

Robotic Implementation of Laser-Induced Phased Arrays for Complex Geometries Towards Industrial Deployment

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Abstract: This study presents a robotic implementation of laser-induced phased arrays (LIPA). The system is targeted towards addressing the challenge of in situ inspection of complex geometries, such as additively manufactured components, curved surfaces and pipes. This Robotic LIPA system aims to combine the non-destructive and non-contact nature of laser ultrasound with the flexibility and adaptability of a robotic inspection to overcome the challenges faced by conventional ultrasound when inspecting complex industrially relevant components.

Keywords: Robo-LIPA, Non-Contact Inspection, Additive Manufacturing, Non-Destructive Evaluation, In-process Inspection

Background

Non-contact, non-destructive evaluation (NDE) techniques are increasingly important across industries such as nuclear energy, aerospace, and advanced manufacturing, where component integrity must be verified without disrupting operations or compromising safety [1]. Traditional ultrasonic inspection methods typically rely on mechanical coupling and direct probe access, limiting their applicability in high-temperature, radioactive, or geometrically complex environments. Laser-Induced Phased Arrays (LIPAs) offer a promising alternative by enabling fully remote, high-resolution ultrasonic imaging without the need for physical contact or couplant [2]. Industrial robots have already been demonstrated in the literature as effective platforms for deploying various NDE techniques, including conventional phased arrays and eddy current testing [3]. This establishes a strong foundation for extending robotic deployment to LIPAs, enabling flexible, automated, and contact-free inspection.

Motivation

In additive manufacturing (AM), in-process inspection is vital for detecting defects as they form, yet the part geometry and enclosed build environments hinder access. Similarly, the inspection of internal components in nuclear facilities is limited by safety risks and restricted physical access. These challenges underscore the need for a compact, modular LIPA platform that combines laser ultrasonic capabilities with robotic actuation to enable autonomous inspection across complex or confined surfaces [4].

A robotic LIPA system has the potential to extend non-contact ultrasonic imaging into environments pre-

viously considered inaccessible, supporting quality assurance in safety-critical applications and advancing LIPA technology towards operational readiness.

Objective

This work aims to develop a modular, robotically deployable LIPA system for non-contact, high-resolution ultrasonic inspection in access-limited industrial environments.

The optical system was designed to reduce physical footprint and optical complexity while maintaining the imaging resolution required to detect subsurface defects. A key objective was to ensure seamless integration with existing robotic platforms, allowing for fully automated inspection workflows. The resulting system not only increases inspection flexibility and accessibility but also supports scalable implementation across advanced manufacturing settings.

Method

To transition LIPA technology toward industrial deployment, the optical and mechanical architecture of the previous LIPA system presented in the literature was redesigned [5]. A single robotic arm was used for global positioning, complemented by linear translation stages for the detection laser and a galvo mirror for local steering of the generation laser. This configuration significantly reduced system complexity while enhancing precision and ease of deployment.

An additional refinement was the optical coupling of the generation and detection lasers via a dichroic mirror. This allowed both beams to share a common optical path while retaining independent control, reducing system size and enabling a wider, more symmetric scanning field for the generation beam. These innovations collectively support a compact, modular

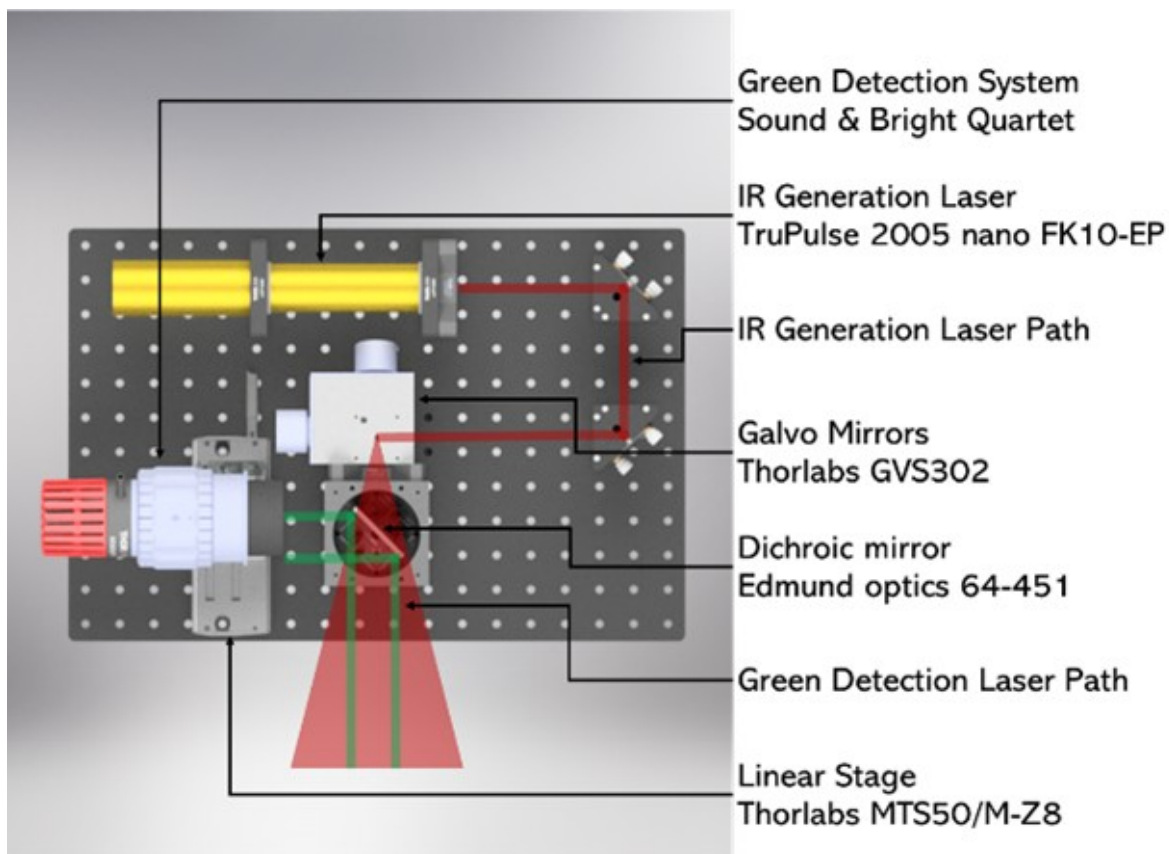


Fig. 1: Experimental schematic of the compact LIPA system mounted on the robotic arm.

LIPA system capable of integration into existing industrial inspection processes, bringing the technology closer to real-world application.

The KUKA KR10 industrial robot was selected for this initial trial due to its compact size and sufficient payload capacity. Despite its smaller form factor, the KR10 could support the 15 kg weight of the prototype LIPA system, making it a practical choice for early-stage development and integration.

The developed LIPA system performs Full Matrix Capture (FMC) by sequentially scanning both generation and detection lasers across discrete spatial positions to acquire ultrasonic signals from all transmit–receive combinations, forming a complete $N \times M$ dataset. This dataset is processed using the Total Focusing Method (TFM), a synthetic focusing algorithm that applies time-delay corrections across all element pairs to achieve focusing at every pixel in the ultrasonic image. The resulting TFM image provides high-resolution imaging without requiring surface contact or coupling.

In addition to its mechanical suitability, the KR10's compact footprint offered significant advantages in terms of laser safety. As the system employs two Class

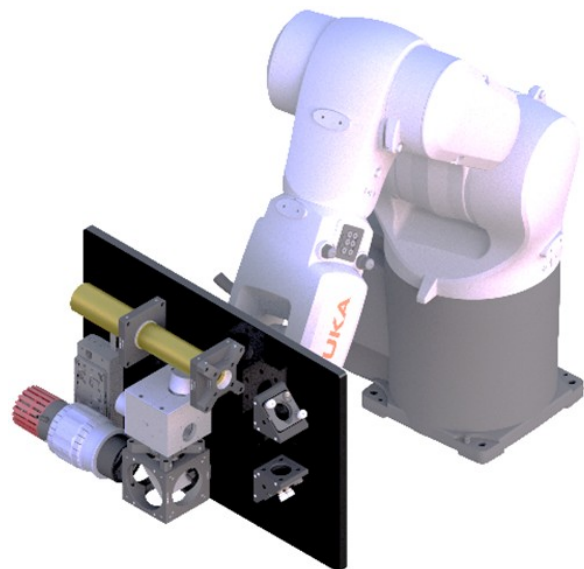


Fig. 2: 3D rendered image of the combined Robo LIPA system using a KUKA KR10 Industrial Robot.

4 lasers, the ability to enclose the entire robotic LIPA

setup within a relatively small, self-contained safety enclosure was a key consideration. This configuration supports the development of future Robo-LIPA systems as Class 1 laser-safe units, enabling safe operation within mixed-use laboratories or workshop environments without the need for dedicated laser facilities.

Results - WAAM

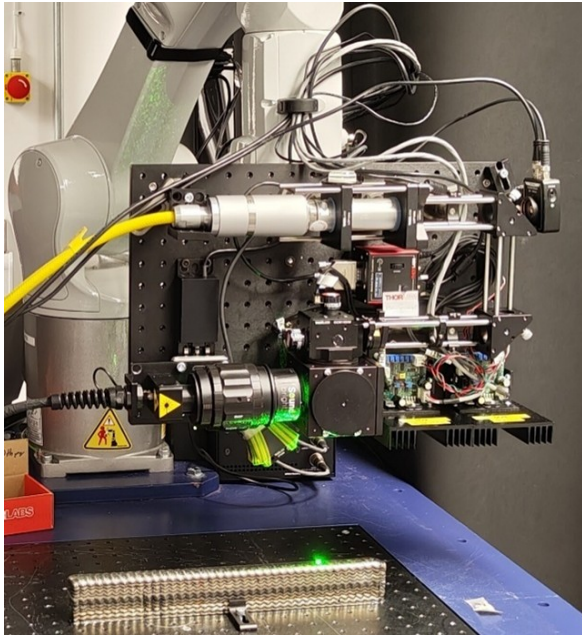


Fig. 3: Image of the Robo LIPA system inspecting a WAAM wall section.

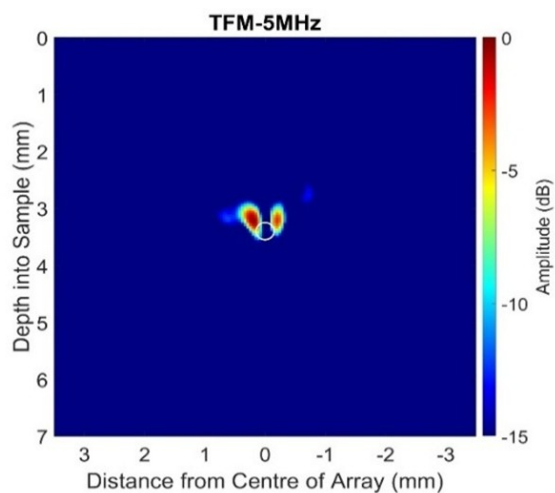


Fig. 4: TFM image from the as-deposited surface of a Ti64 WAAM component, showing two indications about 3 mm below the surface.

The first inspection scenario involved an additively manufactured Ti-64 WAAM wall section containing a 3 mm diameter side-drilled hole located approximately 3 mm below the surface.

Fig. 3 shows the system inspecting a WAAM wall section at a standoff distance of about 150 mm. This marked the first robotic implementation of a LIPA system where the sample remained static while the optical system was moved relative to it.

The TFM image in Fig. 4 demonstrates how the side-drilled hole was imaged as two distinct indications.

Results - Pipe

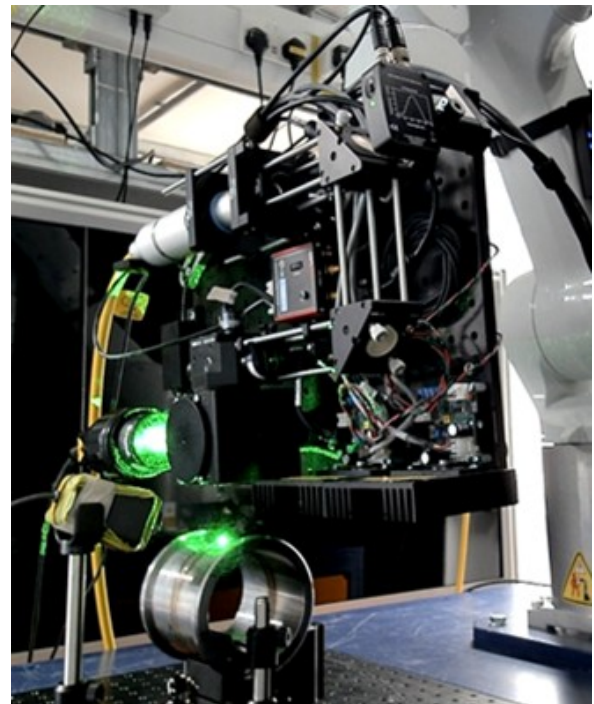


Fig. 5: Image of the Robo LIPA system inspecting the pipe section.

The second inspection scenario involved a laser-welded P91 pipe section. The pipe was positioned horizontally, and the LIPA system was rotated around its central axis, as shown in Fig. 5. This allowed multiple FMC datasets to be acquired from the pipe's outer surface, enabling TFM imaging through its wall thickness.

The LIPA was synthesised on the outside of the cylinder and off-centre to the weld, resulting in the TFM image shown in Fig. 6, where there is a clear indication at the weld root (bottom left).

The flexibility of the robotic LIPA system was used to collect seven TFM images by moving the LIPA system using the robotic arm around the central axis

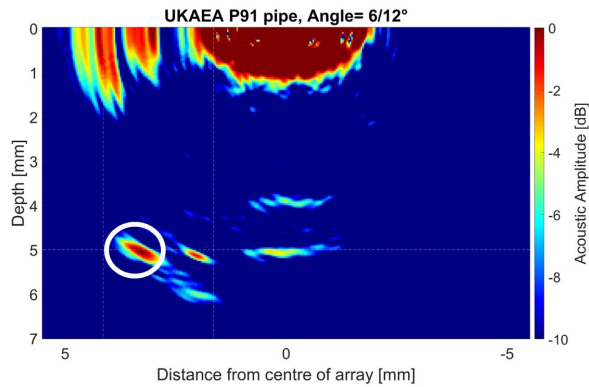


Fig. 6: TFM image, with the array positioned off-centre to the weld (dotted lines), showing an indication at the weld root (white circle). The flexibility.

of the pipe. This data was used to plot the 2.5D image by stacking the individual 2D TFM images taken from the 1D LIPAs scanned parallel to each other [5]. The resulting TFM image can be seen in Fig. 7.

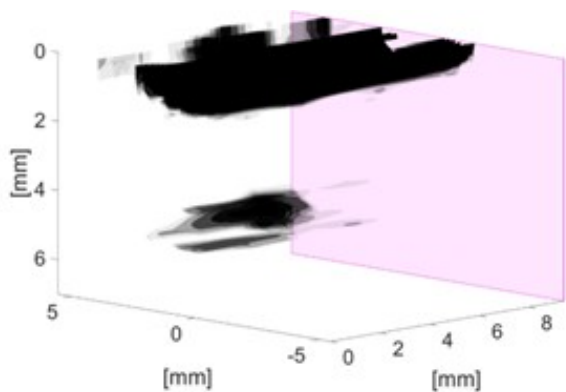


Fig. 7: 2.5D image created by stacking 7 separate 2D TFM images showing an indication of the internal weld defect as the black region at the bottom.

Discussion

The results from both the WAAM wall and the pipe section illustrate the expanded capabilities enabled by a robotically deployed LIPA system. These demonstrations highlight the shift from previous setups—where components had to be brought to a fixed system—to one where the LIPA system can be manoeuvred around the component itself.

This initial robotic LIPA implementation provides a solid foundation for future developments, offering a flexible and mobile platform with the potential to meet the demands of complex, real-world inspection scenarios.

Conclusion

This study has demonstrated the feasibility of integrating LIPAs with industrial robotics to enable non-contact ultrasonic inspection of complex and access-limited components. By combining the optical system and an industrial robot, the developed robotic LIPA system successfully imaged subsurface features in both additively manufactured and welded components. Although operating as an early-stage prototype, the system's modular design and mobility offer a promising route toward in situ ultrasonic inspection in high-value manufacturing and a wide range of other industrial applications.

Future developments will focus on improving SNR, enhancing system robustness, and supporting fully automated inspection workflows.

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