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A NEW MODULAR WHOLE BODY X- RAY SCANNER – INITIAL RESULTS

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Index Terms Medical imaging, x-ray imaging hardware, Plug- Integrate-Play (PIP) medical device development hardware

Abstract— This study presents the design, implementation, and initial performance evaluation of a modular whole-body X-ray scanner based on a Time Delay Integration (TDI) line-scanning architecture. The proposed system was developed using the previously reported open-hardware control platform, SyncBox, and the modular open-source software platform, iBEX, within a customizable Plug-Integrate-Play (PiP) framework for medical imaging device development. By integrating commercially available components with a multilayer control architecture, the system enables synchronized coordination of the X-ray source, TDI detector, motorized mechanical structure, safety sensors, and workstation software. The scanner was designed to support whole-body imaging with enhanced mechanical maneuverability, reduced dependence on patient repositioning, and flexible integration of alternative detector technologies. Initial experimental evaluations, including mechanical motion analysis, calibration alignment, and phantom-based image quality assessment, confirmed stable electromechanical synchronization and high-resolution imaging performance. The results indicate that the proposed modular architecture can provide a practical platform for developing customizable, interoperable, and cost-effective radiographic imaging systems. This approach may serve as a foundation for future open-platform medical imaging devices, including whole-body radiography as well as other direct X-ray imaging modalities.

INTRODUCTION

Medical X-ray systems have been regarded as the gold standard in medical diagnostics for more than 100 years. During this period, the prevailing manufacturing approach has been to develop dedicated X-ray imaging devices for specific sets of clinical examinations [1]. For example, early projectional X-ray scanners were designed for the detection of bone fractures and degenerative changes, fluoroscopic systems were developed for cine-imaging during angiographic interventions, mammography systems were introduced for breast cancer screening, cephalometric imaging systems were developed for the assessment of teeth and jaw structures, and whole-body X-ray scanners have been used for trauma assessment and bone surveys [2]–[5].

A more recent trend in medical product development is the design of modular devices [10,11]. In this paradigm, each medical setup is composed of a set of certified and interoperable components. Accordingly, component interoperability has been defined across five levels [12,13]. At higher levels, namely semantic, pragmatic, and dynamic interoperability, components can exchange information more readily, whereas at lower levels, namely technical and syntactic interoperability, translation patches may be required. In contrast to conventional design approaches, interoperable devices enable healthcare centers to create highly customizable medical systems that meet their specific requirements without being constrained by manufacturers' predefined design decisions.

BACKGROUND

In current clinical practice, full-body examinations are typically performed by acquiring X-ray images of individual anatomical regions and subsequently combining them through digital stitching [17]. However, with the increasing demand for rapid and efficient whole-body imaging in medicine, several dedicated whole-body X-ray radiography scanners have been developed. These systems, which are distinct from tomographic modalities such as CT or DEXA, include slot-scanning and line-detector-based imaging platforms [18]–[20].

Such devices can provide sharp and seamless images of the entire patient body within a short acquisition time while operating in accordance with the As Low As Reasonably Achievable (ALARA) principle for X-ray dose optimization [21]. EOS imaging [18,19] is among the first scanner systems capable of generating full-body 3D images of patients in the standing position, as shown in Fig. 1. This system is primarily used for orthopedic imaging in patients with spine, hip, and lower-limb disorders.



Figure 1 EOS imaging. The patient withstand in fron of the two detectors and two X-ray tubes. Orthogonal fan shape X-ray beams is used to acquire biplanar images. These images are used for constructing a 3D model [18].

Lodox Statscan [22] completes (Fig. 2) a full body scan with a single exposure. In this scanner a slit scanning radiography (LSSR) reduces the patient dose [18]. The device is designed for different applications such as ventriculoperitoneal (VP) shunt visualization, emergency room arteriography (ERA), detection of foreign bodies, and pediatric emergency imaging [20], [23]–[25].

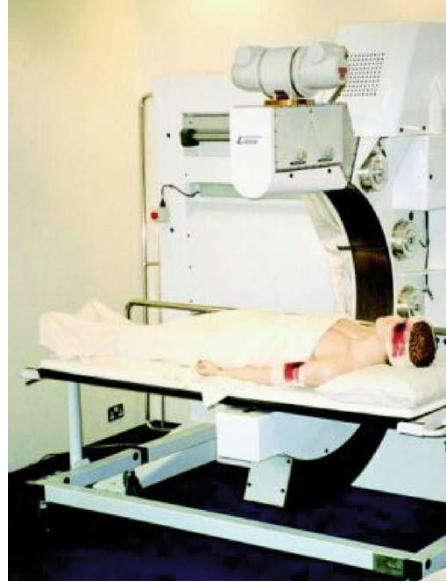


Figure 2 Lodox StatScan. C-arm scanner traces the whole body and provides a seamless radiography image [20].

When compared with conventional stitching-based techniques, these modalities allow seamless whole-body imaging to be achieved within a shorter acquisition time. In addition, slot-scanning and line-detector-based systems may offer advantages in terms of spatial resolution and scatter rejection, owing to their detector geometry and acquisition principles. Under appropriate imaging conditions, these characteristics may contribute to improved image quality [24,25].

In this study, we introduce a new modular whole-body X-ray scanner developed in accordance with Plug-Integrate-Play (PiP) principles [13,14]. Compared with currently available full-body scanners, the proposed design provides three principal advantages. First, its mechanical design overcomes several limitations associated with existing modalities. The system offers improved mechanical maneuverability, which may reduce the need for patient repositioning, particularly in trauma cases. Second, the modality is based on PiP principles. This study presents the initial performance results of a customizable TDI-based X-ray scanner that incorporates our previously reported open-hardware platform, SyncBox, and open-source software platform, iBEX. The dedicated hardware control platform, SyncBox [13], was used to implement multilayer system control and monitoring, as shown in Fig. 3. This architecture reduces development costs and facilitates interoperability between the imaging device and healthcare infrastructure. Third, the proposed design employs a Time Delay Integration (TDI) line scanner [15,16]. Compared with digital flat-panel detectors, TDI line scanners can provide higher spatial resolution and are less prone to geometrical deformation [13].

The iBEX software platform, developed within our research center, follows a modular and service-oriented architecture designed to support interoperability and extensibility. Core functions, including image acquisition, motor control, DICOM handling, and safety monitoring, are implemented as independent modules that communicate through well-defined APIs. This architecture enables the integration of new hardware components and imaging workflows without requiring modifications to the core system. The graphical user interface provides technicians with real-time system status, acquisition parameter control, and safety alerts, thereby improving usability in clinical environments. SyncBox is designed as a hardware-agnostic control platform that is compatible with third-party sensors, actuators, and detector systems through standardized electrical and communication interfaces. This flexibility allows alternative detectors, environmental sensors, and safety modules to be integrated with minimal reconfiguration. To enhance system transparency, block diagrams and assembly schematics illustrating the modular integration process are provided, showing the physical and logical connections between components [13].

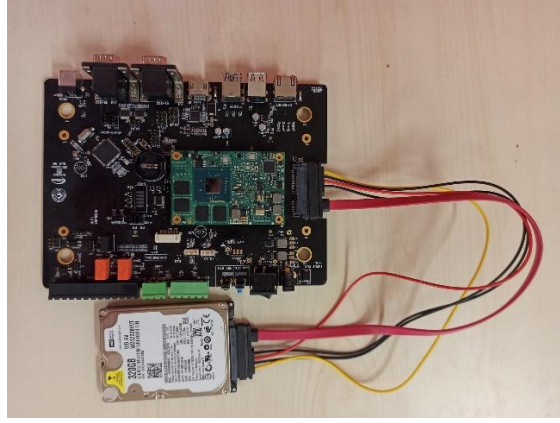


Fig. 3. SyncBox is an open-source hardware platform which realizes the Plug- integrate-Play (PiP) principle for medical X-ray radiography scanners. System both use CPU and microcontroller based connections. MicroProcessor Controlled Units and connections are used for advanced operations such as image acquisition, post processing, network based communication and user interface. Microcontroller Controlled Units and connections are responsible for fast and reliable communications: X-ray exposure control, emergency and safety sensors, mechanical driver communications. [13].

METHODOLOGY

This section presents the mechanical, biomedical, and electrical design characteristics of the proposed modular whole-body X-ray scanner. The design description aims to clarify both the potential advantages and the practical limitations of the proposed system. Building on previous work involving the open-source hardware control unit, SyncBox [13], and the modular open-source software platform, iBEX [14], a whole-body X-ray scanner was developed using commercially available components. The system design, simulation, and integration stages were completed, resulting in a functional prototype with substantial development potential.

I. Mechanical Design

The main components of the proposed design are shown in Fig. 4(a). The X-ray tube housing is designed to accommodate common cylindrical X-ray tubes weighing up to 40 kg. The collimator junction has a flexible structure, allowing both slit and rectangular collimator types to be attached. The detector housing supports both digital flat-panel detectors and TDI detectors with lengths of up to 50 cm. The imaging table measures 200 cm $\times$ 70 cm, and its upper surface is made of an X-ray radiolucent material. The control system manages motor power and coordinates emergency-related interactions. The X-ray tube and detector are mounted on an extendable arm, enabling controlled sliding motion over the tabletop.

The scanner incorporates a telescopic linear actuator, as shown in Fig. 4(a) and Fig. 4(b), to precisely adjust the distance between the X-ray source and the table. The table height is also adjustable, which facilitates patient positioning and is particularly advantageous in emergency situations. In addition, the table can rotate up to 90 degrees, enabling image acquisition while the patient is in a standing position. The extendable arm can slide along the table; however, it remains perpendicular to the tabletop at all times. When the table rotates, the arm rotates at the same angle. This mechanical constraint reduces the likelihood of shadow artifacts in the acquired X-ray images.

The object-to-image distance (OID) plays an important role in both scatter behavior and image geometry. Introducing an air gap between the object and the detector can reduce the amount of scattered radiation reaching the detector by allowing obliquely scattered photons to diverge away from the imaging plane. However, increasing the OID also results in greater geometric magnification, increased sensitivity to focal spot size-related unsharpness, and potential dose-related implications, which limit its practical use in many clinical radiography systems [26]. Therefore, in the proposed design, the OID is minimized and kept constant to reduce geometric distortion and positioning-related variability while maintaining consistent image quality. Since increasing the OID may also cause geometrical deformation in the image, the OID was fixed at 2.4 cm to prevent artifacts and reduce the likelihood of human error during detector positioning.

The X-ray intensity reaching the detector follows the inverse square law with respect to the source-to-image distance (SID) [27]. In clinical radiography, the primary objective is to achieve consistent and clinically useful image quality, which is closely associated with maintaining an appropriate detector dose rather than a fixed patient dose. Therefore, imaging geometry, particularly a minimized OID and fixed SID, is typically kept constant during an examination to preserve geometric consistency and prevent magnification-related artifacts.

In the proposed system, variations in patient size and anatomical thickness are compensated through adaptive control of the X-ray tube current–time product (mAs). The system supports variable tube current (mA) adjustment during scanning, enabling adaptive dose modulation according to patient-specific body characteristics while maintaining consistent detector exposure. This approach allows dose optimization without introducing the geometric inconsistencies associated with dynamic SID variation. Both approaches may be considered applicable depending on the intended clinical use case.

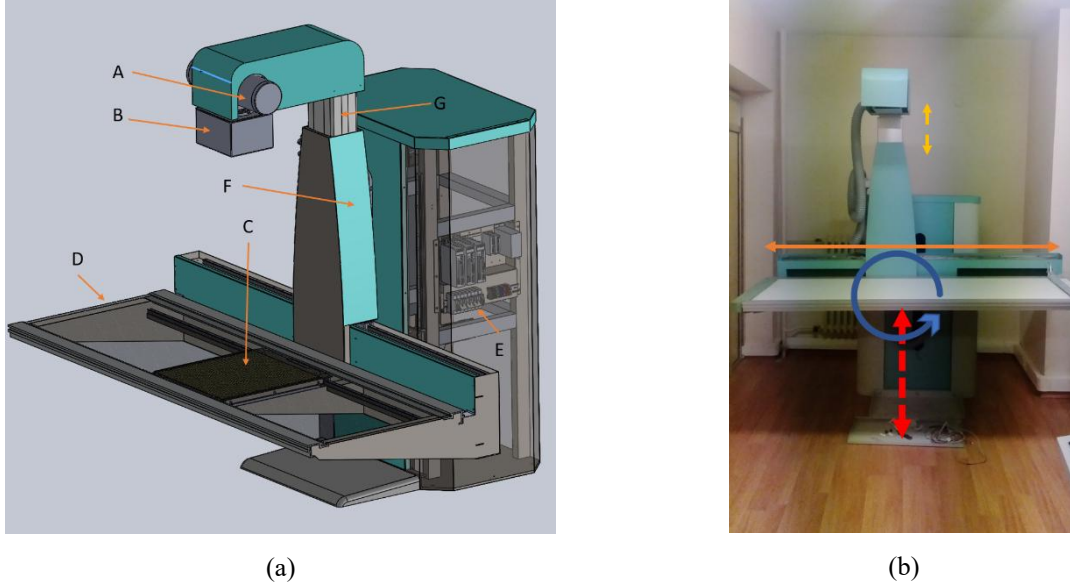


Figure 4 (a) A: is X-ray tube housing, B: Collimator, C: X-ray detector, D: scanning table, E: Control and motor driver, F: Extendable arm, G: telescopic linear actuator (b) The mechanism provides four degrees of freedom: table height from the floor, table angle, X-ray tube distance from table, and sliding the extendable arm over the table.

The scanner incorporates three servo motors that provide three independent axes of motion. A 400 W servo motor controls the vertical height of the table from the floor, a second 400 W servo motor enables the sliding motion of the X-ray tube over the patient table, and a 1 kW servo motor drives table rotation.

The most critical motion in this design is the transfer of sliding motor power to the detector and X-ray tube assembly, as shown in Fig. 5. For this purpose, a rack-and-pinion mechanism is used to convert rotational motion into linear motion. To reduce parasitic friction and ensure smooth arm movement under load, the rack-and-pinion mechanism is supported by two ball-rail systems, one positioned horizontally and the other vertically. In addition, two ball-rail mechanisms are used to support the detector housing and maintain detector balance. The specifications of the ball-rail systems were selected to maximize vibration damping and minimize friction-induced vibrations.

This mechanical stability is particularly important for TDI detectors, which have line widths in the micrometer range. In the present system, for example, a detector with a 25 μm pixel size is installed.

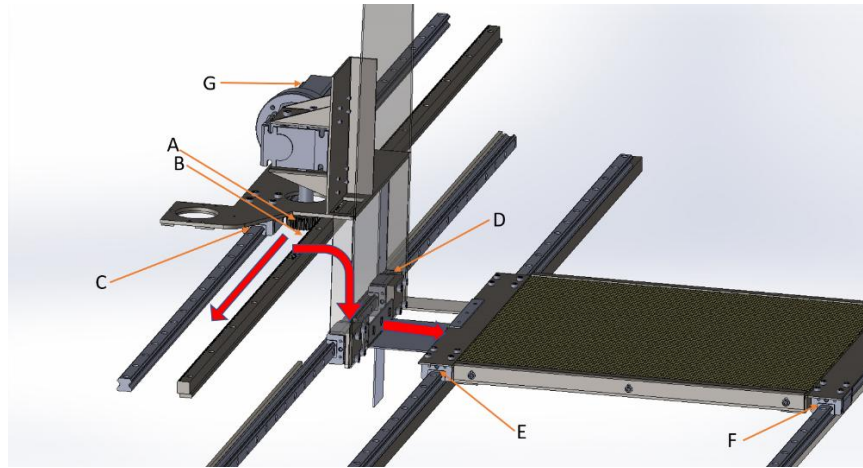


Figure 5 sliding mechanism for moving the detector and X-ray generator. A) pinion B) rack C) horizontal linear slide D) vertical linear sliding rail E, F) detector balance sliding rail. In this design all sliding rails daps the friction forces and provide a balancing counter torque.

Table rotation is driven by a 1 kW servo motor, as shown in Fig. 6. The motor is connected to a reductor, which converts the motor's rotational speed into higher output torque. The reductor operates in a one-way configuration; therefore, when the table is externally pushed or forced, it automatically locks and prevents external torque from being transferred back to the motor. This mechanism protects the motor against external loads, mechanical disturbances, and disruptive torques. In addition, a sensor integrated into the reductor provides overload feedback to the control system.

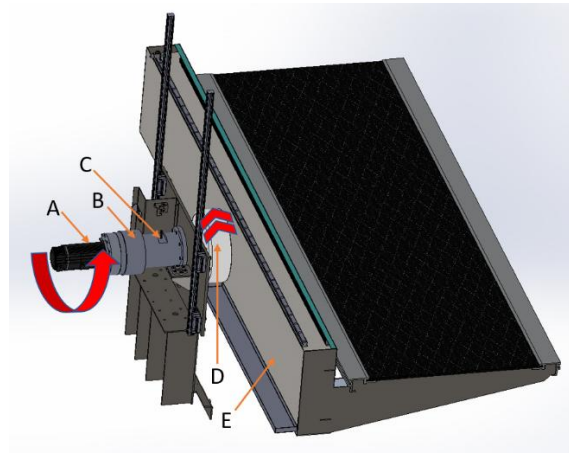


Figure 6 Table rotation mechanism. A) motor B) reductor C) reductor sensor D) table shaft joint E) table

The table height control motor is connected to two 90-degree reducers through a belt mechanism, as shown in Figure 7. These reducers increase the motor torque by a factor of 80 and transmit the resulting motion to the table through two threaded rods, as described in Equation 4. The use of two threaded rods, rather than a single rod, improves the mechanical stability of the table.

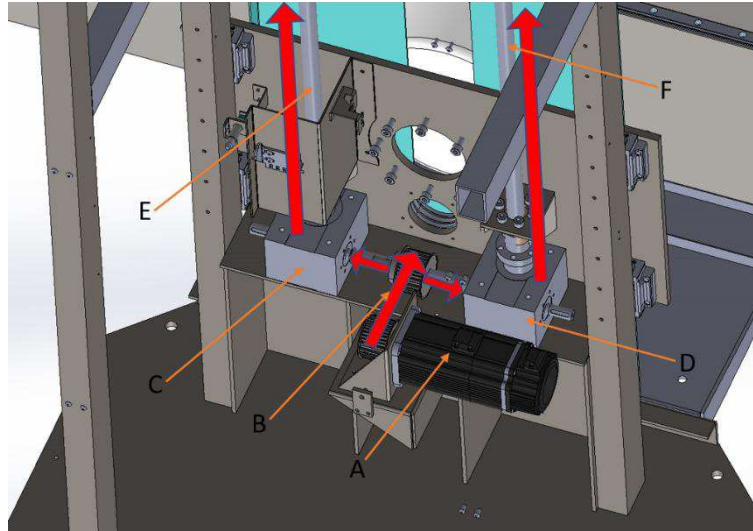


Figure 7 table height control mechanism. A) motor B) belt mechanism C, D) 90 degrees reductor E, F) threaded rods

II. Control Architecture and SyncBox

The mechanical design must be robust against abnormal operating conditions. For example, actuators may lose their reference origin during a power outage. When power is restored, the direction of subsequent movement may become non-deterministic. This uncertainty in motion direction may damage the device or pose a risk of patient compression. To mitigate such rare but critical risks, a multi-level control and protection architecture is implemented. The block diagram of the control units is shown in Fig. 8. The servo motor driver is responsible for supplying motor power and controlling motor torque, speed, and movement direction.

The motion programs are embedded within SyncBox as driver packages. These packages abstract the motor-driver-specific details from the workstation software, thereby simplifying higher-level system control.

SyncBox continuously monitors reset and emergency conditions and automatically intervenes in system operation when an abnormal condition is detected or when the emergency button is activated. In addition, proximity sensors are positioned at the extremities of the actuators and are triggered when an actuator reaches its end position. The outputs of these sensors, together with the load sensors of the reducers, are connected to a motion controller programmed to stop the motion automatically when the mechanical limit is reached. The motion controller is automatically engaged when communication between the driver and SyncBox is lost or when a power outage occurs. In such cases, it functions as a backup controller and returns the actuators to their default positions using UPS power.

SyncBox is an open-source hardware platform designed to integrate all components of a direct X-ray device into a unified hardware system. The system operates with the open-source software platform iBEX [14], which maintains essential functions such as X-ray exposure control and motor driver control, while also providing the fundamental requirements of a workstation environment [14]. The platform is intended to accelerate the implementation of novel and innovative device designs, with potential benefits in terms of reduced development cost and time. This approach is timely, given the ongoing shift in radiography system development from conventional “as-is” designs toward “Plug-Integrate-Play” (PIP) as a hardware design principle.

Unlike other open-source interoperability platforms [31], [42], [43], which primarily aim to establish connections between end systems, SyncBox introduces interoperability at the device design stage. Using SyncBox, manufacturers and developers can build systems tailored to their specific requirements. Similarly, healthcare institutions, academic researchers, and regulatory bodies can assemble customized radiography scanners according to their own needs. This platform democratizes the X-ray device manufacturing process and reduces the limitations imposed by prefabricated device designs, such as restrictions on detector and power source selection, which may affect the acquired data. In the long term, this platform may contribute to the development of more cost-effective radiography devices and shorten overall device manufacturing time.

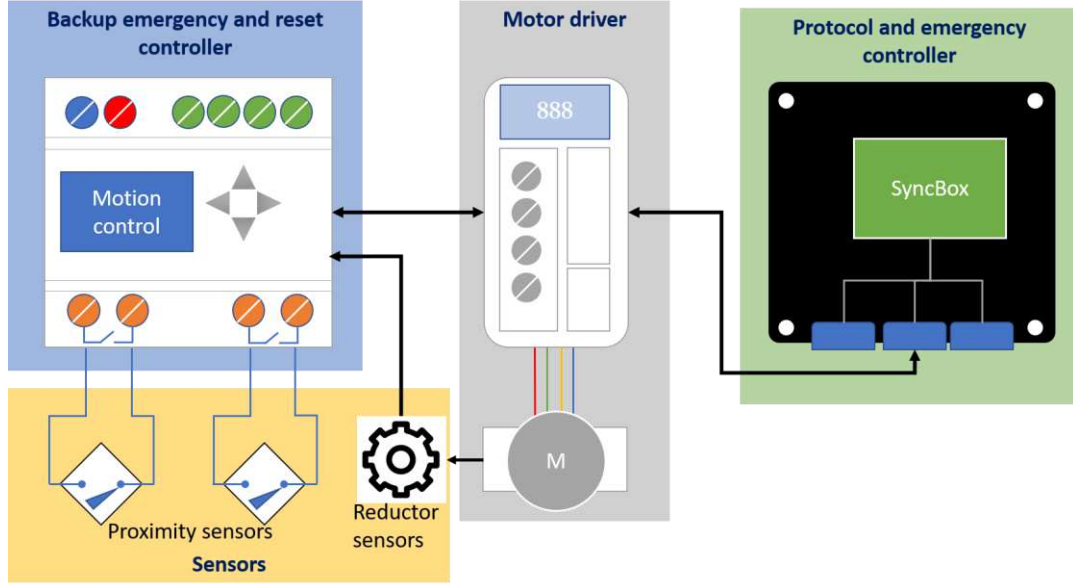


Figure 8 Connection loop to control proximity sensors

Communication between the motor drivers and the central workstation is established through SyncBox. This device provides a unified interface for all peripheral components. It transmits motion-planning commands to the servo motors, acquires data from peripheral sensors, monitors the air-conditioning systems, and communicates with the power generator. These capabilities enable the development of a highly customizable device architecture.

In combination with the iBEX software package [14], this controller implements the major workflows expected from a medical imaging workstation. The iBEX software operates together with the SyncBox hardware and is installed on the internal CPU-based computer system within SyncBox. The software includes acquisition protocols and parameters, DICOM infrastructure, an image-processing toolbox, a control GUI for technicians, logging and security algorithms, and other essential control and system-management functions.

For image acquisition, a TDI line-scanner sensor system was used. This sensor system is directly connected to SyncBox and operates synchronously with the X-ray source and the mechatronic motion systems [13].

RESULTS

Within the scope of this study, the critical performance characteristics of the proposed full-body X-ray scanner were evaluated. System performance was assessed in terms of both mechanical design and image quality, including spatial resolution evaluation, calibration alignment, and phantom-based testing.

I. Mechanical Design Evaluation

To smooth the motor speed command, an S-curve filter was applied, as shown in Fig. 9. The acceleration time was adjusted using the TACC parameter, while the deceleration time was controlled using the TDEC parameter. In the present configuration, both parameters were set to 200 ms. Optimization of the acceleration and deceleration periods is critical for maintaining image contrast and preserving spatial resolution up to the 25 μm pixel scale.

Using these parameters, the closed-loop system performance was evaluated over a wide range of input frequencies. As shown in Fig. 10, the -3 dB gain bandwidth of the closed-loop system was approximately 500 Hz, which is considerably higher than the normal operating frequency of the device. However, the phase response indicated that the control behavior shifted from lead to lag at frequencies above 10 Hz. Therefore, the operating point of the device was adjusted to approximately 10 Hz to ensure stable motion control and minimize motion-induced image degradation.

These findings indicate that the implemented motion-control strategy provides sufficient dynamic response for the intended scanning conditions. The S-curve-based velocity profile also reduces abrupt changes in acceleration, thereby limiting mechanical vibration and improving the synchronization between detector movement and image acquisition.

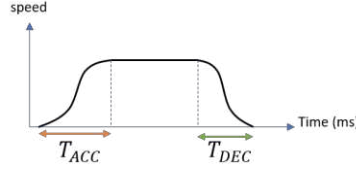


Figure 9 TSL, TACC are parameters used to tune the rise time and TSL and TDEC are used to control the declaration period.



Figure 10 Bode diagram of the control loop. The gain bandwidth is around 500 Hz and the zero phase happens around 10 Hz.

II. Image Quality Evaluation

To evaluate the imaging performance of the proposed scanner, a certified Pro-Digi X-ray resolution and contrast phantom was used. Image acquisitions were performed at variable tube voltages between 80 and 120 kVp, with a total beam filtration equivalent to 2.5 mm Al, under clinically representative exposure conditions. The source-to-image distance (SID) and object-to-image distance (OID) were kept constant throughout the experiments to minimize geometric variability.

A series of scans was conducted at different detector sweeping speeds to assess the influence of mechanical motion on image quality. The acquired images were evaluated in terms of spatial resolution, contrast visibility, and geometric distortion. Motion-induced artifacts were quantified by measuring edge displacement and modulation transfer consistency along the scan direction. The observed image deformation due to mechanical vibration was below 0.1%, indicating stable electromechanical synchronization during image acquisition.

Radiation output was characterized by measuring air kerma at a reference distance of 80 cm from the focal spot using a calibrated dosimeter. This reference dose measurement was used to ensure repeatable exposure conditions across all experiments and to enable comparison between different scanning speeds and acquisition settings. During all measurements, detector dose was maintained within a clinically relevant range for full-body radiographic examinations.

Image acquisition was performed using a TDI line detector synchronized with the mechanical sweeping motion of the scanner. The phantom was scanned at multiple table sweeping speeds ranging from 80 to 140 cm/min, while exposure parameters were kept constant. For each acquisition, the reconstructed images were analyzed in terms of spatial resolution, contrast response, and motion-induced artifacts.

Quantitative image quality analysis was performed using ImageJ software. Spatial resolution and contrast performance were assessed by extracting intensity profiles and histograms from predefined regions of interest corresponding to each step of the phantom. Mean contrast values and standard deviations were calculated for each step to evaluate contrast transfer characteristics, following established phantom evaluation procedures [44].

The Pro-Digi phantom images were further analyzed to verify contrast-detail detectability and line-pair resolution under dynamic scanning conditions. Representative phantom images and corresponding system outputs are presented in Figures 11–13. The results demonstrate that the proposed line-scanning architecture can maintain clinically acceptable image quality while enabling continuous full-body imaging.

In addition to phantom-based evaluation, the system outputs showed consistent alignment during dynamic scanning, suggesting that the mechanical sweeping mechanism and TDI acquisition timing were sufficiently synchronized. The absence of substantial geometric deformation across different scanning speeds further supports the stability of the integrated mechatronic and imaging architecture. Overall, these results indicate that the proposed system can achieve stable motion control, repeatable image acquisition, and adequate spatial resolution for whole-body radiographic imaging applications.

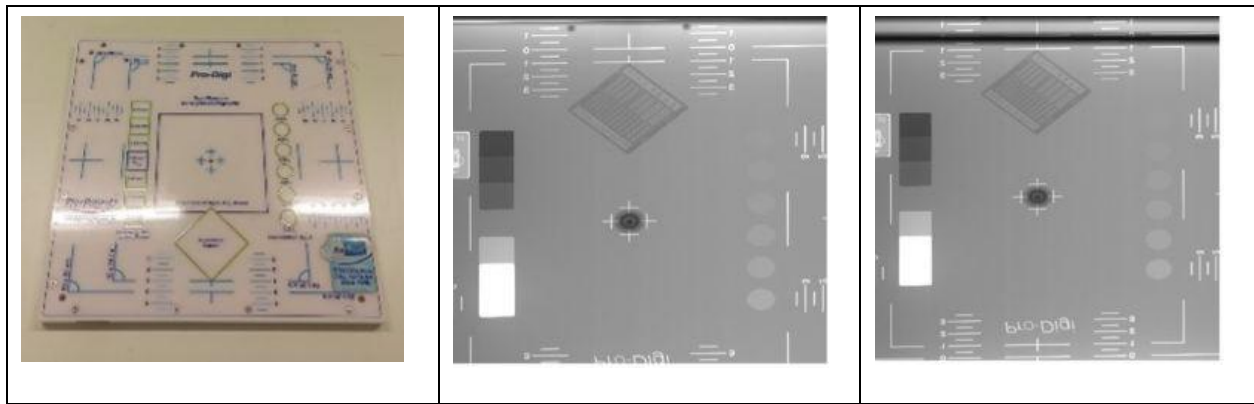


Fig. 11. Evaluation of the motion artifact on the image. (a) pro-project phantom is used (b) phantom image at 50 cm/min scan rate (c) 100 cm/min scan rate. Images has been obtained and evaluated regarding to IEC 61223-3-2 and system has been calibrated and optimized. 61223-3-2:1997 directives.



Fig. 12. Anatomical hand phantom is used to simulate a more realistic contrast examination situation. Victoreen Nuclear Associate Hand Phantom 76-634 x-ray image taken by SyncBox controlled TDI detector x-ray scanner. 0.5 mm aluminum filtration has been used.

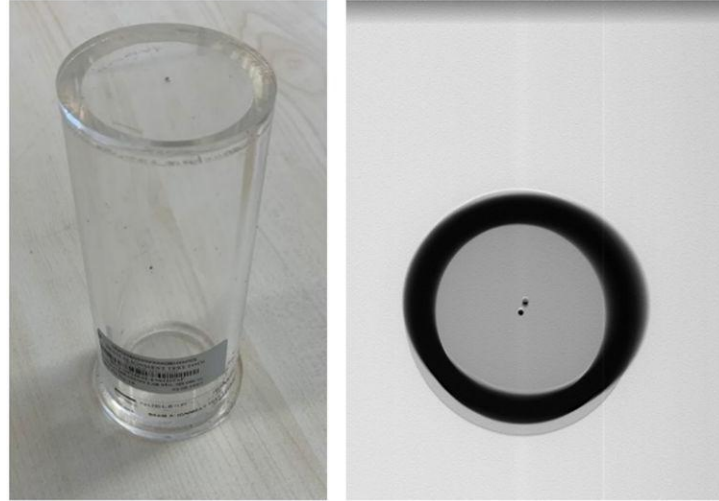


Fig. 13. Point Test Allignment Study to understand the effect of the motion. System has been geometrically calibrated. Phantom has been obtained from Nuclear Associat-s - Beam Allignment Test Tool.

DISCUSSION

Time Delay Integration (TDI) detectors offer several advantages over conventional digital flat-panel detectors. These detectors do not require a grid to filter scattered photons emerging from the patient, convert the incident X-ray dose into image signal more efficiently, and exhibit lower geometrical deformation compared with flat-panel detector systems. However, TDI-based imaging requires highly precise and accurate positioning and sweeping mechanisms. The mechanical design of the proposed full-body scanner was developed to address this requirement. The system was able to achieve an image resolution greater than 5 lp/mm, as shown in Fig. 13.

The control system of the proposed device is based on a multi-level protective architecture. The backbone of this architecture is the open-source SyncBox control unit [13]. This platform reduces device development costs and provides an interoperable framework for medical X-ray devices. Interoperable medical devices have become an increasingly important research and regulatory focus over the last 15 years, and both academic groups and regulatory bodies have been actively working to develop practical solutions for these requirements [28]–[30]. Open-source platforms that provide physical infrastructure for data and signal transfer between medical systems are also emerging, allowing devices and applications to be connected or disconnected on demand [31]. Regulatory standards define generic system models for device interoperation, equipment safety, security, and usability. However, the absence of a comprehensive open-source effort capable of meeting these criteria has limited the progress of existing platforms [32], [33].

A comparison between commercially available full-body radiographic systems and the newly developed scanner was conducted based on the published literature. The LODOX/Statscan system is a digital slit-scanning X-ray device primarily optimized for trauma imaging and rapid fracture detection [22]. The EOS system is a European-developed full-body imaging platform that employs a gaseous MicroMegas detector, originally developed by G. Charpak et al., and is widely used in orthopedic applications, particularly for spine and lower-limb imaging [25].

In contrast to these commercial systems, the TDI-based whole-body X-ray scanner developed at X-Lab, Boğaziçi University, serves as a proof-of-concept implementation demonstrating the capabilities of the proposed open-source control platform, SyncBox. In addition to this prototype system, conventional full-body imaging based on stitched radiographs was also considered. A comparative summary of conventional stitching-based imaging, LODOX, EOS, and the proposed TDI-based system is presented in Table 1, based on reported technical characteristics and literature findings.

The main objective of the proposed design was to achieve maximum mechanical maneuverability during both horizontal and vertical examinations, which is particularly important for trauma imaging. In contrast, the EOS design supports only horizontal scanning, while LODOX uses a C-arm mechanism with a fixed SID.

The developed system employs a TDI line-scanner architecture to improve spatial resolution and contrast performance. It also

provides a comparatively low radiation dose relative to commercial devices and offers a very fine pixel pitch. The system was developed using open-source tools and commercially available components. A comparison between the tested TDI sensors and a commercial flat-panel detector is presented in Table 2.

The broader trend in the development of medical systems, particularly medical imaging systems, is toward “customer-centric design” [6,7]. In this approach, manufacturers analyze market demands and feedback from healthcare centers, then identify a set of requirements that are refined and formalized into technical requirement documents. These documents guide the development of the final product. However, during design and implementation, manufacturers often need to make trade-offs among requirements due to budgetary and time constraints [8,9]. After device testing and evaluation are completed, the final product is introduced to the market. Since the customer is generally not directly involved in the development and implementation process, particularly in the trade-off decisions made by the manufacturer, the final product may not fully satisfy customer-specific requirements and may remain difficult to customize.

	LODOX	EOS	X-Lab Scanner
Scanning Time (seconds)	13	20	18
Radiation Dose (mGy)	0,33	0,92	0,76
Pixel Pitch (μm)	60	N/A	27
Image Resolution (lp/mm)	5	N/A	9
Main Focus	Trauma/Fracture	Scoliosis	Trauma / Emergency

Table 1. Device Comparison Chart, Lodox StatScan. EOS and newly improved X-Lab TDI Scanner technical comparison chart [19,21] “Radiation Dose” refers to the entrance surface air kerma measured at a fixed reference distance under standardized imaging conditions, as reported in the corresponding literature sources for each system. The reported values do not represent detector dose or patient effective dose, but rather the entrance dose to the imaged object, allowing a relative comparison between different full-body radiographic systems.

Step Value	TDI Detector		Flat Panel Detector	
	Standart Deviation	Mean Contrast Value	Standart Deviation	Mean Contrast Value
0	3.196	247	3.191	116
1	4.746	155	11.744	108
2	2.148	103	1.180	85
3	1.147	69	1.125	62
4	0.694	47	0.977	43
5	0.633	37	0.809	32
6	0.710	32	0.982	26

Table 2. Detector Contrast Comparison Detector contrast comparison by using step wedge phantom inside Pro-Digi Pro-Project 02.102. Each step histogram has been calculated using imageJ. Comparison variables are mean contrast value and standard deviation [44].

Successful integration in medical devices can be facilitated through open-source and Plug-and-Play (PnP) approaches, which may help address researchers’ demands for extensibility. The open-source movement has already provided stable, efficient, and cost-effective alternatives in various everyday applications [34], while the PnP paradigm has the potential to improve device

interoperability and human-machine interaction. Several examples of open-source medical hardware have been reported in the literature, including electrocardiogram systems, myoelectric prostheses, infusion pumps, physiological monitoring systems, EEG systems, and even CT scanners [31], [35]. However, due to the strict regulatory environment of the medical device ecosystem, users have generally been reluctant to adopt open-source solutions and PnP systems for applications requiring compliance with interoperable medical device standards [36], [37]. More recently, several efforts have aimed to change this perspective by bringing the medical device industry closer to the PnP paradigm and making it more accessible to the open-source community [37].

In practice, Medical PnP has already been successfully applied in the exchange of electronic health information [26]. In another example, a research group at the University of Florida developed a prototype system to synchronize an X-ray radiography device with a patient's breathing cycle in order to improve radiographic image quality in ventilated patients [39]. Additional examples have demonstrated that medical device interoperability and medical system integration can improve patient safety, particularly in clinical engineering applications such as the prioritization of ventilation system alarms [37], [40]. However, due to the continuing difficulty of crossing the "interoperability chasm," the medical device and health information technology (HIT) ecosystems have progressed relatively slowly, limiting the translation of many promising ideas intended to improve patient care [40], [41].

Despite the availability of alternative approaches, the proposed whole-body X-ray scanner represents an implementation outcome of the SyncBox and iBEX platforms, demonstrating how existing components and infrastructure can be reused through modular building blocks to support the development of safe and interoperable radiography systems. The smoothness of actuator relocation and the resulting image quality were evaluated, and the results indicated that both criteria were satisfied within acceptable tolerances. In addition, a TDI detector was replaced with a flat-panel detector, and SyncBox successfully integrated the alternative detector with minimal additional effort.

This research has the potential to be extended to several imaging platforms, beginning with direct X-ray-based systems such as fluoroscopy and mammography devices. In principle, the proposed approach could also be expanded in the future to support other modalities, including ultrasound devices or multimodality imaging systems. The platform has the potential to communicate with and control a wide range of devices and may be further extended to additional hardware components, such as transducers and advanced mechanical systems. However, such implementations would require collaborative effort and substantial support from imaging device component vendors and research teams, particularly for the necessary API integrations and software development.

A comparative study was conducted to demonstrate the potential of the proposed method. The PiP architecture abstracts certain hardware-specific details and enables researchers to develop new and customizable devices more rapidly. In this regard, it may contribute to the emergence of a new developmental approach and potentially an industrial standard for X-ray imaging systems.

In future work, we aim to further improve the proposed design and develop additional SyncBox-based X-ray imaging modalities, including fluoroscopy and mammography systems. If the necessary regulatory approvals can be obtained, preferably with the support of a medical device manufacturing company, we plan to complete the device performance evaluation and clinical testing stages.

CONCLUSION

The proposed modular whole-body X-ray scanner and its implementation were developed in accordance with established best practices in software, electrical, and system engineering. The main components and operational aspects of the system were modeled and documented at different levels of technical detail. These models and documentation are intended to support knowledge sharing among researchers and manufacturers, enabling the proposed architecture to be adapted, extended, and reused with different software and hardware components.

As a result of this study, a Plug-Integrate-Play (PiP) whole-body X-ray imaging device was developed and experimentally tested. The mechatronic structure, X-ray electronics, and software infrastructure were implemented and evaluated with reduced development cost, while also enabling flexible and centralized system control.

We believe that open-source system development and integration have considerable potential to support faster, more efficient, and cost-effective prototype development for innovative medical imaging devices. If this approach is adopted by different research groups and further improved within an open-platform framework, it may become a standard R&D tool for future medical imaging system development.

Future work will focus on the clinical translation and commercialization of the proposed modular whole-body X-ray scanner. The current system represents a late-stage laboratory prototype corresponding to Technology Readiness Level (TRL) 5–6, in which system design, integration, and functional performance have been validated under controlled experimental conditions. The next development phase will target TRL 7 through extended preclinical validation, including standardized phantom studies and controlled animal experiments to evaluate image quality, dose distribution, and system safety under realistic anatomical and motion conditions.

Following successful preclinical validation, human subject studies will be conducted under Institutional Review Board (IRB) approval to assess clinical image quality, workflow efficiency, and radiation exposure in trauma and emergency imaging scenarios. In parallel, a structured regulatory pathway will be pursued in alignment with CE marking requirements under the EU Medical Device Regulation (MDR). This process will include risk management, electrical and mechanical safety testing, software lifecycle compliance, cybersecurity assessment, and clinical performance documentation. These steps are intended to support the transition of the system from a research prototype to a clinically deployable and commercially viable medical imaging device.

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Author contributions

Aytac F. Durmaz (corresponding author) contributed to the conceptualization, mechanical/electrical system design, experimental investigation, data interpretation, and original draft preparation. Altay Brusan contributed to the software architecture, system integration, methodology development, and review/editing of the manuscript. Cengizhan Ozturk contributed to the study supervision, conceptual guidance, scientific validation, and critical revision of the manuscript.

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Declarations

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