subject to a variety of non-ideal effects. These effects manifest as artifacts—systematic discrepancies between the reconstructed image and the true object—that can obscure features, compromise diagnostic accuracy, and invalidate metrological measurements. Understanding the physical origins of these artifacts is crucial for developing and applying the sophisticated correction algorithms needed to ensure data integrity. These artifacts are not random noise but are structured manifestations of physical processes that are not accounted for in idealized reconstruction models, meaning they can be modeled, predicted, and mitigated.

5.1 Beam Hardening Artifacts: Causes and Correction

Beam hardening is one of the most common physics-based artifacts in X-ray CT, arising directly from the polychromatic (multi-energy) nature of the X-ray beam produced by Bremsstrahlung.[54] As the beam passes through an object, lower-energy ("softer") photons are more readily attenuated than higher-energy ("harder") photons. This preferential absorption causes the mean energy of the beam to increase as it penetrates the material, a phenomenon known as "beam hardening".[93] Standard reconstruction algorithms like FBP assume a monoenergetic beam and a linear relationship between thickness and log-attenuation. The non-linear attenuation caused by beam hardening violates this assumption, leading to characteristic artifacts.[56]

- **Manifestation:** In a scan of a homogeneous cylindrical object, beam hardening causes the center of the object to appear artificially darker (less dense) than its periphery, an effect known as **cupping**.[56] When multiple high-density objects are present, dark streaks or bands can appear in the space between them.[93]
- **Correction Algorithms:** Several strategies exist to mitigate beam hardening:
    1. **Physical Filtering:** Placing a thin filter of material like copper or aluminum in the X-ray beam path pre-filters the softest X-rays before they reach the object. This pre-hardens the beam, making its spectral change less pronounced as it passes through the object, thus reducing the artifact.[50]

2. **Software Linearization:** This is a common software-based correction. The system is first calibrated by scanning known thicknesses of a specific material and measuring the non-linear response. A correction function is then derived to linearize the measured projection data before reconstruction, effectively compensating for the expected hardening effect.[56]
3. **Iterative Reconstruction:** More advanced model-based iterative reconstruction algorithms can explicitly incorporate a physical model of the polychromatic X-ray spectrum and the energy-dependent attenuation of materials directly into the reconstruction process. By simulating the non-linear physics, these algorithms can produce an image that is inherently corrected for beam hardening.[95]
4. **Dual-Energy CT:** This is the most effective solution. By acquiring two datasets at different kVp settings (e.g., 80 kVp and 140 kVp), the energy-dependent behavior of materials can be accurately characterized. This data allows for the creation of "virtual monochromatic" images at any desired energy, which are, by definition, free from beam hardening artifacts.[94]
5. **Deep Learning:** Neural networks can be trained to recognize the specific patterns of cupping and streaking associated with beam hardening and effectively remove them from the reconstructed image.[57]

5.2 Metal Artifact Reduction (MAR): Addressing Photon Starvation and Scattering

The presence of high-density objects, particularly metals such as steel, titanium, or dental implants, poses one of the greatest challenges in CT imaging. Metals have extremely high attenuation coefficients compared to polymers, composites, or biological tissues. This leads to a combination of severe physical effects that corrupt the projection data.[54]

- **Causes:**
  - **Photon Starvation:** The metal can attenuate the X-ray beam so completely that very few or no photons reach the detector elements in its shadow. This leads to projection readings that are either zero or dominated by electronic noise, effectively creating missing data.[93]
  - **Severe Beam Hardening:** The extreme attenuation difference between metal and surrounding material causes severe, localized beam hardening effects.
  - **Scattering:** High-Z materials are also efficient scatterers, increasing the amount of non-diagnostic scattered radiation that reaches the detector.
- **Manifestation:** These effects combine to produce severe artifacts in the reconstructed image, typically appearing as dark and bright streaks radiating from the metal object. These streaks can completely obscure the structure of the metal component itself and any adjacent features, rendering the scan non-diagnostic.[54]
- **Correction Algorithms:** All MAR algorithms involve a trade-off: removing the corrupted data requires making an assumption to fill the resulting gap, which can potentially introduce new, more

subtle artifacts.

1. **Sinogram Inpainting/Interpolation:** This is the most widely used class of MAR algorithms. The process involves several steps: first, an initial reconstruction is performed, and the metal object(s) are segmented from the artifact-ridden image. This segmentation is then forward-projected to identify the regions in the sinogram that were corrupted by rays passing through the metal (the "metal trace"). This corrupted data is discarded and replaced with new data generated by interpolating from the valid, neighboring projection data. A final reconstruction is then performed using this "inpainted" sinogram.[54] While effective at removing the most severe streaks, simple interpolation can blur the true edges of the metal part and may create new artifacts if the surrounding structures are complex.[54]
2. **Iterative MAR:** Model-based iterative reconstruction provides a more robust framework. Instead of simply discarding corrupted data, the algorithm can be modified to assign a very low confidence or weight to the projections affected by photon starvation. The algorithm then reconstructs the image using primarily the reliable data, effectively ignoring the corrupted measurements during the optimization process.[55]
3. **Prior-Image Based MAR:** This is a highly effective but specialized technique. If a prior, artifact-free scan of the object is available (e.g., a scan of a patient before a metal implant was inserted, or a scan of a component before a metal fitting was added), this prior image can be used as a reference. The algorithm uses the anatomical or structural information from the prior image to more intelligently and accurately fill in the data missing in the metal-corrupted sinogram, resulting in a much more faithful correction.[54]

5.3 Detector-Related Artifacts: Ring and Band Artifact Reduction

Ring artifacts are a common type of hardware-based artifact that results from imperfections or miscalibration of individual detector elements in a 2D detector array.[80]

- **Cause:** If a single detector pixel (or a line of pixels) is faulty or improperly calibrated, it will consistently record a signal that is slightly higher or lower than its neighbors for every projection angle.
- **Manifestation:** In the sinogram, this constant offset for a single detector element across all angles appears as a straight horizontal or vertical line. During the back-projection process, this line is rotated around the center of reconstruction, creating a perfect circle or "ring" in the final image. Multiple miscalibrated pixels can lead to a series of concentric rings that can obscure fine details.[80]
- **Correction Algorithms:** Since ring artifacts have a very distinct signature in the sinogram domain (a line), they are most effectively corrected before reconstruction. Various filtering techniques are applied directly to the sinogram data. These algorithms work by identifying the anomalous lines (e.g., using median filters or Fourier analysis) and normalizing the response of the faulty pixels to match that of their immediate neighbors, effectively erasing the line from the sinogram before it can

be transformed into a ring in the image.

Section 6: The Future Horizon of Industrial CT

The field of industrial computed tomography is undergoing a period of rapid innovation, driven by advancements in detector technology, X-ray sources, imaging physics, and computational methods. These emerging technologies are poised to significantly expand the capabilities of CT, transforming it from a specialized offline inspection tool into a faster, more quantitative, and deeply integrated component of advanced manufacturing and scientific research. The overarching trends point towards bringing the capabilities of large-scale synchrotron facilities into the industrial laboratory and evolving CT into a real-time process control sensor.

6.1 Next-Generation Hardware

6.1.1 Photon-Counting Detectors (PCDs): The Advent of Spectral CT

One of the most significant hardware advancements is the development of photon-counting detectors (PCDs). Unlike conventional energy-integrating detectors (EIDs), which measure the total energy deposited by all X-ray photons striking a pixel, PCDs are capable of detecting and counting individual photons. Crucially, they also measure the energy of each photon.[96]

- **Working Principle:** PCDs are direct conversion detectors, typically made from a semiconductor material like Cadmium Telluride (CdTe) or Silicon (Si). When an X-ray photon is absorbed in the semiconductor, it generates a cloud of electron-hole pairs, creating an electrical pulse. The amplitude of this pulse is directly proportional to the energy of the incident photon. By using multiple electronic comparators with different energy thresholds, the detector can sort each incoming photon into one of several energy bins in a single exposure.[98]
- **Advantages and Implications:** This capability provides energy-resolved projection data, enabling **spectral CT**. This marks a fundamental shift in CT's capability, moving beyond mapping morphology and density to enabling quantitative material composition analysis.
  - **Material Decomposition:** The energy-dependent attenuation profiles allow for the decomposition of materials based on their physical properties, such as effective atomic number (Z_{eff}) and electron density (ρ_e). This enables the differentiation of materials with

similar attenuation coefficients that would be indistinguishable in conventional CT.[96]
    - **Artifact Reduction:** By providing spectral data, PCDs allow for the creation of "virtual monochromatic" images. Reconstructing an image using only the data from a single energy bin or a weighted combination effectively eliminates beam hardening artifacts at their source.[97] The direct conversion process also eliminates electronic noise associated with EIDs.
    - **Higher Spatial Resolution:** PCDs do not require the physical septa between pixels that are needed in EIDs to prevent optical crosstalk. This allows them to be fabricated with much smaller pixel sizes without a loss in dose efficiency, leading to a significant improvement in intrinsic spatial resolution.[97]
- **Current Challenges:** The technology is still maturing. At very high photon fluxes, two photons arriving in quick succession can be miscounted as a single, higher-energy photon ("pulse pile-up"). Additionally, charge generated by a single photon can spread to adjacent pixels ("charge sharing"), potentially distorting the measured energy spectrum. These effects require sophisticated correction algorithms to ensure spectral accuracy.[96]

6.1.2 Liquid Metal Jet (LMJ) X-ray Sources: Pushing Brightness and Resolution

A primary limitation of conventional microfocus X-ray tubes is the trade-off between focal spot size and power: a smaller spot can tolerate less power before the solid anode target is damaged by heat. Liquid Metal Jet (LMJ) sources overcome this fundamental limitation.[100]

- **Working Principle:** In an LMJ source, the stationary solid anode is replaced by a continuously flowing, high-speed jet of liquid metal (typically a gallium-based alloy). The electron beam is focused onto this jet, which acts as the target for X-ray generation.[100]
- **Advantages and Implications:** Because the target is already molten and is constantly being replenished at speeds approaching 100 m/s, the power density limitations of solid anodes are effectively removed. The electron beam power can be increased by an order of magnitude or more.[101] This allows an LMJ source to produce a dramatically higher X-ray flux (brightness) from an extremely small focal spot. The result is an X-ray source with a brightness that can be up to 27 times greater than a conventional solid-anode microfocus source of the same spot size.[100] This closes a significant performance gap between laboratory-based X-ray sources and large-scale synchrotron facilities, enabling much faster high-resolution scans or higher resolution at conventional scan times.[100]

6.2 Novel Imaging Paradigms

6.2.1 Phase-Contrast CT: Visualizing the "Invisible"

Conventional CT relies on X-ray absorption to generate contrast. However, for low-density materials (like polymers or biological tissues) or when differentiating between materials with very similar atomic numbers, absorption contrast is often insufficient. Phase-contrast CT offers a solution by utilizing a different physical phenomenon: the phase shift (refraction) of the X-ray wavefront as it passes through the object.[104]

- **Physical Principle:** The refractive index of materials for X-rays is slightly less than one, and the phase shift induced is often thousands of times greater than the absorption. While this phase shift cannot be measured directly, various techniques can transform it into detectable intensity variations, typically creating strong edge-enhancement effects at the interfaces between different materials.[104]
- **Advantages:** Phase-contrast is extremely sensitive to edges, boundaries, cracks, and voids, even in materials that are nearly transparent to absorption-based X-rays. This makes it a powerful tool for the NDE of composites (visualizing fibers and delamination), polymers, and biological samples.[104]
- **Techniques:** Several methods exist, including crystal interferometry, analyzer-based imaging, and grating-based imaging. The simplest and most accessible method for lab-based systems is **in-line phase contrast** (or propagation-based), which requires a highly coherent source (i.e., a very small focal spot) and a significant distance between the object and the detector to allow Fresnel diffraction patterns to form and create the desired edge enhancement.[104]

6.2.2 Dynamic 4D CT: In-Situ Process Monitoring

Dynamic or 4D CT refers to time-resolved 3D imaging, where a sequence of CT scans is acquired rapidly over time to capture a process in motion.[108] This technique adds the dimension of time to the 3D spatial data, allowing for the direct, non-invasive observation of internal structural evolution.

- **Concept:** By using high-speed acquisition hardware (high-flux sources, fast detectors) and rapid reconstruction algorithms, full 3D volumes can be captured in minutes or even seconds.[108] This allows for the in-situ monitoring of components under dynamic conditions, such as mechanical loading, thermal cycling, or fluid flow.[109]
- **Applications:** 4D CT is a transformative tool for materials science and engineering. It enables researchers to visualize crack initiation and propagation in real-time, observe the deformation of additively manufactured lattice structures under compression, track fluid flow through porous rock samples for geoscience applications, or monitor the degradation of battery electrodes during cycling.[109] The resulting data provides invaluable experimental validation for finite element analysis (FEA) and other computational models of material behavior.

6.3 Computational and Systemic Advances

6.3.1 Sparse-View CT and Compressed Sensing (CS)

A major bottleneck in CT, especially for in-line or dynamic applications, is the time required to acquire hundreds or thousands of projections. Sparse-view CT aims to solve this by intentionally violating the traditional sampling requirements.[112]

- **Concept:** Instead of a full set of projections, only a small fraction (e.g., fewer than 100) are acquired. The resulting highly undersampled dataset is insufficient for reconstruction with FBP, which would produce severe streak artifacts.[112]
- **Compressed Sensing (CS) Reconstruction:** To overcome this, advanced iterative algorithms based on the principle of compressed sensing are used. CS leverages the prior knowledge that most real-world objects are "sparse" or compressible in some mathematical domain (e.g., their gradient image consists of mostly zero values). The CS algorithm finds the "sparsest" possible image that is still consistent with the few projection measurements that were taken.[112]
- **Implications:** By drastically reducing the number of required projections, sparse-view CT can reduce scan times and data volumes by an order of magnitude or more. This makes CT viable for high-throughput screening and rapid dynamic studies where capturing transient phenomena is critical.[112]

6.3.2 The Rise of Automation: AI and Robotics

The final frontier for industrial CT is its full integration into the automated factory floor, a concept often referred to as "Quality 4.0." This is being realized through the convergence of AI and robotics.[116]

- **AI for Automated Defect Recognition (ADR):** The analysis of large, complex CT datasets has traditionally been a manual, time-consuming task requiring a highly trained operator. Today, AI, particularly deep learning, is being used to automate this process. CNNs are trained on vast libraries of CT data to automatically identify, segment, classify, and quantify defects like porosity and cracks with a speed and consistency that can surpass human operators.[116]
- **Robotics for In-Line CT:** Robotic arms are being integrated with CT systems to create fully automated inspection cells directly on the production line. The robot can pick a part from a conveyor, place it in the CT scanner, initiate the scan, retrieve the part, and place it back on the line

or sort it based on the inspection results.[92]

The synergy of these technologies is transforming CT from a passive, offline quality assurance tool into an active, in-line process control sensor. The combination of fast scanning (enabled by LMJ sources and sparse-view techniques), real-time reconstruction (enabled by DLR), and automated analysis (ADR) creates a rapid feedback loop. A component can be scanned and analyzed in under a minute, with the results fed directly back to the manufacturing process (e.g., adjusting casting parameters or 3D printer settings) to correct deviations in near-real-time. This enables a move from simply detecting defective parts to preventing defects from occurring, representing a paradigm shift in industrial quality control.[116]

Section 7: Conclusion

X-ray Computed Tomography has traversed a remarkable path from a theoretical curiosity to a cornerstone of modern industrial technology. Its evolution, driven by parallel advancements in physics, computing, and engineering, has fundamentally altered the landscape of non-destructive evaluation and scientific research. Initially conceived for medical diagnostics, its adaptation to the industrial sphere was not merely a transfer of technology but a reinvention, demanding new levels of precision, accuracy, and versatility. The journey from the first qualitative flaw detection in the 1980s to the establishment of traceable metrology in the 2000s underscores a critical shift from a tool for "seeing" to a certified instrument for "measuring."

The operational principles of industrial CT are grounded in the fundamental physics of X-ray generation and interaction. The interplay between the photoelectric effect, which provides essential material contrast, and Compton scattering, which introduces image-degrading noise, defines the central challenges of CT imaging. The development of sophisticated reconstruction algorithms—from the speed of Filtered Back-Projection to the robustness of Iterative Reconstruction and the intelligent power of Deep Learning—represents an ongoing effort to solve the complex inverse problem more accurately and efficiently, each method incorporating progressively more sophisticated prior knowledge about the object and the imaging physics.

Today, industrial CT is an indispensable enabler for high-stakes industries such as aerospace, automotive, and additive manufacturing. It provides an unparalleled ability to validate complex internal geometries, ensure component integrity, and accelerate product development cycles. However, the field is not static. The future horizon is defined by transformative technologies that promise to push the boundaries of what is possible. Photon-counting detectors are set to revolutionize CT by adding a spectral dimension, turning it from a morphological tool into a quantitative material analysis technique. Novel sources like liquid metal jets are closing the performance gap with synchrotrons, enabling faster and higher-resolution imaging in the laboratory. Concurrently, new paradigms like phase-contrast and dynamic 4D CT are opening windows into previously invisible material properties and behaviors.

Perhaps most profoundly, the integration of artificial intelligence and robotics is repositioning CT's role within the manufacturing ecosystem. The convergence of automated defect recognition and robotic handling is transforming CT from a post-production, offline inspection method into a rapid, in-line process control sensor. This shift facilitates a move towards "Quality 4.0," where data from 100% component inspection can be fed back in near-real-time to optimize production, minimize waste, and ensure unprecedented levels of quality and reliability. As these technologies mature, industrial CT will become an even more integral and intelligent component of the entire product lifecycle, from initial materials research to end-of-life failure analysis.

Works cited

1. History of computed tomography - Wikipedia, accessed October 15, 2025, https://en.wikipedia.org/wiki/History_of_computed_tomography
2. X-ray - Wikipedia, accessed October 15, 2025, https://en.wikipedia.org/wiki/X-ray
3. Introduction to computed tomography - DTU Orbit, accessed October 15, 2025, https://orbit.dtu.dk/files/51297792/Introduction_to_CT.pdf
4. X-ray system - Siemens Global, accessed October 15, 2025, https://www.siemens.com/global/en/company/about/history/specials/175-years/x-ray-system.html
5. The History & Evolution of Non-Destructive Testing - cicndt, accessed October 15, 2025, https://www.cicndt.com/history-of-non-destructive-testing/
6. The History of Non-Destructive Testing - Format NDT, accessed October 15, 2025, https://www.formatndt.co.uk/the-history-of-non-destructive-testing/
7. Computed Tomography (CT) – Beyond Traditional X-Rays - Harvard Business School, accessed October 15, 2025, https://www.hbs.edu/ris/download.aspx?name=20-004.pdf
8. History of the CT Scan | Catalina Imaging, accessed October 15, 2025, https://catalinaimaging.com/history-ct-scan/
9. Computed Tomography for NDT - OnestopNDT, accessed October 15, 2025, https://www.onestopndt.com/ndt-articles/computed-tomography-for-ndt
10. Milestones in CT: Past, Present, and Future | Radiology, accessed October 15, 2025, https://pubs.rsna.org/doi/full/10.1148/radiol.230803
11. How CT happened: the early development of medical computed tomography - PMC, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8555965/
12. The Nobel Prize in Physiology or Medicine 1979 - Perspectives: With a little help from my friends - NobelPrize.org, accessed October 15, 2025, https://www.nobelprize.org/prizes/medicine/1979/perspectives/
13. Half A Century In CT: How Computed Tomography Has Evolved - ISCT, accessed October 15, 2025, https://www.isct.org/computed-tomography-blog/2017/2/10/half-a-century-in-ct-how-computed-tomography-has-evolved
14. Hounsfield Introduces the CAT Scan | Research Starters - EBSCO, accessed October 15, 2025, https://www.ebsco.com/research-starters/history/hounsfield-introduces-cat-scan
15. Radiology Rewind Fridays: Computed Tomography (CT) Scans - Radsource, accessed October 15, 2025, https://radsource.us/radiology-rewind-fridays-computed-tomography-ct-scans/

16. Early Days of CT: Innovations (Both Good and Bad) - AAPM, accessed October 15, 2025, https://www.aapm.org/meetings/amos2/pdf/42-12236-29343-41.pdf
17. CT-scan Image Production Procedures - StatPearls - NCBI Bookshelf, accessed October 15, 2025, https://www.ncbi.nlm.nih.gov/books/NBK574548/
18. Industrial applications of computed tomography - CICPND, accessed October 15, 2025, https://www.cicpnd.it/wp-content/uploads/2021/01/Industrial-applications-of-computed-tomography.pdf
19. CT scan - Wikipedia, accessed October 15, 2025, https://en.wikipedia.org/wiki/CT_scan
20. How Does CT Reconstruction Work? - Rigaku, accessed October 15, 2025, https://rigaku.com/products/imaging-ndt/x-ray-ct/learning/blog/how-does-ct-reconstruction-work
21. Industrial computed tomography - Wikipedia, accessed October 15, 2025, https://en.wikipedia.org/wiki/Industrial_computed_tomography
22. The History of Nondestructive Testing (NDT) - SVK Electronics, accessed October 15, 2025, https://svkelectronics.com/the-history-of-nondestructive-testing-ndt/the-history-of-nondestructive-testing-ndt/
23. How Does Industrial Computed Tomography Work? - North Star Imaging Inc, accessed October 15, 2025, https://4nsi.com/how-does-industrial-computed-tomography-work/
24. Industrial CT Scanning Case Studies, accessed October 15, 2025, https://industrialinspection.com/industrial-ct-scanning-case-studies/
25. www.swri.org, accessed October 15, 2025, https://www.swri.org/markets/chemistry-materials/materials/sensor-systems-nondestructive-evaluation-nde/industrial-ct-scanning#:~:text=Industrial%20CT%20scanning%20helps%20visualize,equipment%2C%20and%20conduct%20failure%20analysis.
26. Aerospace NDT | Delphi Precision Imaging | United States, accessed October 15, 2025, https://www.delphiprecisionimaging.com/aerospace-ndt
27. Non-Destructive Testing (NDT) - Lumafield, accessed October 15, 2025, https://www.lumafield.com/applications/non-destructive-testing-ndt
28. X-ray CT Inspection Services - Nikon Metrology Inc., accessed October 15, 2025, https://industry.nikon.com/en-us/services/x-ray-ct-inspection/
29. Industrial CT Scanning for Automotive Parts | X-ray Inspection - North Star Imaging Inc, accessed October 15, 2025, https://4nsi.com/case-study-category/automotive/
30. Industrial Computed Tomography (CT) Solutions for Battery Cell Inspection - ZEISS, accessed October 15, 2025, https://www.theautomonitor.com/industrial-computed-tomography-ct-solutions-for-battery-cell-inspection-zeiss/
31. Industrial CT Scanning for Electronics | X-ray Inspection - North Star Imaging Inc, accessed October 15, 2025, https://4nsi.com/case-study-category/electronics/
32. Industrial CT Scanning in Forensic Engineering: Finding Truth - Nel Pretech, accessed October 15, 2025, https://www.nelpretech.com/blog/the-role-of-industrial-ct-scanning-in-forensic-investigations
33. X-ray CT Applications by Industries - Rigaku, accessed October 15, 2025, https://rigaku.com/products/imaging-ndt/x-ray-ct/industries

34. Computed Tomography | Transportation Security Administration - TSA, accessed October 15, 2025, https://www.tsa.gov/computed-tomography
35. Computed Tomography (CT) - 3D Security Images - Rapiscan Systems, accessed October 15, 2025, https://www.rapiscansystems.com/en/technologies/computerised-tomography-ct
36. Checkpoint CT - Smiths Detection, accessed October 15, 2025, https://www.smithsdetection.com/checkpoint-ct/
37. Industrial & Security X-ray - ams OSRAM, accessed October 15, 2025, https://ams-osram.com/applications/industrial/industrial-security-x-ray
38. Checkpoint CT scanners pave the way for the contactless checkpoint | Smiths Detection, accessed October 15, 2025, https://www.smithsdetection.com/insights/checkpoint-ct-scanners-pave-the-way-for-the-contactless-checkpoint/
39. Production and Component Behaviour - Non-destructive Material Characterization - Micro Computed Tomography - IAM, KIT, accessed October 15, 2025, https://www.iam.kit.edu/wk/english/2740.php
40. Nondestructive Evaluation Techniques : Radiography - NDE-Ed.org, accessed October 15, 2025, https://www.nde-ed.org/NDETechniques/Radiography/xraygenerators.xhtml
41. X-ray Generation, Pictorial Guide [Bremsstrahlung, Characteristic] - How Radiology Works, accessed October 15, 2025, https://howradiologyworks.com/xrayproduction/
42. X-ray Production - StatPearls - NCBI Bookshelf, accessed October 15, 2025, https://www.ncbi.nlm.nih.gov/books/NBK537046/
43. Basics of X-ray Physics - X-ray production - Radiology Masterclass -, accessed October 15, 2025, https://www.radiologymasterclass.co.uk/tutorials/physics/x-ray_physics_production
44. Radiation Physics, accessed October 15, 2025, https://www.uomus.edu.iq/img/lectures21/MUCLecture_2022_12240476.pdf
45. Interaction with matter - Radiology Cafe, accessed October 15, 2025, https://www.radiologycafe.com/frcr-physics-notes/x-ray-imaging/interaction-with-matter/
46. The Interaction of X-rays with Matter and Radiation Safety - Introduction, accessed October 15, 2025, https://www.cigs.unimo.it/CigsDownloads/labs/xrdp/manuali_letture/02-Rad-Safety.pdf
47. X-Ray Interactions, Illustrated Summary (Photoelectric, Compton, Coherent) For Radiologic Technologists And Radiographers, accessed October 15, 2025, https://howradiologyworks.com/x-ray-interactions/
48. Resident Physics Lectures, accessed October 15, 2025, https://www.augusta.edu/mcg/radiology/residency/chap04radint.ppt
49. Gamma- and X-Ray Interactions in Matter - University of Toledo, accessed October 15, 2025, https://www.utoledo.edu/med/depts/radther/pdf/RDII%20-%20Chapter%207n%20handout.pdf
50. Theoretical lecture :Components of CT scanner, accessed October 15, 2025, https://uomus.edu.iq/img/lectures21/MUCLecture_2022_5634193.pdf
51. Tomographic reconstruction - Wikipedia, accessed October 15, 2025, https://en.wikipedia.org/wiki/Tomographic_reconstruction
52. Sinogram restoration in computed tomography with an edge-preserving penalty - PMC,

accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC4344471/
53. Learning to Reconstruct Computed Tomography (CT) Images Directly from Sinogram Data under A Variety of Data Acquisition Conditions, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7962902/
54. Metal Artifact Reduction in X-ray CT via Ray Profile Correction - MDPI, accessed October 15, 2025, https://www.mdpi.com/2076-3417/10/1/66
55. Metal Artefact Reduction - Institute of Medical Engineering, accessed October 15, 2025, https://www.imt.uni-luebeck.de/research/x-ray-based-imaging/metal-artefact-reduction
56. Simplified Beam Hardening Correction for Ultrafast X-ray CT ... - MDPI, accessed October 15, 2025, https://www.mdpi.com/1424-8220/24/10/2964
57. A Beam Hardening Artifact Correction Method for CT Images Based on VGG Feature Extraction Networks - PMC - PubMed Central, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11991146/
58. Phoenix Power|scan HE | Waygate Technologies - Baker Hughes, accessed October 15, 2025, https://www.bakerhughes.com/waygate-technologies/industrial-radiography-and-ct/ct-inspection-systems/power-scan-he
59. X-ray Computed Tomography: A Brief Introduction - Rigaku, accessed October 15, 2025, https://rigaku.com/products/imaging-ndt/x-ray-ct/learning/x-ray-computed-tomography-brief-introduction
60. Industrial computed tomography (CT) | Hamamatsu Photonics, accessed October 15, 2025, https://www.hamamatsu.com/eu/en/applications/industrial-x-ray-ndt-inspection/industrial-computed-tomography--ct-.html
61. Understanding the Basic Components of a CT Scanner - DirectMed Imaging, accessed October 15, 2025, https://directmedimaging.com/understanding-the-basic-components-of-a-ct-scanner/
62. CT Scanner Components: What Does What? - Atlantis Blog, accessed October 15, 2025, https://info.atlantisworldwide.com/blog/ct-scanner-components-what-does-what
63. Industrial CT Scanning and Tomography | Waygate Technologies, accessed October 15, 2025, https://www.bakerhughes.com/waygate-technologies/industrial-radiography-and-ct/industrial-ct-scanners
64. CT Products - Rigaku, accessed October 15, 2025, https://rigaku.com/products/imaging-ndt/x-ray-ct/products
65. How are High-Energy X-ray Installations Operated | Waygate, accessed October 15, 2025, https://www.bakerhughes.com/waygate-technologies/blog/how-are-highenergy-xray-installations-operated
66. Industrial CT Inspection Services - Diondo, accessed October 15, 2025, https://www.diondo.com/en/services
67. In-line Phase-contrast Tomography using Betatron X-rays Produced by a Laser-Plasma Accelerator | Lund University, accessed October 15, 2025, https://www.lunduniversity.lu.se/lup/publication/8916566
68. Computed Tomography | Industrial CT & NDE Services - EWI.org, accessed October 15, 2025, https://ewi.org/services/production-services/computed-tomography/
69. Betatrons | Research Starters | EBSCO Research, accessed October 15, 2025,

https://www.ebsco.com/research-starters/science/betatrons
70. Betatron - Wikipedia, accessed October 15, 2025, https://en.wikipedia.org/wiki/Betatron
71. Low Energy Accelerators for Cargo Inspection - World Scientific Publishing, accessed October 15, 2025, https://www.worldscientific.com/doi/full/10.1142/S179362681530008X
72. New Microfocus Linear Accelerators Called MicroBeam Linatron (MBL) at Varex Imaging | Request PDF - ResearchGate, accessed October 15, 2025, https://www.researchgate.net/publication/394204388_New_Microfocus_Linear_Accelerators_Called_MicroBeam_Linatron_MBL_at_Varex_Imaging
73. Industrial X-ray Components - Varex Imaging, accessed October 15, 2025, https://www.vareximaging.com/industrial-x-ray-components/
74. diondo linac systems - High-energy CT with a linear accelerator, accessed October 15, 2025, https://www.diondo.com/en/linac-systems
75. high-power industrial computed tomography - TEC Eurolab, accessed October 15, 2025, https://www.tec-eurolab.com/en/high-power-industrial-computed-tomography/
76. Computed Tomography (CT) for nondestructive testing - VCxray, accessed October 15, 2025, https://vc-xray.com/technologies/computed-tomography/
77. Deep Filtered Back Projection for CT Reconstruction - PMC, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11361368/
78. Iterative Reconstruction in CT | Image Wisely, accessed October 15, 2025, https://www.imagewisely.org/Imaging-Modalities/Computed-Tomography/Iterative-Reconstruction-in-CT
79. Deep Learning Image Reconstruction for CT: Technical Principles and Clinical Prospects, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9968777/
80. Filtered back projection | Radiology Reference Article | Radiopaedia ..., accessed October 15, 2025, https://radiopaedia.org/articles/filtered-back-projection-1
81. Image Reconstruction Algorithm Using Weighted Mean of Ordered ..., accessed October 15, 2025, https://www.mdpi.com/2227-7390/10/22/4277
82. Benchmarking of different reconstruction algorithms for industrial cone-beam CT, accessed October 15, 2025, https://www.researchgate.net/publication/368822243_Benchmarking_of_different_reconstruction_algorithms_for_industrial_cone-beam_CT
83. Tomographic reconstruction strategies for nondestructive testing with a commercial CT scanner - Frontiers, accessed October 15, 2025, https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2023.1287059/full
84. Iterative Tomographic Image Reconstruction Algorithm Based on Extended Power Divergence by Dynamic Parameter Tuning - MDPI, accessed October 15, 2025, https://www.mdpi.com/2313-433X/10/8/178
85. Development and Evaluation of Image Reconstruction Algorithms for a Novel Desktop SPECT System - PubMed Central, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC5482917/
86. COMPARISON AMONG TOMOGRAPHIC RECONSTRUCTION ALGORITHMS WITH A LIMITED DATA - INIS-IAEA, accessed October 15, 2025, https://inis.iaea.org/collection/NCLCollectionStore/_Public/43/048/43048827.pdf
87. The λ-MLEM Algorithm: An Iterative Reconstruction Technique for Metal Artifact Reduction in CT Images | Request PDF - ResearchGate, accessed October 15, 2025,

https://www.researchgate.net/publication/226941798_The_l-MLEM_Algorithm_An_Iterative_Reconstruction_Technique_for_Metal_Artifact_Reduction_in_CT_Images
88. A Review of Deep Learning CT Reconstruction: Concepts, Limitations, and Promise in Clinical Practice - ResearchGate, accessed October 15, 2025, https://www.researchgate.net/publication/362298388_A_Review_of_Deep_Learning_CT_Reconstruction_Concepts_Limitations_and_Promise_in_Clinical_Practice
89. State-of-the-Art Deep Learning CT Reconstruction Algorithms in ..., accessed October 15, 2025, https://pubs.rsna.org/doi/abs/10.1148/rg.240095
90. Computed Tomography Effective Dose and Image Quality in Deep Learning Image Reconstruction in Intensive Care Patients Compared to Iterative Algorithms - MDPI, accessed October 15, 2025, https://www.mdpi.com/2379-139X/10/6/69
91. A Systematic Literature Review of 3D Deep Learning Techniques in Computed Tomography Reconstruction - MDPI, accessed October 15, 2025, https://www.mdpi.com/2379-139X/9/6/169
92. Robotic X-Ray & CT Systems - VOXLS 30 Series - Nikon Metrology Inc., accessed October 15, 2025, https://industry.nikon.com/en-us/products/x-ray-ct/voxls-30-series/
93. The application of metal artifact reduction methods on computed tomography scans for radiotherapy applications: A literature review - PMC, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8200502/
94. CT metal artifact reduction algorithms: Toward a framework for objective performance assessment - PMC - PubMed Central, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7496341/
95. Optimization of empirical beamhardening correction algorithm - SPIE Digital Library, accessed October 15, 2025, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/12304/1230433/Optimization-of-empirical-beam-hardening-correction-algorithm/10.1117/12.2647155.pdf
96. Material Characterization using Spectral X-ray CT - Data Science ..., accessed October 15, 2025, https://data-science.llnl.gov/sites/data_science/files/material_characterization_using_spectral_x-ray_ct.pdf
97. Photon Counting Detectors PCD - NeuroLogica Corp., accessed October 15, 2025, https://www.neurologica.com/products/photon-counting-detector-pcd
98. Photon-counting detector CT: early clinical experience review - PMC, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10321251/
99. Tutorial on X-ray photon counting detector characterization - PMC, accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC5909414/
100. MetalJet X-ray sources - Excillum, accessed October 15, 2025, https://www.excillum.com/products/metaljet/
101. Revolutionizing X-Ray Technology: The Emergence of Liquid Metal Jet Anode Systems, accessed October 15, 2025, https://www.ijset.in/wp-content/uploads/IJSET_V13_issue2_474.pdf
102. SC-XRD Sources - Bruker, accessed October 15, 2025, https://www.bruker.com/en/products-and-solutions/diffractometers-and-x-ray-microscopes/single-crystal-x-ray-diffractometers/sc-xrd-components/sources.html
103. Excillum - The source for X-ray innovation, accessed October 15, 2025,

https://www.excillum.com/
104. In-Line Phase-Contrast X-ray Imaging and Tomography for Materials ..., accessed October 15, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC5458972/
105. Phase-contrast X-ray imaging - Wikipedia, accessed October 15, 2025, https://en.wikipedia.org/wiki/Phase-contrast_X-ray_imaging
106. (PDF) In-Line Phase-Contrast X-ray Imaging and Tomography for Materials Science, accessed October 15, 2025, https://www.researchgate.net/publication/235655961_In-Line_Phase-Contrast_X-ray_Imaging_and_Tomography_for_Materials_Science
107. Grating-Based X-Ray Computed Tomography for Improved Contrast on a Heterogeneous Geomaterial - Frontiers, accessed October 15, 2025, https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2022.878738/full
108. 4D CT in the Geosciences | Bruker, accessed October 15, 2025, https://www.bruker.com/en/applications/minerals-mining-and-petrochemical/oil-and-gas-exploration-upstream/exploration-and-geologic-characterization/4d-ct-in-the-geosciences.html
109. 4D Computed Tomography for the Analysis of Dynamic Properties of Metallic Additive Manufactured Components, accessed October 15, 2025, https://d-nb.info/1355240808/34
110. Unlocking the Secrets of Additive Manufacturing: Real-time ... - AZoM, accessed October 15, 2025, https://www.azom.com/article.aspx?ArticleID=23359
111. Dynamic CT in Additive Manufacturing - YouTube, accessed October 15, 2025, https://www.youtube.com/watch?v=g-zSV20RX3k
112. Image reconstruction for sparse-view CT and interior CT ..., accessed October 15, 2025, https://qims.amegroups.org/article/view/2233/html
113. Improved compressed sensing-based algorithm for sparse-view CT image reconstruction, accessed October 15, 2025, https://pubmed.ncbi.nlm.nih.gov/23606898/
114. (PDF) Compressed sensing-based image reconstruction for discrete tomography with sparse view and limited angle geometries - ResearchGate, accessed October 15, 2025, https://www.researchgate.net/publication/393618937_Compressed_sensing-based_image_reconstruction_for_discrete_tomography_with_sparse_view_and_limited_angle_geometries
115. Sparse-View Computed Tomography Reconstruction Based on a Novel Improved Prior Image Constrained Compressed Sensing Algorithm - MDPI, accessed October 15, 2025, https://www.mdpi.com/2076-3417/13/18/10320
116. In-line Robotic CT Delivers Real-Time Quality Feedback – Metrology ..., accessed October 15, 2025, https://metrology.news/in-line-ct-delivers-real-time-quality-feedback/
117. How AI Is Revolutionizing NDT in Industrial Applications - Baker Hughes, accessed October 15, 2025, https://www.bakerhughes.com/waygate-technologies/blog/how-ai-revolutionizing-nondestructive-testing-industrial-applications
118. Automated Industrial CT Scanners | X-Ray Automation Systems - North Star Imaging Inc, accessed October 15, 2025, https://4nsi.com/systems/robotix/