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Original Article

Design of an EPICS-Driven Real-Time Control System for Dental CBCT Imaging and Dose Management

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Abstract: *Dental cone-beam computed tomography (CBCT) provides high-resolution three-dimensional imaging but introduces concerns regarding patient radiation exposure [1]–[3]. While conventional dose optimization strategies rely on static protocols [4], [5], real-time adaptive control for CBCT remains largely unexplored [6], [9], [10]. This paper proposes a conceptual EPICS-driven real-time control architecture for dental CBCT imaging and dose management [7], [8]. The architecture introduces a supervisory control layer that interfaces with CBCT hardware, radiation monitoring systems, and adaptive optimization logic, enabling low-latency feedback and safety-aware operation without disrupting existing imaging pipelines [6], [9]. Key features include modular hardware abstraction, closed-loop dose management, and extensible supervisory interfaces for visualization and clinical oversight [7], [8]. Feasibility analysis indicates that the proposed framework is compatible with existing CBCT platforms, supports adaptive dose control within diagnostic constraints, and provides a foundation for future research into intelligent, patient-centric imaging systems [1]–[5]. Future work will focus on prototype implementation, digital twin-based validation, and integration with data-driven optimization strategies [6], [9], [7].*

Keywords: *Dental CBCT, EPICS, Real-Time Control, Radiation Dose Management, Adaptive Dose Optimization, Supervisory Control, Medical Imaging Systems.*

1. Introduction

Dental cone-beam computed tomography (CBCT) has become an indispensable imaging modality in modern dental and maxillofacial practice due to its ability to generate high-resolution three-dimensional (3D) anatomical representations. Compared to conventional two-dimensional radiographic techniques, CBCT enables improved visualization of complex anatomical structures, thereby supporting advanced clinical applications such as implant planning, orthodontic assessment, and maxillofacial surgery. Despite these advantages, CBCT imaging relies on ionizing radiation, and its increasing clinical adoption has intensified concerns regarding patient radiation exposure and long-term radiological risk [1], [2]. Previous investigations have demonstrated that the radiation dose delivered during dental CBCT examinations varies widely depending on system design, exposure parameters (e.g., tube voltage, tube current, and scan time), and the selected field of view (FOV) [3]. Consequently, a substantial body of research has focused on dose optimization strategies aimed at reducing patient exposure while preserving diagnostically acceptable image quality. These strategies typically involve protocol optimization, parameter tuning, or comparative evaluations of effective dose across CBCT systems [4], [5]. While such approaches have contributed to improved dose efficiency, they are predominantly static in nature and rely on predefined acquisition settings rather than adaptive control mechanisms.

In contrast, real-time control and feedback-based optimization have been successfully employed in other imaging and instrumentation domains to dynamically adjust system behavior in response to measured conditions. In medical computed tomography, for example, automatic exposure control techniques modulate tube current based on patient attenuation characteristics to achieve dose reduction [6]. However, the integration of comparable real-time adaptive control frameworks within dental CBCT systems remains limited, particularly with respect to distributed system coordination and scalable software architectures. The Experimental Physics and Industrial Control System (EPICS) is an open-source framework specifically developed for building large-scale, distributed, and real-time control systems. EPICS has been extensively deployed in scientific facilities such as particle accelerators, synchrotron light sources, and other complex instrumentation environments where reliable device coordination and low-latency data exchange are critical [7]. Its modular architecture, process variable abstraction, and support for real-time monitoring and feedback make EPICS well suited for applications requiring deterministic control and high system availability.

Despite its proven effectiveness in industrial and scientific domains, the application of EPICS to medical imaging systems and dental CBCT in particular—has received minimal attention in the literature. Leveraging EPICS for CBCT control presents an opportunity to unify hardware control, radiation monitoring, and adaptive decision-making within a single real-time framework. Such integration could enable dynamic adjustment of imaging parameters based on operational conditions, patient-specific factors, or predefined dose constraints, thereby advancing the state of dose management in dental imaging. This paper proposes a **conceptual EPICS-driven real-time control architecture** for dental CBCT imaging and dose management. The proposed design outlines system components, control and data flows, and feedback mechanisms capable of supporting adaptive dose optimization during image acquisition. By introducing EPICS as a foundational control layer for dental CBCT systems, this work aims to establish a scalable and extensible framework that can support future developments in intelligent, safety-aware medical imaging systems.

2. Background and Literature Review

2.1. Dental CBCT Imaging and Radiation Exposure

Dental cone-beam computed tomography (CBCT) systems acquire volumetric datasets using a divergent X-ray beam and flat-panel detectors, enabling three-dimensional visualization of dentoalveolar and craniofacial structures. This imaging modality has become widely adopted in clinical dentistry due to its ability to provide spatial information that is not attainable with conventional two-dimensional radiography [1]. However, the radiation exposure associated with CBCT imaging has raised persistent concerns, particularly as CBCT examinations are increasingly performed for routine diagnostic tasks [2], [3]. Several studies have reported that the effective dose delivered by dental CBCT varies substantially across devices and clinical protocols, with differences attributed to scanner geometry, beam filtration, exposure duration, and selectable imaging volumes [2], [3]. Comprehensive dose surveys indicate that, under certain configurations, dental CBCT doses may approach or exceed those of traditional medical CT for limited anatomical regions [3]. These findings have reinforced the importance of dose-awareness and protocol optimization in dental imaging practice [4].

2.2. Dose Optimization Approaches in Dental CBCT

Research on dose optimization in dental CBCT has largely focused on modifying acquisition parameters to balance radiation exposure and diagnostic image quality [4], [5]. Investigations have shown that reducing tube current or exposure time can yield significant dose reductions when diagnostic requirements are modest, such as in orthodontic assessments [4]. Similarly, restricting the field of view to the region of clinical interest has been identified as one of the most effective dose-reduction strategies in CBCT imaging [5]. Beyond hardware-level parameter tuning, image processing and reconstruction techniques have also been explored to mitigate noise and enhance image quality at lower dose levels [4]. While these methods improve post-acquisition image interpretability, they do not address dose modulation during the imaging process itself. As a result, most current optimization strategies remain static, relying on predefined protocols rather than responsive control mechanisms [4].

2.3. Adaptive and Real-Time Control in CT Imaging

In the broader domain of medical computed tomography, real-time adaptive exposure control has been successfully employed to reduce patient dose. Automatic exposure control (AEC) systems dynamically adjust tube current in response to patient attenuation, either based on scout images or real-time sensor feedback [6], [9]. These methods demonstrate that feedback-driven control can substantially improve dose efficiency while maintaining image consistency [9]. Despite their success in conventional CT, similar real-time adaptive techniques have not been widely implemented in dental CBCT systems. This limitation is often attributed to the architectural rigidity of commercial CBCT platforms, which are typically designed as closed systems with limited support for external control logic or dynamic parameter adjustment [10]. Consequently, opportunities for real-time dose adaptation in dental CBCT remain largely unexplored [10].

2.4. EPICS as a Framework for Distributed Real-Time Control

The Experimental Physics and Industrial Control System (EPICS) is an open-source software framework developed to manage distributed control systems requiring real-time responsiveness and high reliability [7], [8]. EPICS introduces the concept of process variables to abstract physical device states and control signals, enabling consistent communication across heterogeneous hardware and software components [7]. Its architecture supports modular development, fault isolation, and scalable deployment [8].

EPICS has been extensively validated in large-scale scientific facilities, including particle accelerators and synchrotron light sources, where coordinated control of thousands of devices is required [8]. The framework's support for low-latency communication, event-driven feedback, and integration with higher-level data processing platforms makes it particularly well suited for safety-critical and time-sensitive applications [7], [8].

2.5. Identified Research Gap

Although dental CBCT dose optimization and real-time control systems have both been widely studied, they have evolved along largely independent trajectories. Dose optimization research has emphasized protocol design and retrospective analysis, while real-time control frameworks have been developed primarily in industrial and scientific instrumentation domains [4], [7]. The absence of a unifying control architecture capable of supporting adaptive dose management during CBCT acquisition represents a notable gap in the literature [7], [8]. To date, there is no reported work that investigates the application of EPICS as a foundational control layer for dental CBCT imaging systems [7], [8]. Leveraging EPICS in this context offers the potential to integrate hardware control, radiation monitoring, and adaptive optimization logic within a unified real-time framework. Addressing this gap, the present work proposes a conceptual EPIC

3. Proposed Epics-Driven System Architecture

3.1. Architectural Overview

The proposed system introduces an EPICS-driven real-time control architecture designed to coordinate dental CBCT image acquisition and radiation dose management within a unified control framework [7], [8]. Rather than modifying the internal imaging pipeline of the CBCT scanner, the architecture operates as an external supervisory control layer that interfaces with imaging hardware, radiation sources, and monitoring subsystems [7]. This approach preserves compatibility with existing CBCT designs while enabling extensible and adaptive control capabilities [7], [8].

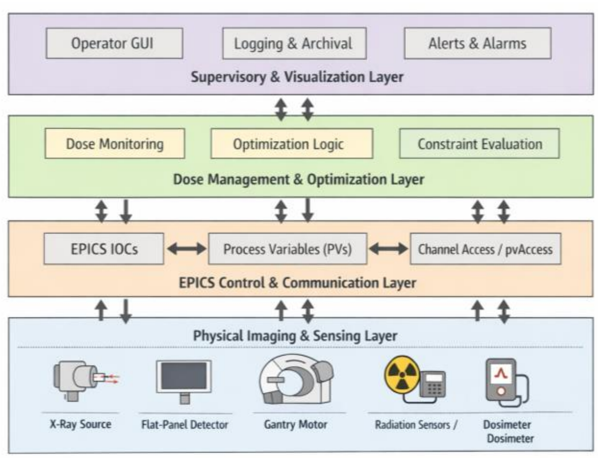

Fig 1: High-Level Architecture of the Proposed EPICS-Driven Real-Time Control System for Dental CBCT Imaging and Dose Management

At a high level, the architecture consists of four functional layers: (i) the physical imaging and sensing layer, (ii) the EPICS control and communication layer, (iii) the dose management and optimization layer, and (iv) the supervisory and visualization layer. These layers interact through well-defined interfaces to support deterministic control, real-time feedback, and safety-aware operation during CBCT acquisition [7], [8], [6].

3.2. Physical Imaging and Sensing Layer

The physical layer encompasses the CBCT scanner hardware, including the X-ray source, flat-panel detector, gantry rotation system, and associated radiation monitoring sensors [1]–[3]. Imaging parameters such as tube voltage, tube current, pulse duration, and gantry position are exposed as controllable or observable signals through hardware abstraction interfaces [7]. Additional sensing components, such as dosimeters or tube output monitors, provide real-time measurements of radiation emission and system state [2], [3]. This layer is intentionally decoupled from higher-level control logic, allowing the system to accommodate diverse CBCT hardware configurations [7]. Hardware signals are digitized and normalized before being mapped to control variables, ensuring consistent interaction with the EPICS framework regardless of vendor-specific implementations [7], [8].

3.3. EPICS Control and Communication Layer

The EPICS layer forms the core of the proposed architecture, providing standardized communication, synchronization, and real-time control across system components [7], [8]. Each hardware parameter and sensor output is represented as an EPICS process variable (PV), enabling uniform access to device states and control commands [7]. Input/output controllers (IOCs) are deployed to manage direct communication with imaging hardware and sensing devices [8].

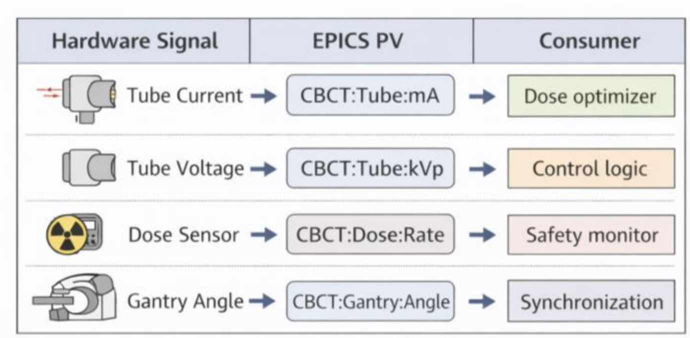

Fig 2: Example Mapping Between CBCT Hardware Signals and EPICS Process Variables Used For Monitoring and Control

Real-time updates of PVs allow continuous monitoring of system status, including radiation output, acquisition progress, and device health [7]. The use of EPICS Channel Access or pvAccess protocols ensures low-latency data exchange and supports event-driven control mechanisms [7], [8]. This layer also facilitates fault detection and recovery by enabling independent supervision of each subsystem through EPICS alarms and interlocks [7], [8].

3.4. Dose Management and Optimization Layer

Above the EPICS control layer resides the dose management and optimization module, which implements decision logic for adaptive dose control [6], [9]. This module consumes real-time data streams from EPICS PVs, including radiation measurements, acquisition timing, and predefined imaging constraints [7]. Based on these inputs, the module evaluates whether current operating conditions satisfy dose targets and diagnostic requirements [6], [9]. The optimization logic is intentionally modular and algorithm-agnostic, allowing rule-based strategies, heuristic approaches, or model-driven methods to be incorporated without altering the underlying control infrastructure [7], [8]. For example, exposure parameters may be adjusted incrementally when radiation output exceeds predefined thresholds or when acquisition conditions permit dose reduction without compromising image quality [6], [9]. Control decisions are translated into updated PV values, which are propagated back to the hardware through EPICS IOCs [7], [8].

3.5. Real-Time Control Loop and Safety Mechanisms

A closed-loop control mechanism governs the interaction between the physical layer and the optimization module [6], [9]. During CBCT acquisition, sensor data are continuously sampled and published as PV updates [7]. The dose management layer evaluates these updates in near real time and issues control adjustments as needed [6], [9]. Timing constraints are enforced to ensure that control actions do not disrupt imaging stability or introduce unacceptable latency [6].

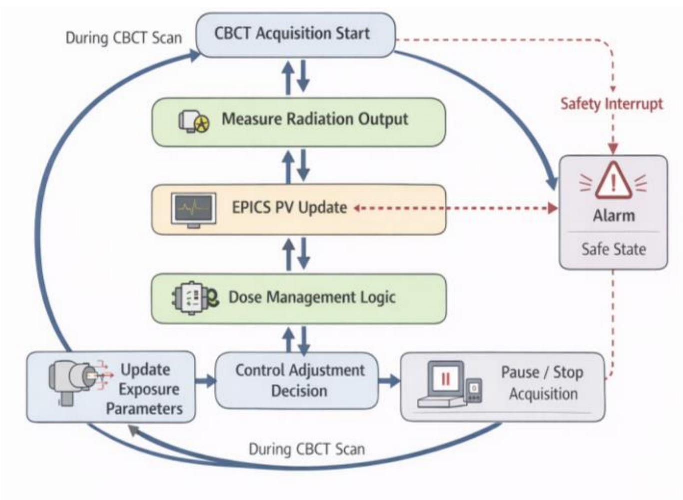

Fig 3: Closed-Loop Real-Time Control Workflow for Adaptive Dose Management during CBCT Acquisition

Safety is treated as a first-class architectural concern. Hardware interlocks, EPICS alarm handlers, and predefined safe operating envelopes collectively ensure that system behavior remains within regulatory and operational limits [7], [8]. In the event of abnormal conditions such as excessive radiation output or communication failure—the architecture supports immediate transition to a safe state, including suspension of acquisition or reversion to conservative exposure settings [7], [8].

3.6. Supervisory Control and Visualization Layer

The supervisory layer provides interfaces for clinicians, operators, and system engineers to observe system behavior and configure imaging protocols [7]. Graphical user interfaces (GUIs) built on EPICS client tools enable real-time visualization of radiation metrics, acquisition status, and control actions [7], [8]. This layer also supports logging and archival of operational data for post-procedure analysis, quality assurance, and regulatory documentation [7]. Importantly, supervisory functions are logically separated from real-time control paths, ensuring that user interactions do not interfere with time-critical operations [7], [8]. This separation enhances system robustness while enabling transparency and traceability of dose management decisions [7], [8].

3.7. Architectural Benefits and Extensibility

The proposed EPICS-driven architecture offers several advantages over conventional CBCT control designs. By decoupling control logic from imaging hardware, it enables incremental upgrades and research-driven experimentation without requiring fundamental system redesign [7], [8]. The use of standardized process variables and modular control components facilitates integration with external analytics platforms, simulation tools, or future machine learning-based optimization modules [7], [8]. While this work focuses on dental CBCT imaging, the architectural principles described here are broadly applicable to other medical imaging systems requiring coordinated real-time control and safety-aware operation [7], [8], [6]. The proposed design thus establishes a foundation for future research into intelligent, adaptive imaging workflows [7], [8].

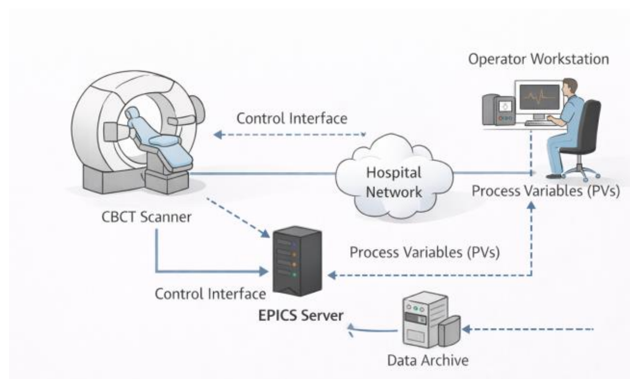

Fig 4: Illustrative Deployment Scenario of the Proposed EPICS-Based CBCT Control System in a Clinical Imaging Environment

4. Feasibility and Discussion

4.1. Technical Feasibility of EPICS Integration

The proposed EPICS-driven architecture is technically feasible due to the modular and hardware-agnostic design principles inherent in EPICS [7], [8]. By abstracting hardware interfaces through process variables, EPICS allows imaging devices, sensors, and control logic to be integrated without tight coupling to vendor-specific implementations [7], [8]. This abstraction is particularly advantageous in dental CBCT systems, where hardware configurations and control interfaces vary across manufacturers [1]–[3].

Table 1: Comparison between Conventional CBCT and Proposed Architecture

Feature	Conventional CBCT	Proposed Architecture
Control model	Static	Adaptive
Dose adjustment	Predefined	Real-time
Extensibility	Limited	Modular
Safety monitoring	Hardware-only	Hardware + software
Research flexibility	Low	High

From a real-time performance perspective, EPICS has demonstrated reliable operation in environments that require deterministic control and continuous data acquisition [7], [8]. The latency requirements of CBCT dose adjustment typically on the order of milliseconds to tens of milliseconds are well within the operational envelope of EPICS-based control systems when deployed on real-time operating systems or appropriately configured Linux platforms [6], [9]. Consequently, the proposed control loop can be implemented without interfering with mechanical motion control or detector synchronization [6], [9].

4.2. Compatibility with Existing CBCT Platforms

A key design objective of the proposed architecture is compatibility with existing CBCT systems [1]–[3], [7]. Rather than replacing proprietary imaging controllers, the EPICS layer functions as a supervisory control system that interfaces with accessible control points and monitoring outputs [7], [8]. This design minimizes disruption to certified imaging pipelines while enabling external oversight and adaptive parameter modulation [7]. In practical deployments, integration would likely be performed through standard industrial communication protocols or manufacturer-provided control interfaces [7], [8]. Although the degree of access varies across CBCT platforms, the architecture supports incremental adoption, allowing dose monitoring and advisory functions to be introduced prior to closed-loop control [7]. This phased integration strategy enhances feasibility in clinical and industrial contexts [1]–[3].

4.3. Dose Optimization Without Image Quality Degradation

A central concern in adaptive dose management is the potential impact on image quality [4], [5]. The proposed architecture addresses this issue by positioning dose optimization as a constrained control problem rather than an unconstrained minimization task [6], [9]. Exposure parameters are adjusted only within predefined diagnostic envelopes that are determined by clinical requirements and imaging objectives [4], [5]. Furthermore, the architecture allows optimization logic to be informed by contextual information such as anatomical region, scan purpose, and acquisition phase [4], [5]. By incorporating conservative decision thresholds and fallback configurations, the system ensures that dose reductions do not compromise the interpretability or clinical utility of reconstructed images [4], [5]. This approach aligns with existing radiation protection principles while enabling more responsive dose management [4], [5].

4.4. Safety, Reliability, and Regulatory Considerations

Medical imaging systems are subject to stringent safety and regulatory requirements, particularly with respect to radiation exposure and system reliability [2], [3]. The proposed architecture explicitly incorporates safety mechanisms at multiple levels, including hardware interlocks, EPICS alarm handling, and predefined safe operating bounds [7], [8]. These mechanisms ensure that adaptive control actions remain subordinate to certified safety controls [7], [8]. From a regulatory standpoint, the EPICS layer can be positioned as a supervisory and monitoring subsystem rather than a primary imaging controller [7], [8]. This distinction is significant, as it allows the core imaging system to retain its certified status while enabling research-driven enhancements in dose management [7], [8]. Extensive logging and traceability features further support compliance with quality assurance and audit requirements [7], [8].

4.5. Scalability and Extensibility

The scalability of the proposed architecture is one of its defining strengths [7], [8]. EPICS naturally supports distributed deployment, enabling additional sensors, control points, or analytical modules to be integrated without architectural restructuring [7], [8]. This capability is particularly relevant for future CBCT systems that may incorporate advanced detectors, patient-specific sensing, or multi-modal imaging components [1]–[3]. The modular design also facilitates the integration of simulation-based validation, digital twins, or data-driven optimization algorithms [6], [9]. While such enhancements are beyond the scope of the present work, the proposed architecture establishes a foundation upon which these advanced capabilities can be developed and evaluated in future studies [7], [8].

4.6. Limitations and Practical Challenges

Despite its potential advantages, the proposed architecture is subject to several limitations [1]–[3], [7]. Access to low-level control interfaces in commercial CBCT systems may be restricted, limiting the granularity of real-time control [1], [3]. Additionally, achieving deterministic timing behavior in general-purpose operating systems requires careful system configuration and validation [6], [9].

Table 2: Key implementation challenges and potential mitigation strategies for EPICS-based CBCT dose control.

Challenge	Impact	Mitigation Approach
Limited hardware access	Reduced control granularity	Supervisory integration
Real-time constraints	Latency risk	RT Linux / prioritization
Regulatory approval	Deployment delay	Non-invasive control layer

Validation difficulty	Lack of data	Simulation and phantoms

Another challenge lies in validating adaptive dose control strategies in clinical settings, where ethical, regulatory, and logistical constraints limit experimental flexibility [1], [3], [4]. As this work presents a conceptual design, empirical validation through simulation, phantom studies, or controlled prototypes is identified as an important direction for future research [6], [9], [7].

4.7. Discussion Summary

The feasibility analysis indicates that EPICS-driven real-time control architecture for dental CBCT dose management is both technically viable and conceptually aligned with current trends in intelligent medical imaging systems [7], [8], [6]. By combining proven control system principles with domain-specific imaging constraints, the proposed design addresses a critical gap between static dose optimization and adaptive, safety-aware imaging workflows [1]–[5]. While practical challenges remain, the architecture provides a structured and extensible pathway toward more responsive and patient-centric CBCT imaging systems [7], [8], [6].

5. Conclusion and Future Work

This paper presented a conceptual design for an EPICS-driven real-time control architecture tailored to dental cone-beam computed tomography (CBCT) imaging and radiation dose management [1]–[3], [7], [8]. Motivated by the limitations of static dose optimization approaches and the lack of extensible control frameworks in current CBCT systems [4], [5], the proposed architecture introduces a structured supervisory control layer capable of coordinating imaging hardware, radiation monitoring, and adaptive control logic within a unified real-time environment [7], [8]. By leveraging the modular and distributed capabilities of EPICS, the design enables consistent device abstraction, low-latency feedback, and safety-aware operation without disrupting existing imaging pipelines [6], [9]. The proposed architecture addresses a critical gap between established dose optimization research and practical system-level control solutions [4], [5], [7]. Rather than focusing solely on imaging algorithms or protocol tuning, this work emphasizes system integration and control orchestration as foundational elements for intelligent dose management [7], [8]. The layered design supports incremental deployment, robust fault handling, and extensibility, making it suitable for research-driven innovation as well as potential clinical translation [7], [8]. Although no experimental validation is presented, the feasibility analysis demonstrates that the architectural principles align with the operational requirements of dental CBCT imaging systems and established real-time control practices [6], [9]. Future work will focus on validating and extending the proposed architecture through simulation and prototype implementation [7], [8]. One immediate direction involves developing a digital twin of a CBCT system to evaluate control latency, stability, and dose reduction potential under realistic acquisition scenarios [6], [9]. Additionally, rule-based optimization strategies may be augmented with data-driven or model-based approaches to further refine adaptive dose management while preserving diagnostic image quality [4], [5]. Integration with clinical workflow systems and regulatory compliance frameworks will also be explored to assess real-world deployability [2], [3], [7]. Ultimately, the architecture presented in this work lays the groundwork for future investigations into intelligent, adaptive, and safety-oriented control systems for dental CBCT and other medical imaging modalities [7], [8], [6].

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