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Advancements in 3D X-Ray Imaging: Development and Application of a Twin Robot System

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Abstract. The development of a novel twin robot system for 3D X-ray imaging integrates advanced robotic control with mobile X-ray technology to significantly enhance diagnostic accuracy and efficiency in both medical and industrial applications. Key technical aspects, including innovative design specifications and system architecture, are discussed in detail. The twin robots operate in tandem, providing comprehensive imaging capabilities with high precision. This novel approach offers potential applications ranging from medical diagnostics to industrial inspections, significantly improving over traditional imaging methods. Preliminary results demonstrate the system's effectiveness in producing detailed 3D images, underscoring its potential for wide-ranging uses. Future research will focus on optimizing image quality and automating the imaging process to increase utility and efficiency. This development signifies a step forward in integrating robotics and imaging technology, promising enhanced outcomes in various fields.

Keywords: Mobile Xray, Robotic Imaging, Robotics Control, Image Processing, Image Stitching

1 Introduction

Two-dimensional (2D) radiography represents a prevalent imaging modality within the medical field, primarily utilized for a variety of clinical diagnoses. Despite its widespread application, 2D radiography encounters significant limitations due to the superimposition of anatomical structures within the imaging plane, which can obscure critical diagnostic details. Conversely, tomographic three-dimensional (3D) imaging techniques offer a substantial advantage by facilitating the reconstruction of cross-sectional images. This method effectively eliminates the issue of overlapping structures, thereby enhancing clarity and diagnostic accuracy.

In clinical practice, the acquisition of 2D and 3D images typically involves the use of distinct systems situated in separate facilities. This separation can affect workflow efficiency and patient experience due to the need for multiple appointments or transfers between different imaging suites. Despite the clear benefits of 3D imaging, its integration into routine clinical practice has been more readily achieved in the medical field compared to industrial applications(Strobel et al., 2009). Robot-assisted medical imaging uses robots to acquire medical images with high precision and accuracy. Examples include robot-assisted endoscopic camera imaging, ultrasound imaging with a robot-held transducer, X-ray imaging with robot-positioned sources and detectors, and actuated capsule endoscopy. This technology allows for controlled trajectories, increased aperture, volumetric or tomographic imaging, tracking of medical instruments, and real-time adjustments. Intraoperative robotic imaging provides valuable information to physicians and aids in registering preoperative images to patients (Salcudean et al., 2022). In the latter, the adoption of advanced imaging techniques such as 3D tomography remains uncommon, possibly due to higher costs, the specific technical expertise required, or the lack of immediate applicability in standard industrial processes (Salcudean et al., 2022).

X-ray Non-Destructive Testing (NDT) is a widely used technique in both medical and aerospace fields(Joseph et al., 2018). The high-resolution capability of low-power X-rays allows for the identification of small defects in critical aerospace components. To transfer this technology into aerospace applications, the feasibility of applying medical X-ray NDT methods directly to aerospace contexts involves considerations of material density and safety standards.

While medical X-ray systems are designed for imaging soft tissue and bones and are certified for safe radiation doses for occasional human exposure, aerospace X-ray NDT/NDE systems tend to require slightly higher X-ray source energy to penetrate higher density materials such as composites, aluminum, and titanium structures. These systems often involve larger and more complex geometries and must adhere to stringent safety protocols to protect operators in the workplace (Towsfyan et al., 2020).

The novelty of this ongoing research is to investigate the integration of portable, rapid low-power X-ray scanning (10-11W, at 35-75kV) with a fixed-to-the-floor robotic solution for flexible non-destructive evaluation and testing (NDE/NDT) of aircraft components, including both metallic and composite materials of varying small geometries and curvatures. This research, conducted at the Aerospace Integration Research Centre (AIRC) at Cranfield University in collaboration with Adaptix, focuses on developing a research framework to understand the robustness of system integration, robotic control for process automation opportunities, health and safety (H&S) clearance to safely operate X-rays in compliance with the UK Ionizing Radiations Regulations 2017 (IRR17), (Mridul Gupta Muhsin Ahmad Khan & Singari, 2022) image data acquisition and processing, and defect detection capability analysis to meet aerospace NDT standards for accuracy, reliability, and repeatability.

The rest of this paper is structured as follows: First, the system description section provides an overview of the robotic cell setup and describes its various elements. Both a virtual digital mock-up (DMU) of the robotic cell and its physical integration are presented to demonstrate the initial results of this ongoing research. Showcasing both the DMU and the real setup aims to highlight the potential applications of this developed system and its prospects for future development. The safety system considerations are described, including novel approaches for validating safe and compliant work with ionizing radiation in a research and development (R&D) environment, with potential implications for production environments.

2 System Description

The experimental cell setup included two industrial robots mounted at a fixed tooling height with floor mounting, an Adaptix low-power X-ray device, and fixed tooling designed for the precise positioning of a 2-meter longitudinal composite aircraft component. The system utilized articulated robotic arms, each with a 20 kg payload capacity, and both robots were safety-rated for remote operation, necessitating additional safety measures to prevent human proximity during operation.

The Adaptix low-power X-ray device, originally designed and certified for medical and veterinary applications, features a low-power X-ray source (10W at 70kV). This generator is specifically designed for use in mobile X-ray instruments and has demonstrated potential applications in scanning relatively small composite aircraft components, offering high-quality image acquisition with low-power X-rays.

In this system setup, the original design of the Adaptix X-ray device was modified by mounting the source and detector separately onto two end-effectors, each attached to one of the robotic arms, as illustrated in Figure 1. This modification allowed for precise and coordinated movements of the X-ray source and detector, ensuring comprehensive scanning coverage of the aircraft component.

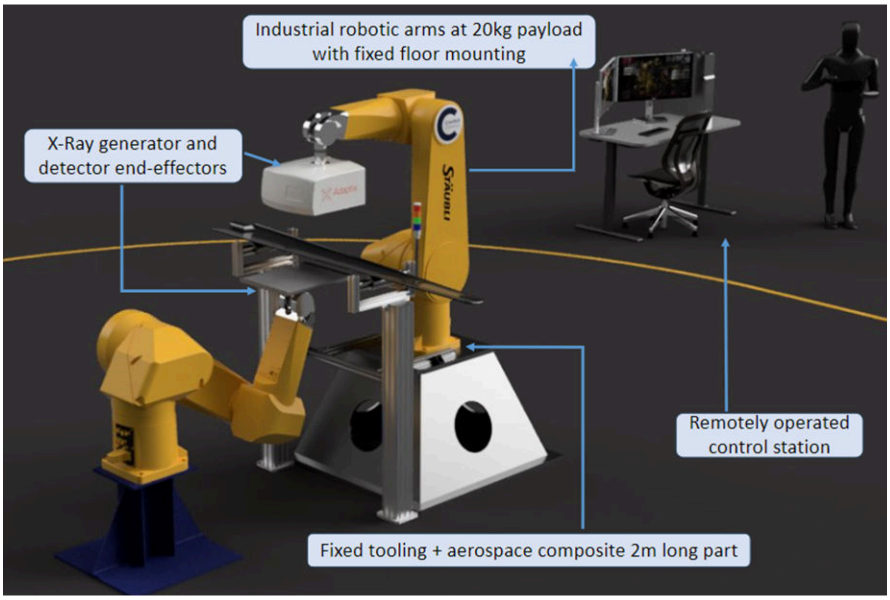

Figure 1: Cell design setup for twin robot low power X-ray

Furthermore, during this initial testing phase, the fixed tooling design concept was developed with flexibility in mind to accommodate relatively small, curved longitudinal aircraft composite parts. This approach aimed to simplify the design and expedite the initial integration process, ensuring readiness for physical demonstration. Future tooling design considerations will incorporate automated positioning driven by tooling and part metrology.

2.1 Process flow for X-ray scanning.

In X-ray radiography, high-energy X-ray photons (short wavelength electromagnetic radiation) are used to penetrate different materials and create a shadowgraph image of the object being tested. With increased material density, the X-ray absorption also increases, leading to greater attenuation of the X-rays as they pass through the object toward the detector. The attenuation of X-rays with a specific energy as they interact with matter is described by the Beer-Lambert law, represented by the following formula:

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

where:

- I is the intensity of the transmitted X-ray beam,
- I_0 is the initial intensity of the X-ray beam,
- μ is the linear attenuation coefficient of the material,
- x is the thickness of the material.

The non-absorbed energy, captured by the detector, results in variations in image darkness, which is a measure of the density of the scanned material. For composite materials, low-power X-rays are capable of characterizing defects such as solid inclusions, fiber misalignment, and matrix cracking. The orientation of the composite internal layup affects the characterization effectiveness.

The choice of scanned part material and thickness is carefully considered for this initial setup, and there is a certain degree of freedom in determining these parameters, as they are crucial for investigating the system's effectiveness and capabilities to match aerospace accuracy standards for non-destructive testing (NDT) and non-destructive evaluation (NDE). In this experimental setup, the X-ray device capability plays a major role in defining the robotics process flow and kinematics. The generated X-ray beam power, projection angle, and the relative distance between the X-ray source, detector, and part within its workspace are critical for acquiring high-quality and accurate images necessary for effective processing software results. Therefore, the concept of separated movement for the source and detector end-effectors robots was integrated.

This concept's flexibility allows for accommodating complex geometry parts for scanning within the same working envelope (Sattar & Brenner, 2009). The robotic kinematics were defined so that different sections (A, B, C, etc.) can be scanned sequentially or repeated on-demand with pre-defined and pre-programmed robot positions for active X-ray scanning, as shown in Figure 2 below.

Different local areas can be scanned with sequential stitching to accomplish full part scan in flexible an on-demand approach for automating rapid 3D X-ray process flow. In contrast to conventional NDT methods, such as ultrasonic and eddy current testing where typically a constant probe contact is required to contoured components surface, 3D X-Ray process allows for contactless scanning of complex geometries, therefore allowing a rapid inspection process with less concern robots position accuracies (Ajman & Abdullah, 2024).

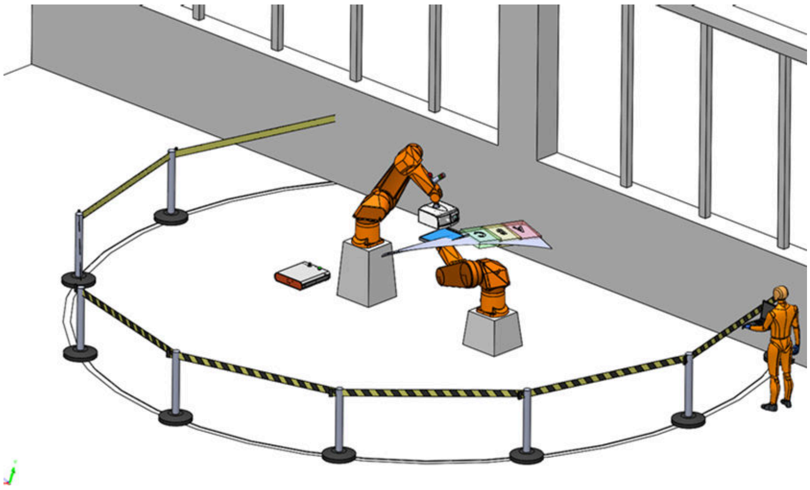

Figure 2: Rapid X-ray Process Flow

2.2 Safety system considerations.

In-built safety system approach had been followed to consider both the robotic safe control and X-ray safety and legal considerations working environment with potential Ionizing Radiation exposure, as summarized in Figure 3 below.

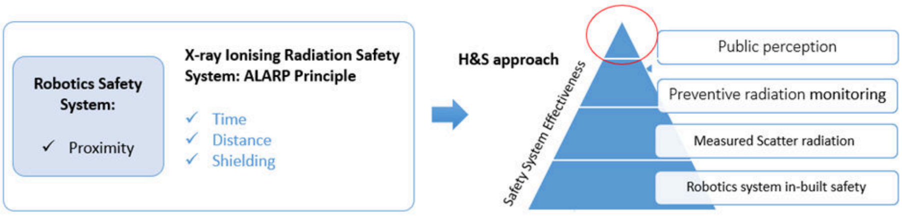

Figure 3: H&S clearance approach for robotic open cell concept with low power X-Ray

This research health and safety (H&S) approach is designed to comply with the annual dose limit exposures to ionizing radiation in the workplace across industry and research fields. Additionally, it ensures that doses follow the ALARP principle (As Low As Reasonably Possible). More detailed work on the methodology will be published following approval from the Health and Safety Executive (HSE).

Given the demanding safety margins for proximity and the additional measures required for the X-ray safety system, the global cell safety in-built design is driven by the X-ray system and is currently under approval by the UK HSE regulator.

Our robotic 3D X-ray concept involves a clear line of sight (LOS) and, therefore, does not use a cabinet for the X-ray equipment or a physical enclosure for the robotic cell. Consequently, scatter radiation monitoring within the controlled area and across the 5-meter perimeter is the primary factor driving the safety system interlocks. For this purpose, a designated Controlled Area has been established, with a safety perimeter of

5 meters to prevent human (or foreign object) access while the system is in operation, as shown in the Figure 4 below.

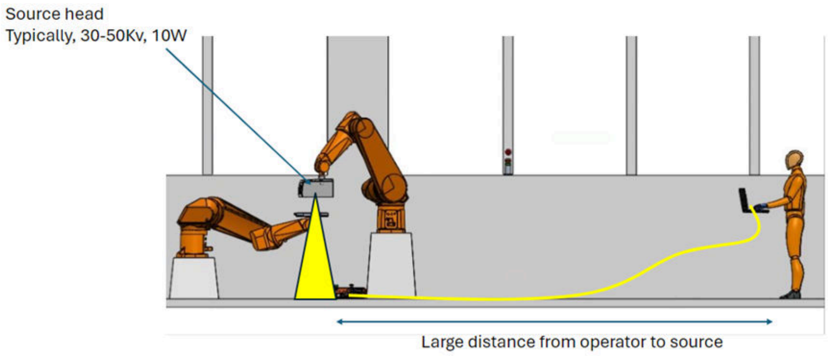

Figure 4: remotely operated robotics system with clear LOS

A breach of the programmed 5-meter perimeter will be automatically detected by the robotics safety proximity sensors, which will trigger an immediate power-off of the X-ray (if it was on) and stop the robots from moving as illustrated in Figure 5. All safety interlocks, including proximity sensors and emergency stops (E-stops), are wired through the safety Programmable Logic Controller (PLC). Additionally, the X-ray generator beam angle and the synchronized movements of the robots (source and detector) are preprogrammed to operate in safe positions at all times while the X-ray is armed and powered on (scanning in progress).

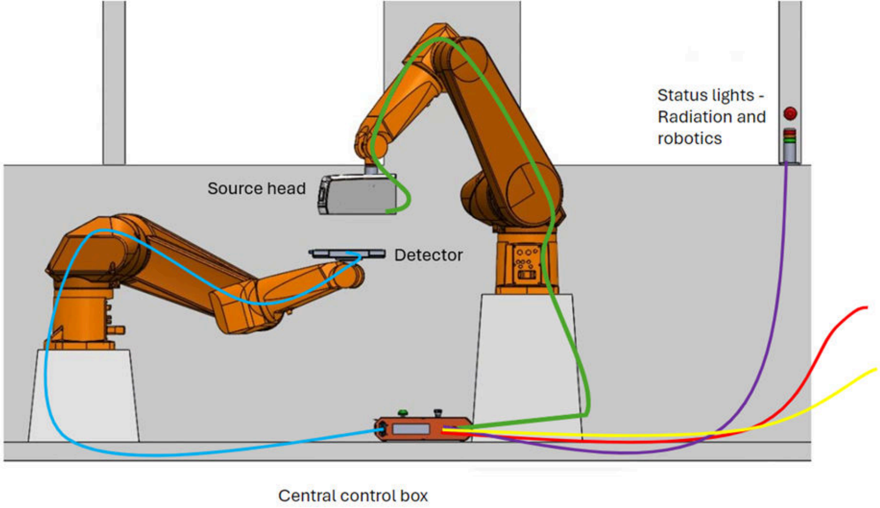

Figure 5: X-Ray system data acquisition wiring, visual and audible signage.

Both robots' controllers and the X-ray data acquisition system are wired into the safety PLC to enable the relevant safety triggers to be lifted automatically, preventing unsafe system operation. Moreover, the process status is indicated through traffic lights and an audible alarm during the brief process step when the X-ray is on, as shown in the figure below. This integrated safety system ensures that any breach of the controlled area is promptly addressed, maintaining a safe environment for personnel and equipment. The use of proximity sensors, E-stops, and safety PLC wiring, combined with preprogrammed safe positions for the X-ray beam and synchronized robotic movements, provides a robust safety framework. The visual and audible alarms further enhance the safety measures by alerting personnel to the operational status of the X-ray system, ensuring compliance with stringent safety protocols and minimizing the risk of exposure to ionizing radiation (Great Britain. Health and Safety Executive, 2017).

3 Xray System

The Adaptix 3D X-ray system employs a technique known as tomosynthesis. Unlike computed tomography, which captures images through a 360° rotational motion around the subject, tomosynthesis involves acquiring a series of images from a limited range of angles along a line or, in the case of the Adaptix system, a grid pattern. In the Adaptix approach, a source head held in a stationary position above the subject, emitting a sequence of X-rays from many different positions within the source head. A detector is placed underneath the subject, as close as possible to the unit being examined. A control module powers and synchronizes the interaction between the source and the detector, ensuring operational safety as the operator remains at a safe distance. The X-ray device is synchronized with robotic systems and safety protocols, enabling operation only when the surrounding area is clear and the robots are stationary.

A rectangular array of emission positions provides enhanced depth resolution compared to a linear sweep of emitter positions, as it captures projection images over a two-dimensional sweep. Additionally, a rectangular array allows for a reduction in the source-to-image distance (SID). Halving this distance decreases the required beam current by a factor of four, potentially reducing the size, weight, and cost of the overall system, albeit with an increase in the angular width of the focal spot. Both simulations and physical experiments indicate that depth resolution significantly improves with a rectangular array compared to a linear array. When utilizing a rectangular array at half the SID and a quarter of the power, this benefit is maintained despite the larger angular width of the focal spot. This approach facilitates enhanced imaging from lower-cost, smaller devices compared to conventional systems, making practical-sized robot cells feasible for production lines and non-destructive testing areas. Moreover, this reduces the weight of the source head, ensuring it remains within the load limits of smaller robotic arms.

3.1 X-Ray Image Acquisition

During a tomosynthesis acquisition, a series of images are captured with the X-ray source positioned at various locations, while the sample and detector remain stationary. Consider two objects placed at different heights but centered on a flat-panel X-ray detector. As illustrated in Figure 6, when illuminated by an X-ray source positioned such that it aligns with both objects (Position 2), the detector displays an overlapping shadow formed by the shadows of each object.

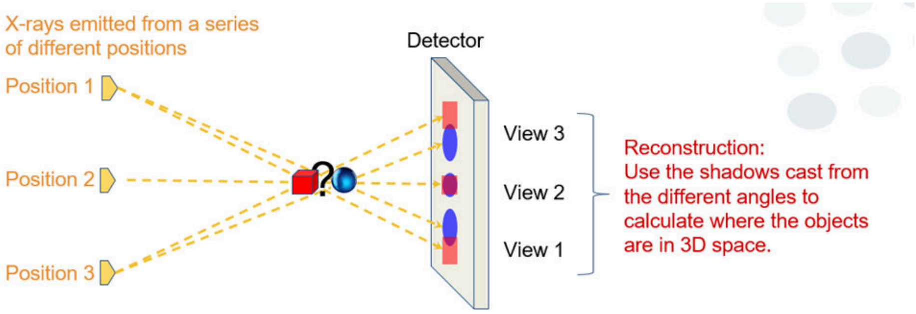

Figure 6: Shadow formation on a detector during tomosynthesis.

Objects that created overlapping shadows with 2D X-ray can then be seen in isolation. Acquiring images from multiple positions allows for the reconstruction of the 3D positions of each element along the path between the X-ray source and the detector.

3.2 Image Reconstruction

Once all X-ray images are collected, the 3D information is extracted using the method described in (Soloviev et al., 2020). In digital tomosynthesis, a stack of 2D planes is generated, each corresponding to a different height from the detector, rather than rendering a 3D volume as in computed tomography.

The approach can be briefly described without delving into the mathematical details of the reconstruction algorithm. The algorithm is akin to the filtered back-projection method used in traditional CT scans. For each acquired image, the source position and the X-ray cone angle of emission are recorded, and the image is propagated back to the original source position. As illustrated in Figure 7: (a) Pixels' backprojection at the specified height along rays connecting pixel's corners to the emitter. (b) Backprojected pixels mapping onto the reconstruction slice grid. As illustrated in Figure 7, the same pixel on the acquired image can correspond to different spatial positions at a given height from the detector, necessitating a "pixel remapping" strategy (Evangelista et al., 2020).

In traditional CT algorithms, acquired images are filtered in the Fourier space, and a 3D mesh is built to remap the projection into the same coordinate system. In this method, the images are back-propagated to the emitter position while applying an offset based on the source position for each image. A spatial frequency filter is then applied, and the average resulting image is calculated. This process, repeated for each reconstructed slice, creates an "out-of-focus effect" for objects at heights different from the reconstructed plane. Objects in the selected plane appear brighter and with sharper edges due to the averaging effect.

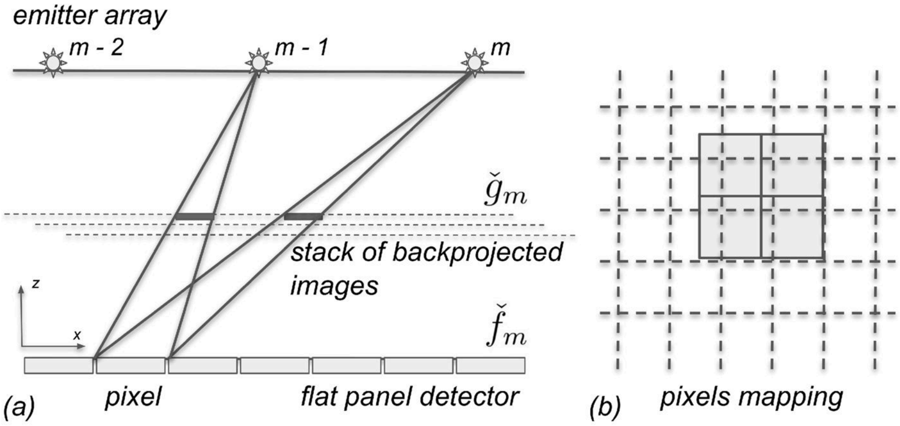

Figure 7: (a) Pixels' backprojection at the specified height along rays connecting pixel's corners to the emitter. (b) Backprojected pixels mapping onto the reconstruction slice grid.

Some artifacts or impressions of all the back-projected images may still be present in the reconstructed slices, but these become less prominent as the number of images increases.

4 Image Processing

Image processing encompasses exploration and enhancement of X-ray scans and other types of images, for improved insight and decision making in technical operations across various fields including material science, medical diagnostics and robot platforms. In the context of X-ray scans, this includes acquiring multiple x-ray image measurements around a sample from different angles to provide a comprehensive view of x-rays attenuation throughout the sample. The x-ray penetrates the material, revealing details such as hidden flaws or irregularities. This produces 2D X-ray images of the object from different perspective and are used to facilitates image reconstruction providing detail information about the sample's density and material composition. Different challenges limit effective reconstruction and 3D visualization of the 2D slices which include variation in x-ray beam and material's absorption capability (Ou, X., 2021). These affects noise rate, defect detection ability and general image quality. These requires relevant processing techniques that can reduce noise, enhance contrast, quality and uniformity in the acquired 2D images slices. Figure 8 shows samples of pre-processed images slices acquired from composite material with the plot of average intensity value showing significant changes in the image's structures and components. This can guide further adjustment and enhancement to achieve visual improvements and facilitate accurate reproduction of image structures and properties. Image processing techniques like image stitching are among the commonly applied methods and have shown significant improvement in data visualization picking up defect profile and structures with clarity and high fidelity.

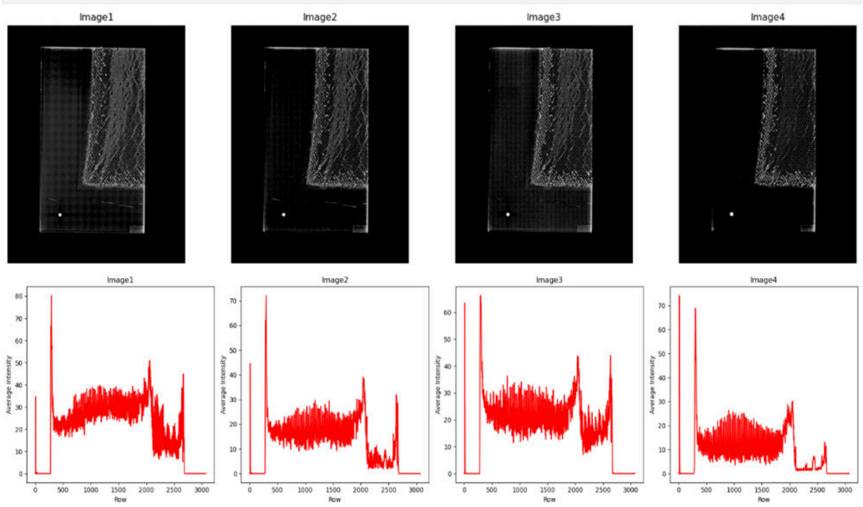

Figure 8: Image slices and plot of average intensity value.

4.1 Image Stiching

Image stitching methods combines 2D image slices to create comprehensive and high-resolution image representation. This requires identifying and matching corresponding key points or features between the overlapping images using algorithms like SIFT (Scale-Invariant feature transform) (Burger & Burge, 2016) and SURF (speeded-Up Robust Features) (Oyallon & Rabin, 2015). These algorithms align and merge multiple overlapping images based on the matched features to produce a single seamless image. Techniques like feathering and blending(Gu & Rzhanov, 2006) help achieve smooth transitions, reducing visible seams and resulting to high quality and high-resolution visualization of 3D model structures. Leveraging image stitching approaches has shown significant improvement and application in domains like robotics, composite material science and medical imaging leading to enhanced analysis and better decision-making in technical operations.

5 Discussion & Conclusion

The development of the twin robot system for 3D X-ray imaging represents a significant advancement in both medical diagnostics and industrial inspections. The collaborative efforts between Cranfield University and Adaptix Ltd. have resulted in a system that not only enhances imaging capabilities but also improves the accuracy and efficiency of diagnostic procedures. The integration of advanced robotic control with portable X-ray technology has shown promising results in initial tests, particularly in producing high-quality 3D images for NDE environments.

One of the critical aspects of this system is its ability to operate in tandem, providing comprehensive imaging from multiple angles. This dual-robot approach ensures that the subject is thoroughly scanned, reducing the likelihood of missed anomalies and improving diagnostic confidence. The system's precision and reliability are bolstered by its sophisticated control algorithms and image processing techniques, which enable precise positioning and consistent image quality.

The potential applications of this technology are vast. In the medical field, it can be used for more accurate and detailed imaging of complex structures, such as bones and organs, which is crucial for diagnosing conditions that are difficult to detect with traditional 2D X-ray. In industrial settings, the system can be employed for non-destructive testing of materials and components, ensuring safety and integrity in critical infrastructure.

However, the system is not without its challenges. The complexity of coordinating two robots and the associated computational requirements for real-time image processing and stitching are significant. Future research will focus on optimising these processes to enhance the system's performance further. Additionally, exploring automation in the imaging process can reduce the need for manual intervention, making the system more user-friendly and accessible for various applications.

In conclusion, the twin robot system for 3D X-ray imaging developed by Cranfield University and Adaptix Ltd. represents a promising step change in imaging technology. The system's ability to provide detailed and accurate 3D images has the potential to revolutionize both medical diagnostics and industrial inspections. Preliminary results have demonstrated the system's effectiveness, and future research will aim to refine its capabilities and expand its applications.

The successful integration of advanced robotics and portable X-ray imaging highlights the potential for interdisciplinary collaboration to drive technological innovation. By addressing the current challenges and optimizing the system's performance, this technology could become a standard tool in various fields, offering significant benefits in terms of diagnostic accuracy, efficiency, and overall outcomes. The continued development and refinement of this system will be crucial in realizing its full potential and ensuring its widespread adoption.

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