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9-13 June, Sozopol, Bulgaria
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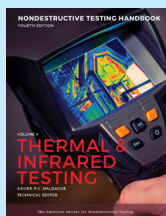
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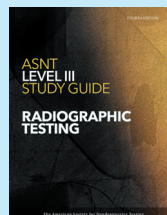
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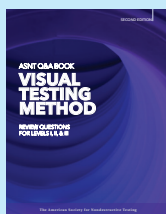
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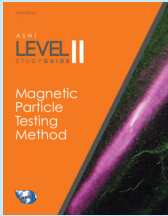
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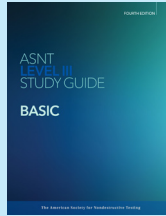
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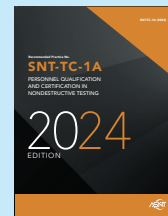
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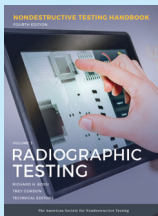
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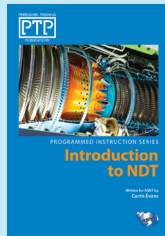
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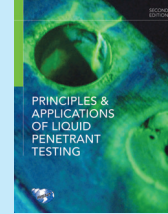
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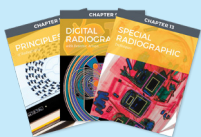
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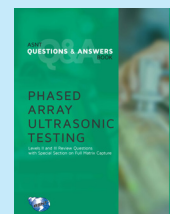
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BEYOND ROBOTICS, MATERIALS, AND SENSING: UNVEILING BIOINSPIRATION IN NONDESTRUCTIVE EVALUATION FROM "NATURE'S NDE SPECIALISTS"

BY EHSAN DEGHAN-NIRI

While bioinspiration research has led to advancements in fields such as robotics, materials, sensing, and neural computation over the past few decades, its application to more mission-oriented tasks, like nondestructive testing/evaluation (NDT/E), remains largely unexplored. Bioinspiration in NDT/E offers innovative approaches to advance current technologies by drawing inspiration from natural systems that perform similar tasks or processes. This paper explores three unique biological systems—aye-ayes, termites, and red/arctic foxes—referred to as “nature’s NDE specialists.” These organisms have evolved specialized food foraging processes to detect, characterize, assess materials, and detect targets in their environments without disruption, mirroring the goals of NDT/E methods such as tap testing and leakage detection. By studying these specialized processes, we can pioneer new NDT/E technologies or advance the current ones, by means of enhancing reliability, sensitivity, adaptability, and accessibility in challenging environments. Additionally, integrating bioinspiration into NDT/E education can attract a new generation of students, creating opportunities to address the workforce challenges in the NDT/E field.

1. Introduction

Biological systems have evolved over millions of years, exhibiting remarkable adaptations that enhance survival in diverse and sometimes harsh environments. Throughout this evolutionary journey, these systems have developed specialized capabilities that allow them to thrive in various conditions, positioning them as a rich source of inspiration to pioneer sophisticated tools, algorithms, and machines [1]. Bioinspiration involves understanding the principles underlying the behavior, structure, and sensory aspects of biological systems, and applying these principles to the development of engineering systems designed to serve specific purposes, mirroring the

functions of the biological systems. The key steps in transforming bioinspiration into practical NDT/E technologies or tools are outlined in Figure 1. These steps can be utilized for the development of robots, as well as advancements in materials, control systems, data processing algorithms, and sensing technologies.

Among various mechanisms, three aspects are particularly influential in the development of new technologies:

- sensing, sensory intelligence, and neural computation,
- materials and structures, and
- mobility, control, and autonomy.

The first key aspect is the evolution of advanced multifunctional sensing systems and neural computation that enable organisms to communicate, forage for food, and evade predators. Additionally, the development of unique structural and morphological features, along with the materials that constitute their bodies, contributes to their exceptional adaptability. Finally, the actuation and mobility mechanisms that allow them to perform essential tasks further highlight their success in the survival journey. These remarkable traits make biological systems a powerful source of inspiration for innovating and engineering new technologies.

1.1. Sensing, Sensory Intelligence, and Neural Computation

Since life first emerged on land hundreds of millions of years ago, reliable information has been essential for organisms across all biological systems to make reliable decisions critical for their

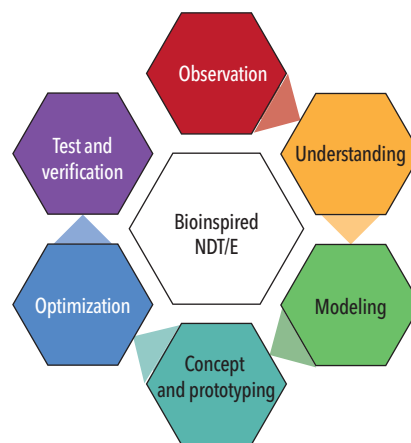


Figure 1. Key steps in transforming bioinspiration into nondestructive testing/evaluation tools and technologies.

survival [2, 3, 4]. Much research focuses on drawing inspiration from the remarkable evolutionary strategies employed by the sensing mechanisms of biological systems for survival and adaptation across the natural world [5, 6]. Over millennia, these organisms have developed an array of senses such as olfaction (smell), gustation (taste), tactile (touch), vision (sight) [5], and audition (hearing) [2, 7, 8] each serving a unique purpose and complementing one another to enhance their adaptation to the specific environments in which they operate. Combining sensing and robotic inspiration can substantially enhance the development of mechanical systems, enabling them to perform specialized tasks more autonomously [9].

1.2. Mobility, Control, and Autonomy

The most obvious aspect of bioinspiration research is related to the development of robotic platforms that replicate natural movements and processes in their mobility [10, 11]. From insects [12] to mammals [13, 14], whether on land [15], in water [1, 16, 17, 18], or in the air [19, 20, 21], evolution has led to remarkable mobility adaptations and energy efficiency across the animal kingdom. These adaptations have inspired numerous innovative approaches in robotics, particularly in the areas of motion, mobility [1], and control strategies [10, 22] and autonomous systems [23, 24] derived from biological systems.

1.3. Materials and Structures

Bioinspired materials replicate the properties or functions of natural materials using synthetic substances [25]. Bioinspiration in materials has already been revolutionized by emerging manufacturing technologies [25], such as additive manufacturing, which facilitate novel design concepts for applications in sectors like aerospace [26]. From the material level to the structure and architectural level, this methodology has transformed the way we design and manufacture new components. These components are characterized by a high strength-to-weight ratio and

multifunctional capabilities, paving the way for advancements in both performance and efficiency [27].

2. Bioinspired Nondestructive Testing/Evaluation

Inspiration from biological systems has generally been applied to the broad three categories mentioned, but it has rarely been explored in more specific, mission-oriented domains such as NDT/E. While one might argue that NDT/E methods can fall under the broader field of sensing—where sensors are used to indirectly gather information from materials and structures without impairing their functionality—our approach differs. The key distinction is that NDT/E is not just sensing; it is a comprehensive process. This process involves multiple steps, including sensing, the use of specialized materials in the hardware, implementation (whether manual or automated, such as through robotics), preparation, calibration, and, finally, interpretation of the data. The ultimate goals—detection, localization, diagnosis, and potentially prognosis—are all integral parts of NDT/E methods. We aim to learn the entire process from biological systems that perform similar tasks, not just individual components. In this sense, we seek to understand biological processes that, in an abstract way, align with the objectives of NDT/E goals. These systems detect cavities (analogous to defects in our mission), characterize material properties such as dampness or dryness (similar to modulus of elasticity), and measure thickness (akin to corrosion inspection)—functions directly relevant to NDT/E.

To better explore the concept of bioinspired NDT/E, let's examine three unique biological systems belonging to a specialized category we refer to as “nature's NDE specialists”—aye-ayes, termites, and red/arctic foxes—that perform tasks similar to NDT/E.

2.1. Nature's NDE Specialist #1: Aye-Ayes

The aye-aye (*Daubentonia madagascariensis*) is one of the most unique primates in the world, first documented



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Figure 2. The aye-aye (*Daubentonia madagascariensis*).

on the island of Madagascar around 1780 [28]. This species represents a remarkable evolutionary lineage that has persisted for over 50 million years [29] (see Figure 2).

The aye-aye, the world's largest nocturnal primate, is a relatively small mammal, measuring an average of 80 cm from nose to tail and weighing between 2.5 to 3 kg. It also has a notably large brain (larger than other prosimians) [30] and the largest pinnae (ears) among all primates [31]. The aye-aye is best known for its remarkable acoustic-based foraging behavior, known as “tap-scanning” or “percussive foraging” [32]. As it moves along a tree's surface, the aye-aye taps the wood with its distinctive middle finger while positioning its nose close to the tree and angling its large, cupped pinnae forward. These unique morphological traits in its auditory sensory and movement systems enable the aye-aye to access food resources such as larvae in cavities unavailable to most other animals in Madagascar [33]. This evolutionary success is attributed to the aye-aye's advanced movement coordination and its specialized foraging technique, which involves acoustic-based actuation and sensing, synchronized with sensor data fusion and learning capabilities.

Remarkably, aye-ayes are able to forage using tap-scanning in acoustically challenging and cluttered environments like the forests of Madagascar, relying on their “bat-like pinnae” and “finger-tapping” to detect grubs and larvae deep beneath tree bark.

As evident, the aye-aye performs tap testing in a highly specialized manner, like the NDT/E techniques used for composite material inspection, such as detecting disbonds. The complex geometry of tree bark and the composite-like structure of wood highlight that the aye-aye’s process is highly specialized, having evolved over millions of years to be exceptionally efficient. Recent studies by the author’s team [34, 35, 36] demonstrate that the unique shape of the aye-aye’s pinnae and the mechanics of its auditory system play a crucial role in filtering out unwanted signals while enhancing sensitivity to discontinuities, such as cavities, during tap-scanning. The current tap-testing technologies offer simple but effective solutions in several applications such as composite material inspection [37, 38, 39, 40]. However, they are limited by low resolution, signal-to-noise ratio (SNR), and depth of penetration in generating high frequency acoustic waves in damped materials. Consequently, they lack the capability to, as effectively as aye-ayes, evaluate deep cavities in composites. Utilizing the morphological features of the aye-aye’s pinna and ear canal to pioneer a new design for tap testers can substantially enhance SNR [34] and provide a hardware that can filter out unwanted signals.

Given their extraordinary abilities, the aye-aye truly deserves the title of nature’s most fascinating NDE specialist.

2.2. Nature’s NDE Specialist #2: Termites

Utilizing an exceptional tapping mechanism to generate acoustic waves, aye-ayes rely on near-field acoustic cues to detect and characterize cavities within dry wood. Remarkably, even smaller biological systems like damp-wood and dry-wood termites exhibit similar vibroacoustic generation abilities. Termites,

small herbivorous social insects, are well-known for their use of vibrational signals and are inherently noisy biological systems [41, 42, 43]. Vibrations caused by body shaking, head drumming, and chewing have been extensively documented [44, 45, 46, 47, 48, 49, 50]. In 1781, Smeathman described the audible sound produced by soldier termites during the drumming process, referred to as “head banging,” as a “signal of alarm” [51]. Two distinct types of termite movements have been identified: convulsive movements, sometimes described as “cries” without audible sound, which are used to summon help, and head drumming (head banging) (see Figure 3), in which termites strike the ground with their mandibles, producing audible “alarm signals.”



Figure 3. *Zootermopsis nevadensis* termite: (a) soldier and worker; and (b) soldier drumming (head banging).

Traditionally, termites have been viewed as indiscriminate eaters. However, recent studies suggest that termites exhibit a clear ability to assess the quality and potentially the thickness of wood. Research has shown that termites prefer blocks with higher wood content [49, 52]. Wood, the primary substance for dry-wood and damp-wood termites, presents a wide range of material properties, including

significant damping, making it difficult to efficiently generate sound within or from the material [53]. Given that worker termites are blind, and chemical cues alone cannot fully explain their selection process [54], recent studies indicate that vibroacoustic cues serve as the primary mechanism for wood characterization. Recent findings show that termites’ decision to consume specific wood is influenced by vibroacoustic signals, which are directly linked to the material properties of the wood [52, 55, 56]. Howse demonstrated that substrate vibrations caused by drumming (head banging) or vertical oscillatory movements can prompt continued behavior in nearby termites that sense the vibrations. This suggests that these vibroacoustic signals may be used by termites to assess wood in terms of thickness, quality, and quantity of available food [44].

Despite their small size, termites are capable of characterizing the thickness of complex materials like wood and evaluating how damp the wood is—similar to how the modulus of elasticity is assessed. This makes them a unique biological system that can inspire the development of combined robotics and miniaturized NDT/E capabilities, particularly for applications where accessibility is a challenge. Understanding termites’ foraging behavior and the influential factors, such as head shape and dynamics, will enable engineers to pioneer a miniature acoustic wave generation mechanism inspired by the exceptional vibroacoustic wave generation capabilities observed in termites. This could lead to innovative small-scale material characterization and inspection processes.

2.3. Nature’s NDE Specialist #3: Red and Arctic Foxes

Throughout evolution, species have developed specialized acoustic sensory systems to adapt to their ecological niches. Arctic and red foxes, for example, possess unique hearing abilities that allow them to detect distant acoustic sources underground or beneath snow [57]. In winter, these fox species rely on their extraordinary hearing to locate and

capture prey, such as lemmings, burrowing under thick snowpack [58, 59]. The exceptional acoustic sensing abilities of these animals result from a combination of external ears and coordinated motion of the pinna, head, and body known as head tilting (see Figure 4). This allows for multitasking in binaural hearing (acoustic sensing using only two ears). However, limited research has been conducted on how their external ears and head-tilting strategies affect sound localization in the acoustic field, particularly when detecting low-amplitude sounds beneath packed snow. The aye-aye and termite perform active acoustic-based testing, actively generating vibroacoustic cues to detect and characterize their environment, while the fox engages in passive acoustic-based foraging by listening to movements and noises during its search for prey. One of the most promising applications for such tasks is underground leakage detection. Gaining insights into this process could result in the development of advanced noncontact acoustic sensing technologies for subsurface leakage inspections, using binaural acoustic sensing. The fundamental principle of aeroacoustics leak detection revolves around the generation and propagation of sound waves when gas escapes from a pipeline [60]. One of the main drawbacks of this sensing modality is its reduced sensitivity as the sensors move further away from the acoustic source due to significant attenuation [61]. Traditionally, an array of microphones has been used to increase the SNR and enable effective source localization through beamforming techniques [62]. However, this technique generates a substantial amount of data, which is not ideal for the development of an automated leak detection platform as well as a digital twin approach in infrastructure monitoring. Fortunately, this issue has been ingeniously addressed by biological systems such as red and arctic foxes utilizing only two ears (binaural sensing). Instead of relying on an increased number of sensors to enhance sensitivity, these biological systems evolved external ear (pinna) shapes to act as hardware for amplifying sound

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Figure 4. Red fox head tilting.

from specific directions, a capability further complemented by the strategic motion and control of the pinna and head (e.g., head tilting). This approach could revolutionize applications such as leak detection or human localization in rescue missions.

The three examples mentioned are just a few among many species that potentially perform processes similar to NDT/E methods. Such bioinspiration can lead to the development of new technologies or the evolution of existing ones, enhancing the reliability and sensitivity of NDT/E methods.

2.4. Bioinspiration Impact on NDT Education and Workforce Development

One of the challenges we face as instructors and researchers in the field of NDT/E is attracting students, as we often compete with more visibly appealing fields like robotics and data science, which the younger generation perceives as more attractive career paths. However, bioinspiration offers a unique opportunity to help attract students to the field of NDT/E. The integration of bioinspired concepts not only allows us to pioneer new NDE technologies that can make our world safer, but also serves as a compelling tool to engage and attract students. By highlighting the innovative intersection between nature and technology, educators can increase student involvement in NDT/E, bringing fresh talent into the field and encouraging the next generation of NDT/E professionals.

3. Conclusions

These three biological examples—aye-ayes, termites, and foxes—are among millions of species that use processes remarkably similar to those we conduct in the NDT/E fields. Through evolution, these species have developed highly specialized sensory systems for survival processes such as foraging for food, avoiding predators, and communicating for mating. In many cases, these functions are analogous to detecting defects, characterizing materials, and assessing environmental conditions—all achieved without disrupting their surroundings. By studying these biological systems and in particular the processes, for example tap-scanning, we can gain valuable insights and inspiration for advancing NDT technologies. The precision and efficiency seen in “nature’s NDE specialists” offer promising avenues for pioneering more adaptive, autonomous, and efficient NDT/E technologies, particularly in challenging environments. Furthermore, bioinspiration provides an engaging platform for NDT/E education and workforce development, attracting younger generations to the field of NDT/E and fostering the next wave of innovation as well as keeping the world a safer place to live.

As we continue to identify and explore new “nature’s NDE specialists,” the potential for revolutionary advancements in robotics, sensing, and materials—specifically focused on NDT/E and material characterization processes—becomes increasingly

evident, opening possibilities for innovative NDT/E methods with applications in industries such as infrastructure, aerospace, and environmental monitoring. Applications in hard-to-access inspection areas, advanced processes for detecting undetectable discontinuities, data management with reduced dimensionality and size, and increased autonomy are just a few areas where bioinspiration can significantly impact NDT/E technologies. 

AUTHOR

Ehsan Dehghan-Niri: Intelligent Structures and Non-destructive Evaluation Laboratory, The School of Manufacturing Systems and Networks, Arizona State University; nde@asu.edu

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Although it is uncommon to acknowledge animals in scientific publications, I would like to take this opportunity to recognize two specific aye-ayes from the DLC, Merlin and Medusa. While I never had the chance to meet Merlin, an article written by Dr. Erin Ehmke about him, following his passing, sparked my interest in bioinspired NDT. Merlin contributed to several research projects at DLC, and even after his death, his CT scan helped us better understand the external auditory system of aye-ayes and its impact on acoustic field measurements. Medusa, a younger aye-aye at DLC, recently assisted our team in collecting thermal images of the tapping process, and we are grateful for her contribution to our research.

CITATION

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BIOINSPIRED VERTIPORT SYSTEM DESIGN FOR SUPPORTING DRONE SWARMS IN METHANE GAS DETECTION FROM ORPHANED WELLS

FAHAD MANNAN[†], LOGAN MOORE[†], JORGE QUIROGA[‡], ARTHUR WIETHARN[†],
SIHUA SHAO[§], XIANG SUN^{††}, AND MOSTAFA HASSANALIAN^{*†}

ABSTRACT

The aim of this paper is to explore bioinspired vertiport designs—a hub for drones' vertical takeoff and landing (VTOL) and servicing, also referred to as a nesting station, docking station, hangar, or landing station—for drone swarms tasked with specific missions. The vertiport system design is inspired by tree structures, with branches represented by capsules that house drones. Solar panels mounted on actuators at the top of the vertiport adjust their orientation to maximize sun exposure, supplying power to the vertiport's isolated grid for continuous energy day and night. A weather station located at the top transmits data to a computing system, ensuring environmental safety for drone operations. The vertiport's key components include capsules that open and close during drone launch and landing. Each capsule is equipped with charging contacts for the drones, AprilTags to facilitate precise landing, and a mechanism to center the drone within the capsule upon closure. Designed to protect the drones from environmental conditions, these capsules feature robust structures capable of withstanding harsh weather, ensuring the drones are safeguarded inside. This design highlights the potential of bioinspired approaches in creating efficient vertiport systems.

KEYWORDS: AprilTags, bioinspiration, drones, vertiports, precision landing

* Corresponding author: mostafa.hassanalian@nmt.edu

† Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801

‡ Department of Electrical Engineering, New Mexico Tech, Socorro, NM 87801

§ Department of Electrical Engineering, Colorado School of Mines, Golden, CO 80401

†† Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM 87131

1. Introduction

Orphaned, abandoned, or inactive wells are natural oil and gas wells that have been decommissioned or left unmanaged by fossil fuel extraction companies due to low production capacity or lack of economic viability. Once a well is declared abandoned, the extraction company deactivates it. While these wells no longer produce oil or gas, they continue to emit methane into the environment. Methane, a flammable natural gas, is harmful to both the environment and human health and is a significant contributor to global warming due to its impact on the ozone layer [1].

Methane emissions from orphaned wells occur because many of these wells are left unplugged after being abandoned; plugging wells is an expensive process. It is estimated that across the United States, there are approximately 2.15 million unplugged orphaned wells still releasing methane and carbon dioxide, with an annual emission rate equivalent to 7.11 million metric tons. This amount of greenhouse gas is comparable to the emissions produced by 1.54 million vehicles running for a year [2]. To address this issue, the US Department of the Interior allocated US\$4.7 billion in January 2022 to plug orphaned wells across the country [3]. However, climate-focused think tanks estimate that fully plugging all documented orphaned wells in the US could cost around US\$280 billion [4]. Given the high cost of the plugging process, it would be more efficient to prioritize wells that are emitting methane at the highest rates. To do this effectively, we must first identify which wells are the largest emitters at each site. This task is challenging because many orphaned wells are located in remote areas that are difficult for humans to access and can be hazardous to their health. Therefore, developing an automated process that can autonomously survey these sites and detect wells with high methane emission rates without human intervention would be highly effective. In this paper, we propose a method to identify orphaned wells with high methane emissions using a drone vertiport concept. Inspired by nature, this concept combines an autonomous vertiport system with a drone swarm [5].

The drone vertiport system supports the detection of methane emissions from orphaned wells by serving as a storage, charging, and landing hub for drones equipped with sensing tools. It also offers a valuable solution for enabling maintenance tasks in smart cities, towns, and villages [6–11]. While the emphasis of this work is on the design and functionality of the bioinspired vertiport system, the methane detection

task itself is carried out by drones equipped with appropriate sensing technologies. The vertiport facilitates these missions by providing a reliable infrastructure for drone storage, charging, and precise landing in remote or challenging environments. The concepts of smart cities and drone vertiports are closely related, as various maintenance operations in smart cities can be carried out using the autonomous drone vertiport system, reducing the need for human involvement, saving time, and lowering costs. This system is fully autonomous and powered by solar energy. The vertiports are designed to resemble tree-like structures, inspired by nature, where the drones are housed in capsules that function like tree branches, providing protection and maintenance for the drones [12].

The rest of the paper is organized as follows: Section 2 explores the role of drones in smart cities and their potential applications. Section 3 discusses the design of drone vertiports, including considerations for support systems. Section 4 focuses on the structural analysis of the drone vertiport. Section 5 examines power supply solutions for the drone vertiport. Section 6 delves into the integration of drones with vertiports, including precision landing techniques. Section 7 outlines future work and development areas. Finally, Section 8 presents the conclusions.

2. Smart Cities and Drones

The rising interest in drones for urban operations has led to significant investments due to their versatility and efficiency in tasks like traffic monitoring, parcel delivery, and farmland irrigation [13–22]. In smart cities, drones assist with surveillance, emergency responses, and firefighting, while in towns and villages, they are used for crop irrigation and livestock monitoring, showcasing their adaptability to diverse environments [6].

Beyond agriculture and recreational markets, drones are now employed in industrial site evaluations, hazard identification, structural health monitoring, wildlife surveys, and atmospheric analysis, emphasizing their role in environmental monitoring [23–27]. Additionally, drones carrying emergency equipment, such as defibrillators and fire-extinguishing canisters, have proven effective in lifesaving and first-responder operations [28, 29].

Drones are increasingly being integrated into goods delivery systems, with companies like Alphabet and Amazon leading the way. Regulatory frameworks such as the US FAA's Part 135 Air Carrier Certification and UTM (Unmanned Aircraft System Traffic Management) framework are critical for ensuring safe and efficient operations in urban airspaces [30–36]. While these regulations primarily focus on drone operations in populated areas, they also emphasize the importance of reliable infrastructure, such as vertiports, to support autonomous drone missions. Our vertiport design aligns with these regulatory requirements by providing a robust and safe system for drone storage, charging, and precise landing, enabling compliance with emerging urban airspace management standards.

2.1. Drone Support and Vertiports

Recent advancements in wired and wireless charging systems have enabled drones to recharge autonomously. Wired systems, such as contact-based charging pads, and wireless methods, including inductive power transfer and resonant coupling, eliminate the need for manual intervention [37–39]. Nesting stations like SkyX's xStation and Volatus Aerospace's AeriePort extend drone range by providing temporary housing, charging, and telemetry for operations spanning hundreds of miles. These stations also mitigate the impact of adverse weather and GPS limitations by guiding drones to safe locations [40, 41].

The current state of drone infrastructure is largely focused on singular hangars, which are designed to support individual drones. While effective for limited operations, these designs lack scalability and efficiency, especially in high-traffic environments such as smart cities or remote locations requiring large-scale drone deployments. In this paper, we aim to address this limitation by developing a bioinspired vertiport system capable of supporting multiple drones simultaneously. This approach not only optimizes space utilization but also enhances the operational efficiency of autonomous drone systems. Urban environments, however, require innovative solutions due to limited real estate and high drone traffic. Approaches like resonant wireless power systems and high-powered lasers have shown potential but are still in developmental stages [42, 43]. Companies like Amazon and DJI have proposed using existing urban infrastructure, such as lampposts and rooftops, for drone docking and charging, enabling scalable operations in densely populated areas [44–45]. Independent companies like SkyX, Volatus Aerospace, Matternet, Heisha, Hextronics, and Skycharge are also developing autonomous charging stations that serve both housing and communication purposes. Additionally, the development of larger, multi-drone hubs could provide significant benefits in smart cities by optimizing space and supporting high-volume operations [46–50].

2.2. Bioinspired Drone Vertiports

Nature offers innovative inspirations for drone vertiport designs, such as blooming flowers, bird nests, and paper wasp nests, to address challenges like environmental protection, modularity, and scalability [12]. Flower-inspired designs use petal-like capsules to encapsulate drones, providing protection from the elements and interference. Similarly, water lilies inspire floating vertiports like FlyOnE's Lilypad Elevate™, which could serve coastal or aquatic operations, although these open-top designs may be less effective at protecting drones from harsh weather conditions [51, 52]. Mobile stations inspired by carrion beetles can combine drones with unmanned ground vehicles (UGVs) for tasks like delivering packages or accessing challenging terrains, but their open structure may also expose drones to environmental elements [53]. Bird nest-inspired designs elevate drones above ground-level activity, making them ideal for urban recharging hubs while providing some degree of weather protection. In contrast, paper

wasp-inspired designs feature compact, multi-cell configurations for vertical takeoff and landing (VTOL) drones, enabling simultaneous operations and efficient cargo storage, while also offering better environmental shielding [8, 29, 54].

3. Drone Vertiport Design

Building on insights from previous designs, a novel vertiport system was developed inspired by the natural architecture of trees, with “branches” serving as suspension mechanisms for drone capsules, similar to bird nests. Solar panels mounted on actuators at the top of the structure track the sun to maximize energy capture, ensuring efficient and sustainable operations. Elevated placement protects against environmental challenges such as flooding and snow, making the design resilient in rugged conditions like the San Juan Basin (testing site), which experiences high winds, moisture, extreme heat, and dust.

To enable autonomous drone operations, the vertiport integrates contact-based charging, weather prediction systems, and a central computing unit connected to a monitoring hub. Solar panels and weather stations are positioned for optimal functionality, while power banks and computing units at the base ensure stability. The modular and portable design allows deployment at multiple sites, meeting the demands of diverse environments.

The initial test site, the San Juan Basin, required a robust structure capable of withstanding wind speeds of up to 75 mph (33.5 m/s) and harsh desert conditions. The system combines lightweight, modular construction with durability, ensuring long-term performance. The conceptual phase focused on creating a design adaptable to severe environments while maintaining functionality and portability. This resulted in a versatile solution for autonomous drone operations.

To ensure portability, the vertiport incorporates folding telescopic features, reducing its size for transport and enabling deployment by just two people. Leveraging existing solutions, a satellite tower was selected as the base for its compact storage and stable, elevated platform when deployed. This approach minimized design and fabrication time while providing a reliable foundation for integrating system components.

The system is designed and selected with a focus on simplicity and portability, employing straightforward deployment mechanisms and a lightweight yet sturdy aluminum framework. The telescopic features of the structure enable easy adjustments to both the trunk height and the base, enhancing adaptability in various environments. Initially, the design included cable winches attached to the legs, anchoring them to the top of the structure to minimize oscillation at the maximum deployment height of approximately 27 ft (8.23 m). However, to mitigate the risk of structural failure, the operational height was reduced to 20 ft (6.1 m). This adjustment not only eliminates the need for a cable system, providing clearer flight paths for the drones, but also reduces the moment arm, improving resistance to higher wind speeds.

This structure serves as an ideal foundation for integrating additional components of the design, most notably the capsule

system. The initial capsule design drew inspiration from the natural world, particularly from plants known for their endurance and adaptability.

Each design concept aimed to create a secure landing zone and sheltered housing for drones, enabling charging and protection from environmental conditions. Two concepts—the pitcher plant and fungi capsules—were prioritized for further development. The pitcher plant capsule was the first to undergo detailed design due to its straightforward fabrication and lid actuation approach. Multiple iterations led to the final version, depicted in Figure 1a, which became the first to be manufactured.

The capsule’s key feature is a dynamic platform mechanism that extends when the lids open, more than doubling the landing and takeoff areas. This design improves error tolerance for autonomous drone landings, guiding drones to the center as the lids close. The expandable platform also acts as the primary actuation mechanism for the lids, using the rigidity of the capsule shell. Figure 1b shows the CAD model and manufactured version of the expanding base mechanism.

The design features a lightweight aluminum 5052 H-32 shell, weighing 11.3 kg, with natural weather resistance. A single-motor actuation system powers the capsule, using a scissor jack mechanism to convert rotational motion from a lead screw into vertical displacement. The stepper motor and lead screw achieve a thrust capacity of 890 N, while custom components enable precise movement of the scissor jack arms. Figure 1c illustrates the actuation mechanism in open and closed states, highlighting a high-precision track that ensures level drone landings and reduces tilt risk.

Experimental trials highlighted challenges specific to this design’s actuation mechanism, particularly friction along the high-tolerance tracks used to ensure precise movement of the platform. This friction is attributed to the unique requirements of the capsule’s expanding base mechanism, which demands precise alignment and structural rigidity to function effectively. While friction is a common challenge in systems requiring high precision, the combination of dynamic loading during lid operation and the compact, lightweight construction of this design intensified the issue. To mitigate these challenges, 3D-printed adapters and graphite were applied to reduce friction, while adjustments were made to address mechanical strain and motor overload during lid descent. These observations informed the development of a second capsule concept aimed at overcoming these limitations and improving overall performance.

Despite these complexities, the fungi design also offered several potential advantages over the initial concept. These benefits theoretically included a lower drag coefficient due to its hemispherical shape, more reliable actuation, a smaller overall footprint, reduced lid volatility, enhanced weather-proofing, direct lid actuation, and optimal zones for heat sink placement. Similar to the previous design, this concept also utilized single-motor actuation.

The dynamic platform within the capsule, as depicted earlier, utilizes a tensioned sheet stretched across its “arms” to

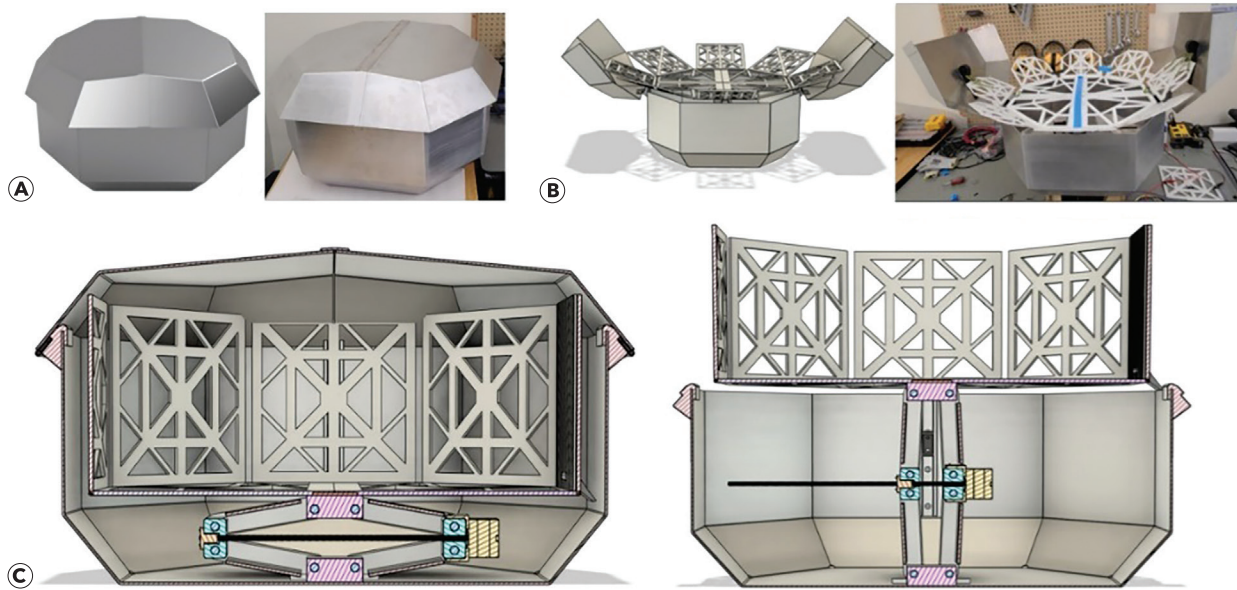


Figure 1. Views of (a) CAD model and manufactured pitcher plant capsule, (b) open state of the capsule (CAD model and manufactured), and (c) closed and open states of the capsule.

provide a landing surface surrounding the drone. This sheet, along with the walls, functions as a self-centering mechanism, similar to the previous design but with more flexible walls. The closing actuation of the capsule is particularly critical for the closing dynamic platform. Because the two opposing “Arms 1” are positioned directly within the “jaw” of the capsule lids, there is a risk of pinching during closure. Figure 2b provides a detailed overview of the capsule’s components and terminology.

To ensure precise movement of the arms, a carefully calibrated spring tension system is implemented. “Arm 1” is spring-loaded to naturally return to the closed position, as shown in Figure 2a. In contrast, “Arm 2” is tensioned to remain in the fully open position. The spring tension on “Arm 2” exceeds that of “Arm 1,” causing them to flatten, holding this

position until the capsule starts to close. During the closing process, the capsule counteracts the downward force on “Arm 2,” releasing the tension and allowing “Arm 1” to return to its closed position, causing “Arm 2” to collapse into the capsule with its adjacent arms. These arms, which are the walls, lie on the same plane as the red base acrylic. When fully open, the drone can rest anywhere and slide from one side to another without interruption. This creates a smooth, flat surface for the drone and will slant the walls upon closing, causing the drone to slide to the center.

The integration of these capsule systems into the base design is achieved through a branch system. The main telescoping trunk of the structure is equipped with four mounting brackets specifically engineered for this application. These brackets are secured to the trunk using simple fasteners, which

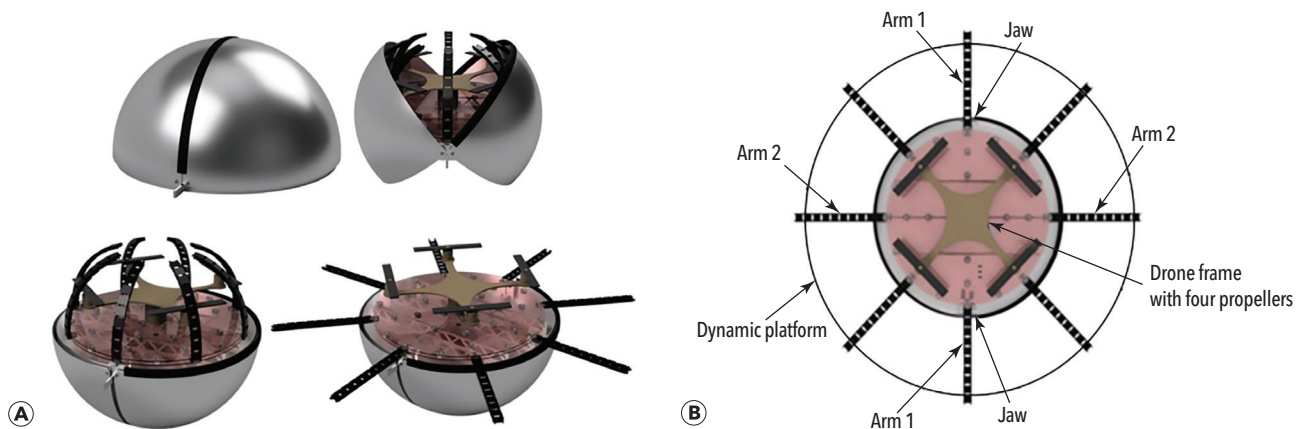


Figure 2. Views of (a) the opening cycle of the fungi capsule, and (b) the dynamic platform of the capsule.

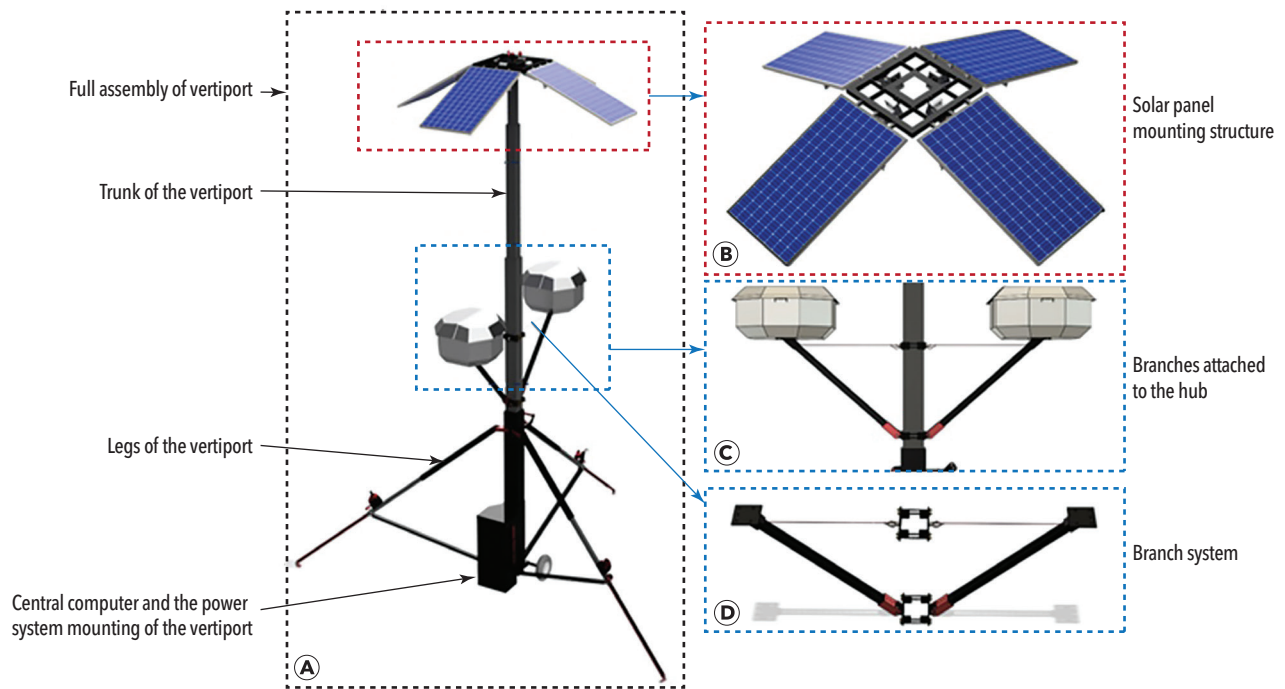


Figure 3. Views of (a) full assembly of the vertiport, (b) solar panel mounting structure, (c) branches attached to the hub, and (d) branch system.

apply clamping force to hold them in place. A combination of slotted channel struts and custom-machined hinges provides an affordable, temporary, yet robust solution for mounting the capsules. The current configuration of the branch system, with pitcher plant capsule mounts in place, is illustrated in Figure 3d. The placement of these branches can be adjusted along the primary mast of the base structure according to specific requirements.

The upper section of these branch mounts employs the same clamping bracket design; however, instead of a hinge, it utilizes a weather-resistant, high-strength multi-strand cable, facilitating the rapid attachment of drone capsules. The branches were designed to accommodate various capsule iterations and can withstand a static force of up to 680 N (150 lb) before any plastic deformation occurs. Figure 3c depicts the branches mounted on the purchased hub, with two pitcher plant capsules attached.

A critical component of this design is the solar panels installed at the top of the structure, which serves as the primary power source for the sustainable vertiport, supplying sufficient energy to support up to eight drones. Due to their extensive surface area, these solar panels are subject to significant wind loads. The four solar panels, as illustrated in Figure 3b, are mounted on a rigid body structure engineered to withstand wind speeds exceeding 112 km per hour (70 mph). Linear actuators are mounted on the back of each solar panel and connected to the rigid support structure. These actuators, with a stroke length of 30 cm (1 ft) and a dynamic load capacity of 1468 N (330 lb), enable the panels to track the sun's position throughout the day. They also reposition the panels to a

neutral stance in high wind conditions and adjust their orientation to accommodate incoming drones. Figure 3a shows the solar panels mounted atop the vertiport structure.

4. Structural Analysis of Drone Vertiport

The height of the vertiport structure introduced several challenges, particularly due to the central pole extending over 6 m (20 ft), creating a substantial tilting force. Ensuring the structure's stability and preventing it from reaching a critical load under high wind conditions is essential. To evaluate the wind-induced loads on the structure, simulations were performed using COMSOL. Figure 4a presents the von Mises stress analysis results with a deformation scale of one, based on a wind load of 30 m/s (67 mph) applied to the model. Although the solar panels are not depicted in the figure, their effects were calculated beforehand to determine the resulting load at the top of the structure.

The simulation results indicate that the structure begins to tip at this wind speed (30 m/s), and the original design with aluminum legs starts to yield. The stress and displacement values at specific points on the structure are detailed in Table 1, corresponding to the locations marked in Figure 4b. Points 6 and 7, located near the base of the legs, exhibited the highest stress levels, as anticipated. As the structure experienced concentrated loading on a single leg, the material reached its yield strength, leading to failure. To address this issue, the legs were redesigned using AISI 1018 steel, a material known for its enhanced yield strength, durability, and robustness. An analysis was conducted to evaluate the performance of the redesigned structure under both static and dynamic

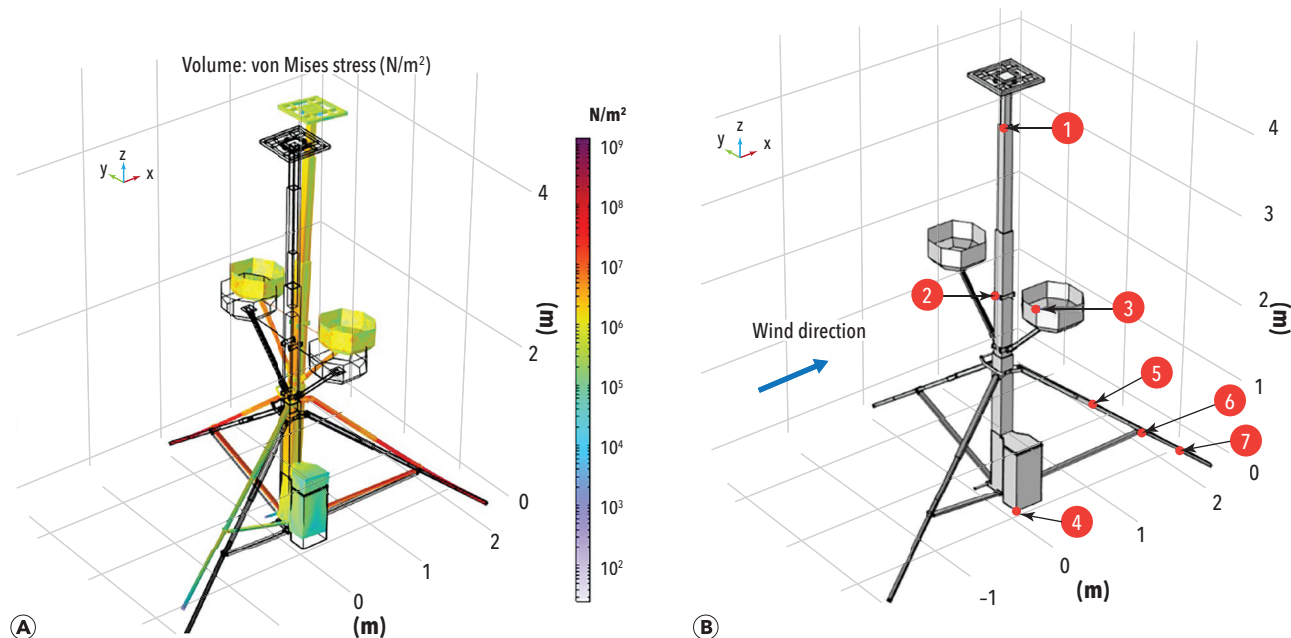


Figure 4. Views of (a) von Mises stress for gravity applied and 30 m/s wind loading, and (b) stress and displacement points.

TABLE 1
COMSOL results; tabulated displacement and stress, gravity applied, and 30 m/s wind loading

Point	Displacement in x (m)	Displacement in y (m)	Displacement in z (m)	von Mises stress (N/m ²)
1	4.16E-01	2.70E-01	0.12864	7.36E+05
2	2.12E-01	1.40E-01	0.1255	1.77E+06
3	2.54E-01	1.69E-01	0.2150	3.12E+06
4	-2.96E-02	-1.46E-02	0.16679	1.29E+07
5	5.81E-02	4.13E-02	0.057984	1.01E+07
6	1.99E-02	1.53E-02	0.020503	3.86E+07
7	4.61E-03	3.78E-03	0.0046386	1.46E+08

conditions, including wind loads of up to 30 m/s (~67 mph). The new design demonstrated the ability to withstand anticipated environmental stresses with minimal deflection, and the stress levels remained well below the yield strength of the steel, ensuring overall stability and reliability.

5. Power Supply of the Drone Vertiport

The system is designed with an isolated grid, necessitating a renewable energy source to minimize maintenance and ensure continuous operation (see Figure 5). Drawing inspiration from nature, particularly how trees harness solar energy, solar panels were chosen as the primary energy source, allowing the vertiport to function in various environments. During daylight hours, the solar panels will power the system, while a power

bank stores excess energy to maintain operations overnight, ensuring the system runs continuously. Any surplus energy generated by the panels is stored in the power bank located at the base of the vertiport.

The energy flow within the system starts with electricity generated by the solar panels, which then passes through a controller. This controller regulates the voltage and current from the solar panels, protecting the power bank from any erratic behavior or excessive current that could cause damage. An inverter, connected in parallel with the power bank, is used

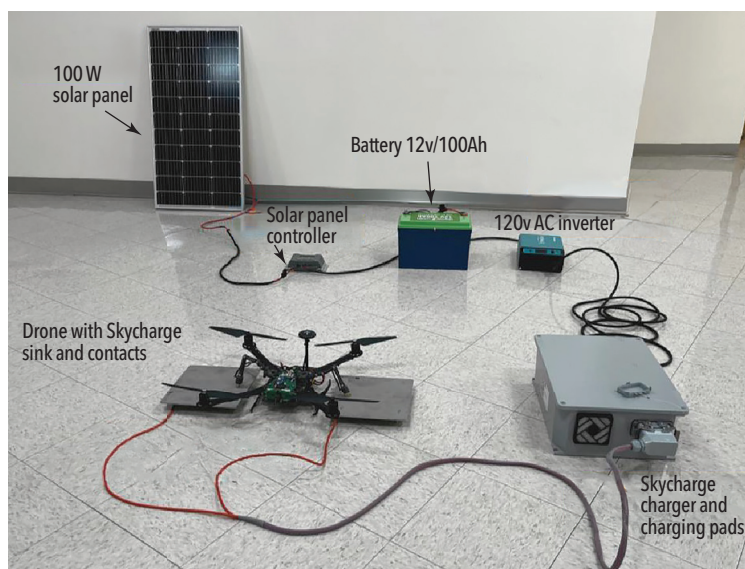


Figure 5. View of the system's main isolated grid.

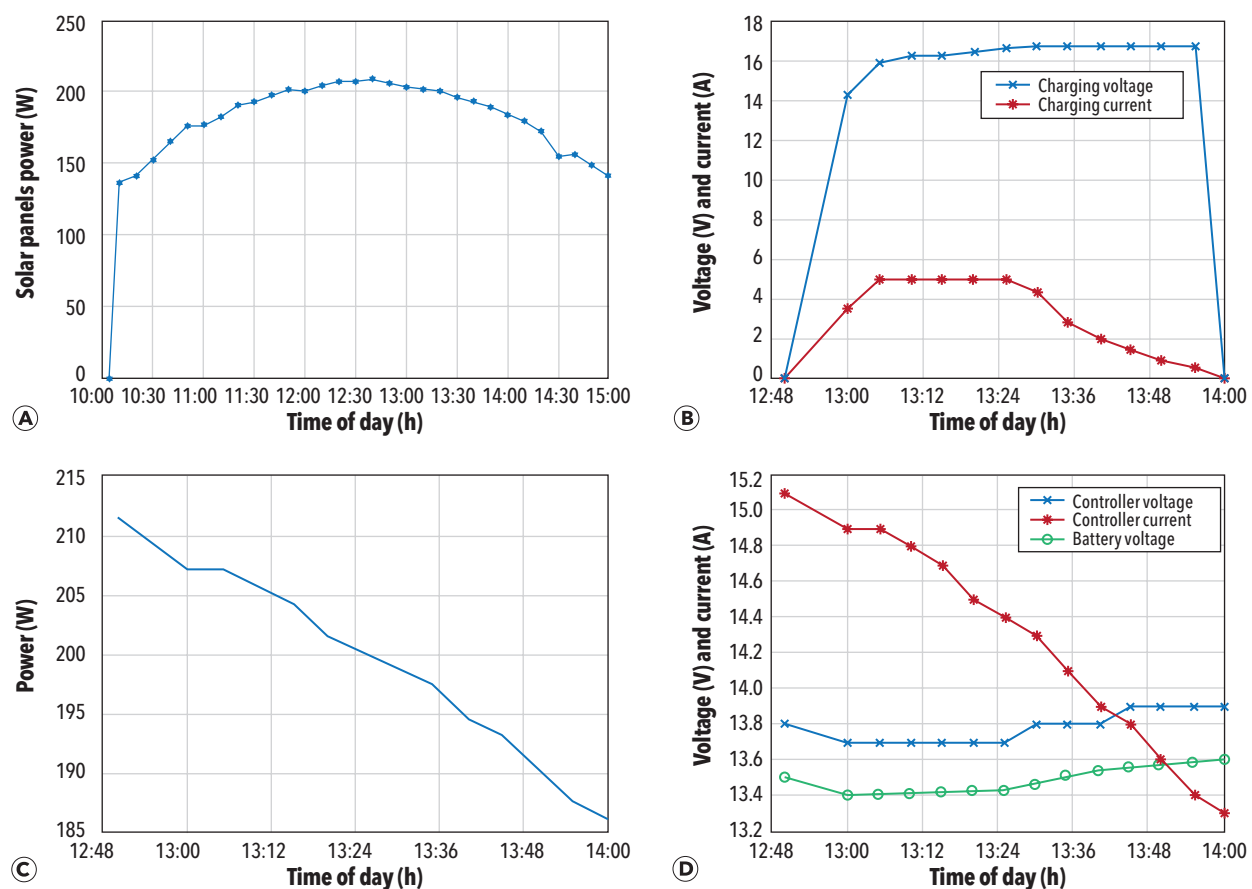


Figure 6. (a) Power from solar panels throughout the day; (b) charging system data for drone battery; (c) power; and (d) voltage and current from solar panels with active charging system.

TABLE 2
Collected data on the power bank and solar panels

Time (p.m.)	Solar panel voltage (V)	Solar panel current (A)	Voltage from controller (V)	Battery voltage (V) (actual)	Battery current (A)	Battery level (%)
12:50	14	15.1	13.8	13.5	15.1	97
1:00	13.9	14.9	13.7	13.4	14.9	97
1:05	13.9	14.9	13.7	13.4	14.9	97
1:10	13.9	14.8	13.7	13.42	14.8	97
1:15	13.9	14.7	13.7	13.42	14.7	97
1:20	13.9	14.5	13.7	13.43	14.5	97
1:25	13.9	14.4	13.7	13.43	14.4	97
1:30	14	14.3	13.8	13.8	14.3	97
1:35	14	14.1	13.8	13.54	14.1	97
1:40	13.9	13.9	13.8	13.54	13.9	97
1:45	14	13.8	13.9	13.56	13.8	97
1:50	14	13.6	13.9	13.57	13.6	97
1:55	14	13.4	13.9	13.58	13.4	98
2:00	14	13.3	13.9	13.6	13.3	98

TABLE 3
Collected data on the Skycharge device

Time (p.m.)	Energy (Wh)	Provided voltage (V) by Skycharge	Provided current (A) by Skycharge	Drone battery charge (Ah)	Drone battery level (%)
12:50	0	0	0	0	0
1:00	0.39	14.25	3.6	0.034	1
1:05	5.8	15.933	5.009	0.376	11.4
1:10	14.7	16.27	5.009	0.918	27.82
1:15	18.542	16.322	5.009	1.154	34.97
1:20	25.996	16.345	5.009	1.62	49.09
1:25	31.609	16.634	5.009	1.971	59.73
1:30	40.056	16.79	4.374	2.501	75.79
1:35	45.899	16.79	2.864	2.835	85.91
1:40	48.86	16.764	1.997	2.999	90.88
1:45	50.776	16.764	1.466	3.122	94.61
1:50	52.286	16.764	0.952	3.206	97.15
1:55	53.537	16.764	0.582	3.285	99.55
2:00	53.985	16.764	0	3.312	100

to power any AC devices. A notable challenge in this design is the conversion from DC to AC and then back to DC, which can lead to power losses through heat. However, this issue is mitigated by the fact that the equipment is primarily used to test the feasibility of supporting multiple drones with off-the-shelf components.

The first experiment aimed to evaluate the power output of the solar panels over the course of a day. A single solar panel was positioned flat at approximately 10:00 a.m., and the power output was recorded every 15 min until 3:00 p.m., resulting in a total of 30 data points. Plotting these data points against time produced the results shown in Figure 6a. This data provides a baseline for the amount of power generated around midday. The next step involved assessing the power consumption of the contact-based charging system while charging a single drone battery. The device measured both the power output and consumption during this process, and the resulting data are plotted to illustrate the power usage of the system (see Figure 6b).

The Skycharge charging system for drone batteries is an intelligent charging system that adjusts the charging voltage and current according to the drone battery's charge level. From Figure 6b, we can see that as the drone battery's charge level increases, the charging current gradually decreases. The capacity of the drone battery is 3300 mAh. Once the drone battery was fully charged, the system immediately stopped providing voltage. For better understanding, see the collected data in Table 3.

Before analyzing the data to estimate the number of drones that can be supported throughout the day, a final experiment was conducted to evaluate the system's overall performance.

This experiment tested whether the controller could effectively regulate an additional load connected in parallel to the battery. For the setup and datasets collected during this experiment, the solar panels were laid flat on the ground surface, providing key insights into the system's ability to handle varying power demands while maintaining stable operation. Tables 2 and 3 show the collected data on the battery and solar panels, as well as on the Skycharge device. The power, voltage, and current data are shown in Figures 6c and 6d, respectively.

The results from the final experiment demonstrated that the grid system is capable of supporting an additional load while simultaneously charging a battery, provided the load does not consume a substantial portion of the energy generated by the solar panels. Using the collected data, an estimation was made to determine the number of drones the system could support throughout the day. These calculations were performed manually using a calculator. It was observed that the battery could power the inverter until its charge dropped to 15%, but it could only be recharged up to 96%. During all trials, the battery started with a 20% charge, and within one hour, its charge increased at a rate of 50% per hour. Based on this data, the graph shown in Figure 7 was generated. Given the conclusion that the vertiport's electrical grid can support up to eight drones during daylight hours, it is recommended to limit the number of drones to seven or fewer. This reduction ensures sufficient power allocation for the main computing system, maintaining optimal operational efficiency and stability.

For this part of the study, the objective was to determine the optimized number of drones the vertiport's power bank can support. The power bank has a capacity of 1280 Wh, while each drone battery has a capacity of 48.84 Wh. Using

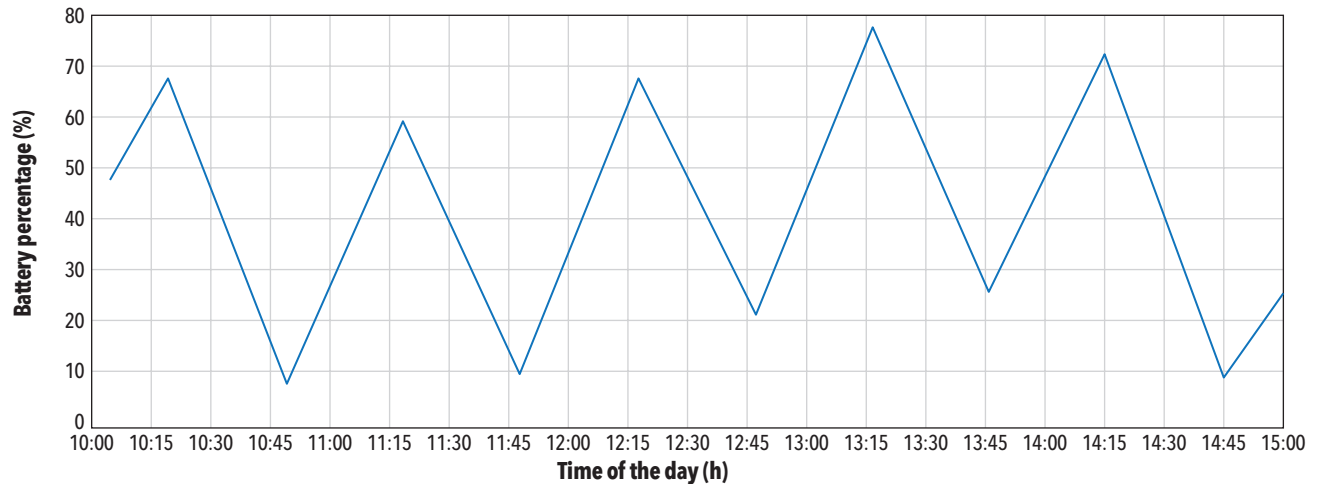


Figure 7. Estimated charging pattern for eight drones.

experimentally collected charging and discharging data for both the power bank and drone batteries, it was estimated that the vertiport's power bank could support up to eight drones continuously, along with other vertiport components.

The estimation assumes that a swarm of eight drones actively conducted surveillance tasks over a 5 h period. At the start of the estimation at 10:00, the power bank level was assumed to be ~50%. During this time, the solar panels were actively generating power to charge the power bank. After 15 min of charging (from 10:00 to 10:15) without drones connected, the power bank level increased to 69%. At 10:15, all eight drones returned to the vertiport with battery levels between 10% and 15%, initiating simultaneous charging.

From 10:15 to 10:45 (30 min), the drones charged sufficiently to conduct another 30-min surveillance task, reducing the power bank level to ~9%. After the drones departed for their next mission, the power bank recharged, reaching ~60% by 11:15 through the solar charging system. At this time, the drones returned, and the process repeated. During this cycle, the power bank level dropped from 60% to 10%.

The power drop of the power bank was not consistent throughout the process due to the solar panels providing power to both the drone batteries and the power bank. At 1:45 p.m., the power drop of the power bank was at its lowest (~26%), coinciding with the highest power generation rate of the solar panels due to the optimal orientation of the sun. The solar panels operate at maximum capacity when the sun's orientation is perpendicular to them. As the sun's position changed, the power generation rate decreased, causing the power bank's energy depletion rate to increase gradually. Throughout the process, the solar panels remained horizontally aligned with the ground surface, with no adjustments made to their orientation.

6. Drone Integration to Vertiport and Precision Landing

The drone used for this project is equipped with a flight system that combines a flight controller and an onboard computing unit. The onboard processor handles all data collected

from the drone's sensors and cameras and runs the necessary software to manage communication and configuration for flight operations. The flight controller operates with open-source firmware, which can only be accessed via the terminal on the onboard processor unless a direct-wired connection is established with the flight controller's port, typically required only for firmware updates via image flashing.

The primary reason for selecting this drone was its high functionality and the robust usability of its autopilot features. These capabilities are enabled by a modular software architecture running on the onboard computing unit. This architecture consists of services, pipelines, and tools. The services include software that handles the processing, calculation, configuration, and maintenance of the drone's individual components. For example, the camera server manages optical input, processes the data based on the task, and configures the cameras for identification and filtering. Tools are used to manipulate or inspect services, such as examining the drone's IMU (inertia measurement unit) servers or battery status through the PX4 software. The pipelines, a critical component of this architecture, function as data carriers between different services that request specific information. This architecture is particularly valuable to the project as it allows for the integration of data from these pipelines into custom software applications. An example of this architecture in action is a visual-inertial odometry (VIO) system, which requires camera data from the camera processing module and IMU data from the inertial measurement unit module to calculate VIO, demonstrating the interconnected functionality of the system.

6.1. AprilTag Relocation

For landing precisely in any specific location, we use AprilTags detected by the drones utilizing an in-built deep learning algorithm. Building on the understanding of the drone's software and hardware capabilities, the focus shifts to deep neural networks and AprilTag detection. The drone is already equipped with software to detect and localize AprilTags using

VIO data from the camera. The detection process is facilitated by TensorFlow Lite, a pre-trained deep learning neural network, specifically a convolutional neural network (CNN). This type of deep learning AI is designed to recognize patterns across various media, including video, audio, and text [55, 56]. Upon detecting an AprilTag, the camera places five reference points: four at the corners and one in the center. These points are then used to calculate the position of the tag relative to the drone using trigonometric functions, enabling precise localization and navigation.

Utilizing this data for relocalizing the drone involves more complexity than simply inputting Cartesian coordinates (XYZ). In autopilot mode, the drone does not navigate using XYZ coordinates; instead, it relies on a different orientation convention known as Euler angles or RPY (roll, pitch, yaw). The conversion between these two systems is feasible through the application of Euler angles of angular velocity. However, a challenge arises because there are 12 possible Euler angle sequences, and it is not immediately clear which sequence is being used for the coordinate system conversion. Further research indicates that the ZYX sequence is commonly employed for most drones, leading to the following rotation matrix:

$$\begin{aligned}
 (1) \quad Z_r &= [\cos(r) \ -\sin(r) \ 0, \ \sin(r) \ \cos(r) \ 0, \ 0 \ 0 \ 1] \\
 (2) \quad Y_p &= [\cos(p) \ 0 \ \sin(p), \ 0 \ 1 \ 0, \ -\sin(p) \ 0 \ \cos(p)] \\
 (3) \quad X_y &= [1 \ 0 \ 0, \ 0 \ \cos(y) \ -\sin(y), \ 0 \ \sin(y) \ \cos(y)] \\
 (4) \quad Z_r \ Y_p \ X_y &= M = \begin{bmatrix} C_p C_r & C_r S_p S_y - C_y S_r & S_r S_y + C_r C_y S_p \\ C_p S_r & C_r C_y + S_r S_p S_y & C_y S_r S_p - C_r S_y \\ -S_p & C_p S_y & C_p C_y \end{bmatrix} \\
 (5) \quad \tan^{-1}\left(\frac{M_{21}}{M_{11}}\right) &= roll^*; \tan^{-1}\left(\frac{M_{31}}{\sqrt{1 + M_{31}^2}}\right) = pitch^*; \\
 \tan^{-1}\left(\frac{M_{33}}{M_{32}}\right) &= yaw^*
 \end{aligned}$$

Understanding these conventions is crucial for comprehending how the drone calculates its path to relocalize above the AprilTag. The drone achieves this by rotating its axis and determining its position over time based on angular velocity. This underscores the importance of specifying the correct commands and orientations when working with robot operating system (ROS) and configuring parameters that enable the drone to hover above the AprilTag before landing. Additionally, it is essential for developing algorithms that manage scouting and landing operations. By leveraging the AprilTag detector service through the Modal Pipe Architecture, the RPY values can be extracted and utilized within ROS.

6.2. AprilTag Detection

Data was collected using the drone to assess its AprilTag detection capabilities in an indoor environment (see Figure 8). The drone utilized a tag-detection system, which continuously ran to capture AprilTag location data. Upon detecting the AprilTag's size and position, the drone processed its own RPY data to navigate toward the tag. For this experiment, an AprilTag

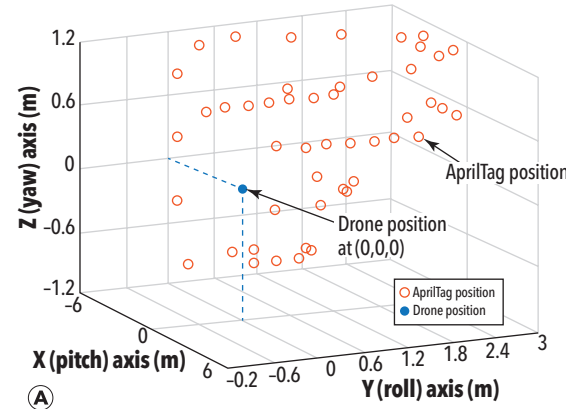
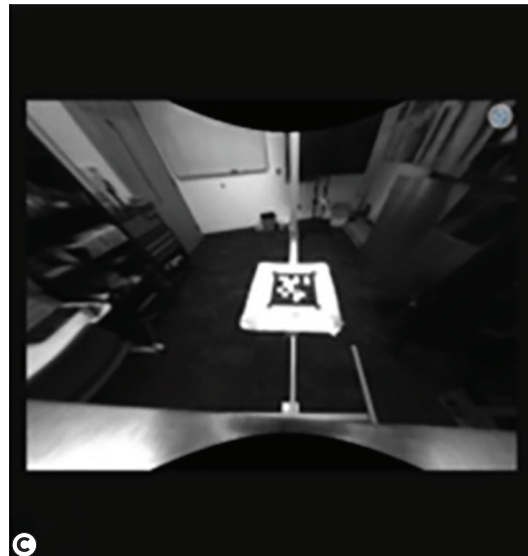
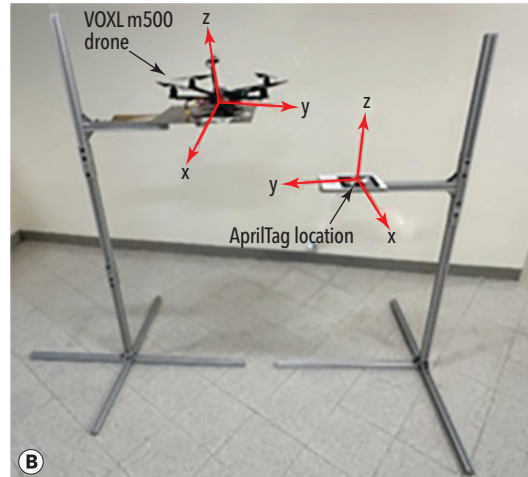


Figure 8. Visual points from drone to AprilTag: (a) graphical representation of AprilTag detection range; (b) experimental setup; and (c) drone camera view.



measuring 6 in. $\times$ 6 in. was used. The minimum and maximum distances at which the drone could successfully detect the AprilTag were recorded.

The coordinate system was established relative to the drone's position, and the location of the AprilTag was measured accordingly. The drone's ability to detect the AprilTag was evaluated across various positions, encompassing nearly all possible placements of the tag. This testing consisted of 32 trials focusing on AprilTag detection accuracy and the drone's RPY adjustments relative to the tag. Detection was successful in 21 of the 32 tests, highlighting the system's ability to detect and navigate to the AprilTag based on coordinate system alignment. Additionally, 34 tests were conducted to identify the minimum and maximum detectable distances of the AprilTag. Detection was successful in 26 of these tests, providing a quantified range of the drone's AprilTag detection capability. It was observed that the drone has a specific detection range within which it can reliably identify the AprilTag. Figure 8 provides a graphical representation of this detection boundary, illustrating the area within which the drone successfully detected the AprilTag at any given point. The figure shows the AprilTag detection range of the drone, with the unchanged position of the drone considered as the origin (0,0,0) of the 3D coordinate system. The distance is measured in meters.

6.3. MAVLink and ROS Implementation

A notable challenge encountered during the integration process was the limitation of the drone's onboard computer, which restricts the direct installation of packages or applications without utilizing Docker. In a typical ARM Linux environment, the 'sudo apt install' command would suffice to install necessary packages. However, for this specific drone, the procedure requires creating a designated directory and downloading a compatible Docker image, such as "voxl-cross." After configuring the image, it must be built into a tar.gz file. This file is then transferred to the onboard computing unit using a wired connection and a debugging tool to push the file into the root shell directory. It is crucial to ensure that the Docker daemon is running as a background service before proceeding with building and deploying the image.

MAVROS, unlike MAVLink and ROS, operates as an active command-line interface, functioning akin to a frontline application that communicates directly with the flight controller through pipelines connected to the vision processing hub. The integration of MAVROS is particularly important because it enables direct communication with the flight controller, allowing for arming and disarming of the drone without relying on external signals from a transmitter or QGroundControl.

In previous testing phases, the drone's autopilot and AprilTag detection capabilities were evaluated using MAVLink and vision-processing-hub demonstration packages [57]. With the implementation of MAVROS, the process begins by initiating ROScore and the necessary nodes for flight, followed by executing the required packages to facilitate communication with the PX4 software on the flight controller. Once the

connection between PX4 and MAVROS is established, the ROS script is initiated to arm and control the drone, all of which is executed with a single command from the terminal. Despite the generally smooth operation, sporadic communication errors between MAVROS and PX4 were encountered, indicating unexpected command inputs. However, these errors did not significantly impact the overall flight performance.

6.4. Drone Relocation Results

The coordinate system was established relative to the drone's position, and the location of the AprilTag was measured accordingly. The drone's ability to detect the AprilTag was evaluated across various positions, encompassing nearly all possible placements of the tag. This testing consisted of 32 trials focusing on AprilTag detection accuracy and the drone's RPY adjustments relative to the tag. Detection was successful in 21 of the 32 tests, highlighting the system's ability to detect and navigate to the AprilTag based on coordinate system alignment. Additionally, 34 tests were conducted to identify the minimum and maximum detectable distances of the AprilTag. Detection was successful in 26 of these tests, providing a quantified range of the drone's AprilTag detection capability.

To test the drone's ability to relocate using AprilTag detection, the drone was taken to an open field, and a QR code was placed on a flat surface. The objective was for the drone to detect the QR code mid-flight and autonomously land on it. Initially, the drone was set to position flight mode and manually controlled using a transmitter to fly closer to the QR code. Upon detecting the QR code, the drone was switched to off-board flight mode (see Figures 9a and 9b). In this mode, the drone accurately determined the position of the QR code and hovered steadily at a height of 1.5 m (5 ft) above it. After maintaining a stable hover, the drone was switched back to position flight mode and landed on the QR code.

To rigorously evaluate the system's AprilTag detection and precision landing capabilities, extensive testing was conducted in both indoor and outdoor environments. Nine outdoor flight tests were performed to assess the impact of environmental factors, including wind, shadow, and varying detection distances. During some trials, vibrations were intentionally introduced on the branch structure to simulate wind effects. Despite these disturbances, the drone reliably detected the AprilTag and executed precise landings, demonstrating the system's robustness under dynamic conditions (see Figure 9c).

7. Future Work

The next steps in this project focus on enhancing the autonomous capabilities of the drone system. A key area for development is refining the use of MAVROS to create software that can autonomously plan flight paths and incorporate algorithms to assist the drone in locating its designated landing site. Once the drone can reliably navigate its flight path independently, the integration of a second drone into the system will be pursued to explore coordinated swarm operations. Additionally, there will be a focus on integrating an automatic

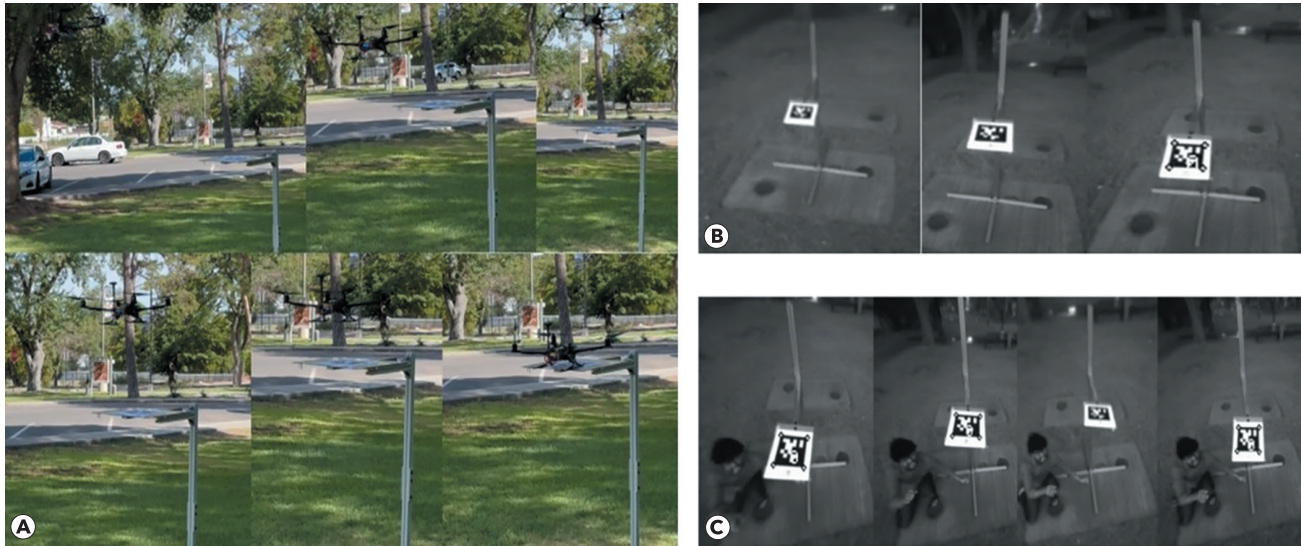


Figure 9. Photographs of AprilTag detection by the drone during (a, b) precision landing and (c) under dynamic conditions.



Figure 10. Proposed concept and current prototype of the vertiport.

charging system. This will involve configuring the drones to establish a closed circuit with the charging pads upon landing, allowing for seamless recharging without manual intervention. These advancements will further the system's ability to operate autonomously in inaccessible environments, enhancing its versatility for various applications beyond the original scope of detecting abandoned oil wells emitting greenhouse gases. Views of the proposed concept and the current prototype are shown in Figure 10.

8. Conclusions

Drones have a wide range of applications across various sectors, including smart cities, towns, villages, and industrial and mining areas. This work focused on the development of a bioinspired vertiport system to support drone-based methane detection missions. The vertiport provides a robust and efficient infrastructure for drone storage, charging, and landing, enabling autonomous operations in remote areas where methane-emitting orphaned wells are located. These wells are often located in remote areas that are challenging for technicians to access. Additionally, methane inhalation poses significant health risks. Identifying orphaned wells emitting methane gas across the US is a costly process due to their increasing numbers and hard-to-reach geographical locations. The task requires expensive equipment, which is also difficult to move from place to place, operated by experienced and expert human technicians. As orphaned wells are often scattered randomly across a particular site, this makes them difficult to reach, making the task even more arduous and time-consuming. In this context, the drone vertiport system presents an effective solution to this problem. It requires only two human technicians to place and activate the vertiport system at any site, and the autonomous system will do the rest. The drones will continuously scan the site to detect methane emissions from orphaned wells in a proper surveillance manner and send data to a remote data analysis and control center. This approach will reduce the overall operational cost as well as the human effort involved. It also saves time and lowers the risk to human safety.

Given the high costs associated with plugging orphaned wells, this autonomous system provides a cost-effective approach by prioritizing wells with the highest emissions for remediation. The strategy aims to minimize overall methane emissions by addressing the most critical sources first, thereby reducing the maximum emissions with the minimum number of wells plugged. The drone vertiport system is designed to be sustainable, portable, and fully autonomous, powered by solar energy, and capable of continuously supporting up to six drones simultaneously. These drones are equipped with advanced autonomous features, including precision landing using QR codes (AprilTags). The vertiport capsules are automated and feature a contact-based charging system, ensuring seamless and continuous drone operations. Future work will focus on enhancing drone communication and path planning algorithms, as well as optimizing the drone battery

management system, to further improve the efficiency and effectiveness of the system in various environments.

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GUIDED BY HEARING: ROBOTIC MOTION PLANNING FOR PRECISION IN GAS LEAKAGE LOCALIZATION

MOHAMMAD NASR[†], NIHAR MASURKAR[†], POURIA MESHKIZADEH[†], AND EHSAN DEGHAN-NIRI^{*†}

ABSTRACT

This research proposes a motion planning framework for a robot equipped with a bioinspired hearing system to enhance its sound source localization, specifically for gas leak detection. Similar to how animals use movements, such as changing positions or rotating their ears, to precisely localize a sound source, this framework enables the robot to improve its estimation of both direction and distance through strategic motion. The proposed method uses the time difference of arrival (TDOA) between two wideband optical microphones, obtained through this motion, to accurately estimate the direction and distance of a sound source. We first introduce the underlying concepts and validate the approach using experimental data collected with a collaborative robotic arm. We then demonstrate the implementation of the method on a quadruped robot. The results show that the method can be effectively deployed on mobile robots, achieving directional and distance accuracy for gas leak localization.

KEYWORDS: gas leakage, source localization, quadruped robot, robotic dog, robotic inspection

Introduction

Gas leakage is a significant source of failure in various industries, including oil and gas, clean energy systems such as hydrogen-based fuel cells, and the automotive sector. Early detection of gas leaks is crucial to prevent catastrophic failures, ensure safety, and reduce environmental impact. Gas leakage detection and localization involve using a wide range of gas sensing hardware, including metal oxide (MOX) gas sensors, e-noses, and photoionization detectors (Francis et al. 2022). Relying on human labor is demanding, while installing sensor equipment can be expensive and often financially unfeasible. As a result, there is growing interest in using mobile robots for inspection, such as Boston Dynamics' Spot (Guizzo 2019).

While the use of robots for industrial inspection is not new, the application of mobile robots for inspection remains an active research area. A review of various pipeline robots, considering factors such as inspection accuracy, adaptability, cost, and efficiency (Ambati et al. 2020), as well as the development of inspection robots for nuclear power plants (Yamamoto 1992; Fu et al. 2006), demonstrates a long-standing interest in this field. Furthermore, the use of robots has expanded into other industrial applications, including waste deposits and electric power cables (Jiang et al. 2005); civil engineering tasks like inspecting building facades and concrete structures (Ilyas et al. 2021); examining structures such as ships, wind turbines, and aircraft (Almadhoun et al. 2016); and underwater facility inspections (X. Wang et al. 2022). More recently, several systems have been proposed for surveying nuclear power plants to assess radiation levels (Abadi et al. 2023; Mitchell et al. 2023). In the context of gas source localization, Francis et al. (2022) provide an overview of gas detection principles and review existing works that propose the use of mobile inspection vehicles.

Since vertebrates became terrestrial 370 million years ago, reliable information has been essential for making survival decisions (Munoz and Blumstein 2020; Thewissen and Nummela 2008). In our paper, we draw inspiration from the remarkable evolutionary strategies employed by vertebrates in their survival and adaptation within the animal kingdom. The fundamental principle of aeroacoustics leak detection revolves around the generation and propagation of sound waves when gas escapes from a pipeline (S. Wang and Yao 2020). These acoustic signals carry crucial information about the leak, such

* Corresponding author: nde@asu.edu

[†] Intelligent Structures and Nondestructive Evaluation (ISNDE), School of Manufacturing Systems and Networks, Arizona State University, Mesa, AZ 85212

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as its magnitude, location, and potential impact on the pipeline's integrity (Liang et al. 2013). The main advantages of using acoustic signals for gas leak diagnosis include swift response time, long range, and precise localization (S. Wang and Yao 2020). A key drawback of using acoustic signals is their reduced sensitivity as the sensors move farther away from the source due to significant attenuation (Liu et al. 2017). This attenuation is even more pronounced with higher-frequency sounds (ultrasound), which are often involved with smaller leakages. One effective approach to mitigate this problem is by employing an array of microphones along with acoustic imaging techniques (Li et al. 2021; Fluke 2021; Drives & Controls 2021). However, this method generates a substantial amount of data, which is not ideal for a near-real-time approach required for creating a semi-autonomous platform and quick response. Fortunately, this issue has been ingeniously addressed by biological systems in their evolutionary acoustic sensing systems, using only two ears (binaural sensing). Instead of relying on increased sensor numbers to enhance sensitivity, these biological systems evolved their external ear (pinna) shapes to act as hardware for magnifying sound coming from specific directions. This evolution was further complemented by strategic motion and motion control of the pinna and head as well as their movement (Populin and Yin 1998; Fletcher 2014), allowing them to dynamically change acoustic directionality and sensitivities as needed. Inspired by these biological mechanisms, we propose in this paper an acoustic sensing system that comprises two microphones, mimicking two ears and binaural hearing, with a framework designed to optimize or strategize movement to improve source localization accuracy.

Sound source localization (SSL) is a prominent topic in robotics, with a detailed review of common methods provided by Rascon and Meza (2017). While gas and air leak localization is essential for industrial inspections and has been explored in earlier research, many existing approaches rely on fixed microphone arrays (Eret and Mesckell 2012), handheld devices (Liao et al. 2013) for manual detection, and statistical time-domain features for pinpointing leaks in pipes (F. Wang et al. 2017). Yan et al. (2018) used a four-element linear array to identify multiple sources with the MUSIC algorithm within the 63–187 kHz emission range. Focusing on ultrasonic emissions from leaks in pressurized pipes, Schenck, Daems, and Steckel (2019) employed a peak search on a beam-formed spectrum and use a 32-element microphone array. By leveraging multiple poses of the robot and integrating simultaneous localization and mapping (SLAM) techniques with the microphone array, potential leaks are effectively localized. Most recently, G. K. J. Fischer et al. (2024) introduced an autonomous robotic system for comprehensive plant inspection, equipped with a variety of sensors, including lidar, stereo, UV/IR/RGB cameras, electronic noses, and five microphones. These sensors detect factors like methane leaks, flow rates, and infrastructure issues. The system was tested at a wastewater treatment site, achieving gas leak localization with a 50 cm error through acoustic assessments.

Current robotic systems for industrial inspection rely on various sensors, such as lidar, stereo, and depth cameras, to map environments for navigation and distance estimation. However, little attention has been given to optimizing the robot's movement and positioning to enhance leak localization once an anomaly, such as sound generated by a leak, is detected by the microphones. Typically, these systems use microphone arrays to estimate the direction of arrival (DOA) of sound, combined with techniques like SLAM and lidar to locate the leak. While multi-microphone array techniques can perform well from fixed positions, they often require more complex hardware setups, increased costs, and larger physical space. In contrast, the proposed method achieves accurate localization using a simpler hardware setup (two microphones) with lower computational demands. This is accomplished by strategically leveraging the robot's mobility, effectively trading hardware complexity and computational power for movement. Specifically, this paper explores how motion, combined with a two-microphone array inspired by an animal's external auditory system, enhances sound source localization. In other words, we focus on optimizing the robot's movement strategies to acquire samples that enable precise sound source localization while maintaining a lightweight system configuration. First, we examine the effect of motion using a fixed-base collaborative robotic arm. Based on the insights gained from this study, we propose a motion strategy to enhance the robot's source localization. Finally, we implement this strategy on a quadruped robot to explore its effectiveness for mobile platforms.

Method

This section provides a comprehensive overview of our methodology, covering the sound source localization approach, acoustic data acquisition process, robotic systems, and experimental setup.

Source Localization Method

The time difference of arrival (TDOA) between two signals is commonly estimated by calculating a cross-correlation vector (CCV). The Pearson correlation factor, as shown in Equation 1, provides the simplest way of calculating the CCV (Rascon and Meza 2017):

$$(1) \quad CCV[\tau] = \frac{\sum_i (a_1[t] - \bar{a}_1)(a_2[t - \tau] - \bar{a}_2)}{\sqrt{\sum_i (a_1[t] - \bar{a}_1)^2} \sqrt{\sum_i (a_2[t - \tau] - \bar{a}_2)^2}}$$

where

- a_1 and a_2 are the two discrete signals being compared,
- τ is the time shift applied to a_2 , and
- $\bar{a}_1$ and $\bar{a}_2$ are the mean values of a_1 and a_2 , respectively.

Although computationally efficient and straightforward, CCV-based TDOA estimation is highly susceptible to environmental noise and reverberations, often leading to inaccurate estimates (Brandstein and Silverman 1997). To mitigate these challenges, the Generalized Cross-Correlation with Phase

Transform (GCC-PHAT) method has become widely preferred due to its robustness against noise and reverberation (Knapp and Carter 1976). Additionally, GCC-PHAT demonstrates resilience in high signal-to-interference ratio (SIR) environments, effectively managing interference from additional sources (Kwon et al. 2010). This characteristic aligns well with the experimental conditions in our study, where high SIR levels are preserved despite background noise from air conditioners, laboratory equipment, and the robots themselves. These factors support the selection of GCC-PHAT for TDOA estimation in our setup.

To provide a comprehensive comparison with alternative TDOA estimation algorithms, we also implemented the coherence-based method (Carter 1987) and the Smoothed Coherence Transform (SCOT) method (Carter et al. 1973). The results reveal that TDOA estimates are consistent across all methods, exhibiting a standard deviation of 1×10^{-6} relative to GCC-PHAT. However, in terms of computation time, SCOT and the coherence-based method performed slightly better, with average times of 0.050 s and 0.0519 s, respectively, compared to GCC-PHAT's 0.0685 s.

The GCC-PHAT operates in the frequency domain, as shown in Equation 2:

$$(2) \quad CCF[f] = A1[f]A2[f]^*$$

where

$A1$ and $A2$ are the Fourier transforms of a_1 and a_2 , respectively, and the $\{.\}^*$ operator denotes the complex conjugate.

By applying a weighting function $\psi[f]$, the generalized cross-correlation (GCC) is obtained, as shown in Equation 3:

$$(3) \quad GCCF[f] = \psi[f]A1[f]A2[f]^*$$

The phase transform (PHAT) weighting, given in Equation 4, normalizes the magnitude of the cross-spectrum, preserving phase information and enhancing robustness to amplitude variations:

$$(4) \quad \psi[f] = \frac{1}{|A1[f]A2[f]|}$$

Finally, the GCC-PHAT function is expressed as:

$$(5) \quad PHAT_F[f] = \frac{A1[f]A2[f]^*}{|A1[f]A2[f]|}$$

TDOA is computed by taking an argmax over $PHAT_F$. Once the TDOA is calculated, it can be used to determine the distance of the sound source from the microphones:

$$(6) \quad \Delta d = c * \Delta t$$

$$(7) \quad \Delta d = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} - \sqrt{(x_1 - x)^2 + (y_1 - y)^2}$$

where

c is the speed of sound (set to 343 m/s for this study), Δt denotes TDOA, and the coordinates (x_1, y_1) and (x_2, y_2) represent the known positions of the microphones, forming a hyperbola.

In two dimensions, sound source localization (SSL) can be achieved by calculating two or more hyperbolas and identifying their intersections, as indicated in Figure 1. To determine these intersections, we apply the nonlinear least-squares method to solve the resulting system of equations (Coleman and Li 1996; Levenberg 1944).

In this study, we focused on two-dimensional source localization for the following reasons: (1) Simplifying the problem to better understand path planning strategies that can improve source localization accuracy, (2) Assuming the source is approximately at the same level as the moving platform, (3) The source was considered far enough that the Z-dimension was less significant compared to the X and Y dimensions, and (4) The platform's motion was limited, and we did not account for sensor rotation around the X or Y axes.

Acoustical Data Acquisition

Gas leaks typically produce acoustic frequencies ranging from 10 kHz to 100 kHz, with the most pronounced energy difference between leak signals and ambient noise occurring around 40 kHz. This makes 40 kHz an ideal frequency for gas leak detection due to its clear distinction from background noise. For this study, directional optical microphones were used due to their broad detection range (10 Hz to 1 MHz) and low self-noise (B. Fischer 2016; Delic 2019).

Data was collected using a NI data acquisition system, capable of sampling up to 20 MS/s per channel. To meet the Nyquist theorem requirements for 40 kHz detection, the system used a sampling rate of up to 400 kHz, ensuring accurate signal representation. To simulate a gas leak, compressed air was released through an open valve.

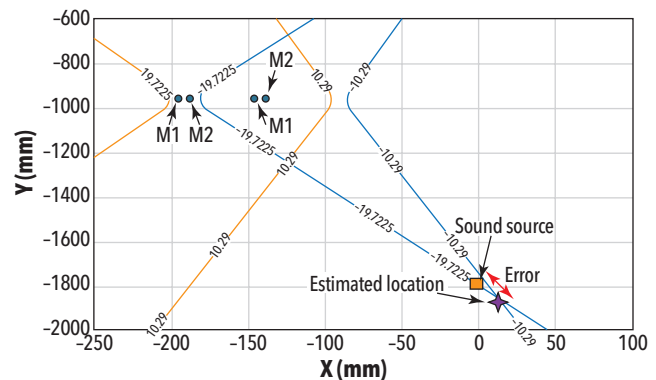


Figure 1. Sound source localization (SSL) using formed hyperbolas.

Robotic System

To explore the impact of dynamic motion on gas leakage source localization, two robotic systems equipped with microphones were used: a fixed-based robotic arm and a quadruped robot (robotic dog). The robotic arm, a collaborative robotic arm developed by Universal Robots and known for its precision and repeatability (± 0.03 mm), was used to study the effects of translational and rotational microphone motions while the sound source remained fixed. Its high accuracy supports the development of localization algorithms by minimizing estimation errors. However, its fixed-base design and 850 mm reach limit its applicability in industrial settings.

In contrast, the robotic dog, a quadrupedal robotic platform, is more suitable for deployment in industrial settings. This robotic dog is equipped with a 16-channel lidar and a depth camera. It can map the environment, detect pipelines with potential gas leakage, and generate depth maps for precise localization. Its ability to navigate varying terrains enables broader coverage for gas leak detection. It can also be enhanced with biomimetic pinnae-like structures, mimicking feline ear movements (yaw, pitch, roll, and independent motion) to improve sound localization by capturing multiple acoustic samples in complex settings. This enhancement presents an intriguing direction for future work, as the findings of Ruhland et al. (2015) suggest that the coordinated movements of a cat's head and pinna enable the collection of multiple acoustic samples to improve sound localization accuracy. This also introduces the possibility of fully emulating animal head and ear movements for enhanced sound source localization. Although we attempted to incorporate feline pinnae and head movements into our system, the inconsistency and unreliability of the data, compared to findings from Young et al. (1996), prevented us from achieving the desired results.

For the initial study, the microphones were mounted on a custom plate attached to the robotic arm, as shown in Figure 2a. Positioned 90 mm apart on a circular disc, they mimic the locations of feline pinnae. A similar mounting

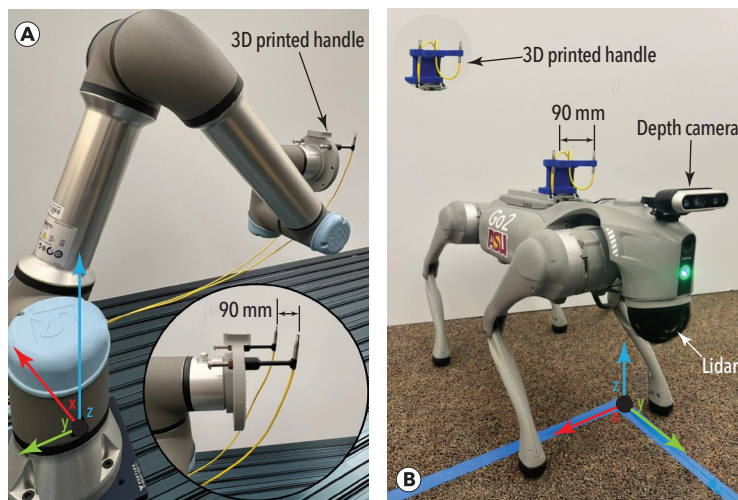


Figure 2. Microphone attachments to (a) the robotic arm and (b) the robotic dog.

bracket was created to hold and position the two microphones on the back of the robotic dog, as depicted in Figure 2b.

Experimental Setup

Biological creatures like cats and dogs rotate their heads or move their bodies to localize sound sources and enhance the TDOA of sound waves at their ears. These movements improve auditory cues that the brain uses to determine the direction and distance of a sound. When a sound originates from one side, it reaches the nearer ear slightly earlier than the farther ear. This small difference in time, known as the interaural time difference (ITD), helps the brain determine the direction of the sound source. By moving their heads or bodies, these creatures change the relative position of their ears to the sound source, creating different TDOA patterns that provide additional spatial cues for more accurate localization.

To replicate these complex motions in a simplified manner, they are divided into linear and rotational components. For linear movements, microphones were mounted on the robotic arm's end-effector. The arm followed a linear path using a linear path planner (MoveL), traversing an 8×8 grid with 50 mm increments along the X and Y axes. This systematic movement covered the designated area for sound localization experiments, with the sound source positioned 1.79 m from the robotic arm's base along the Y-axis, as shown in Figure 3a.

Rotational movements were also replicated in a separate experiment to mimic the head-turning behavior of biological creatures during sound localization. Microphones mounted on the robotic arm's end-effector were rotated along the Z-axis from 10° to 170° in 5° increments, as shown in Figure 3b. This systematic variation in microphone orientation was designed to evaluate how angular positioning affects the TDOA and enhances the accuracy of determining the direction of arrival (DOA) of sound.

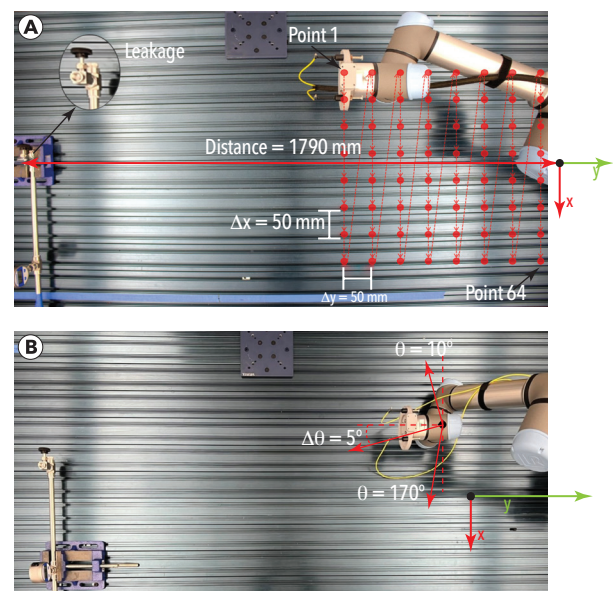


Figure 3. Movement of robotic arm: (a) linear along the X and Y axes; (b) rotational around the Z-axis.

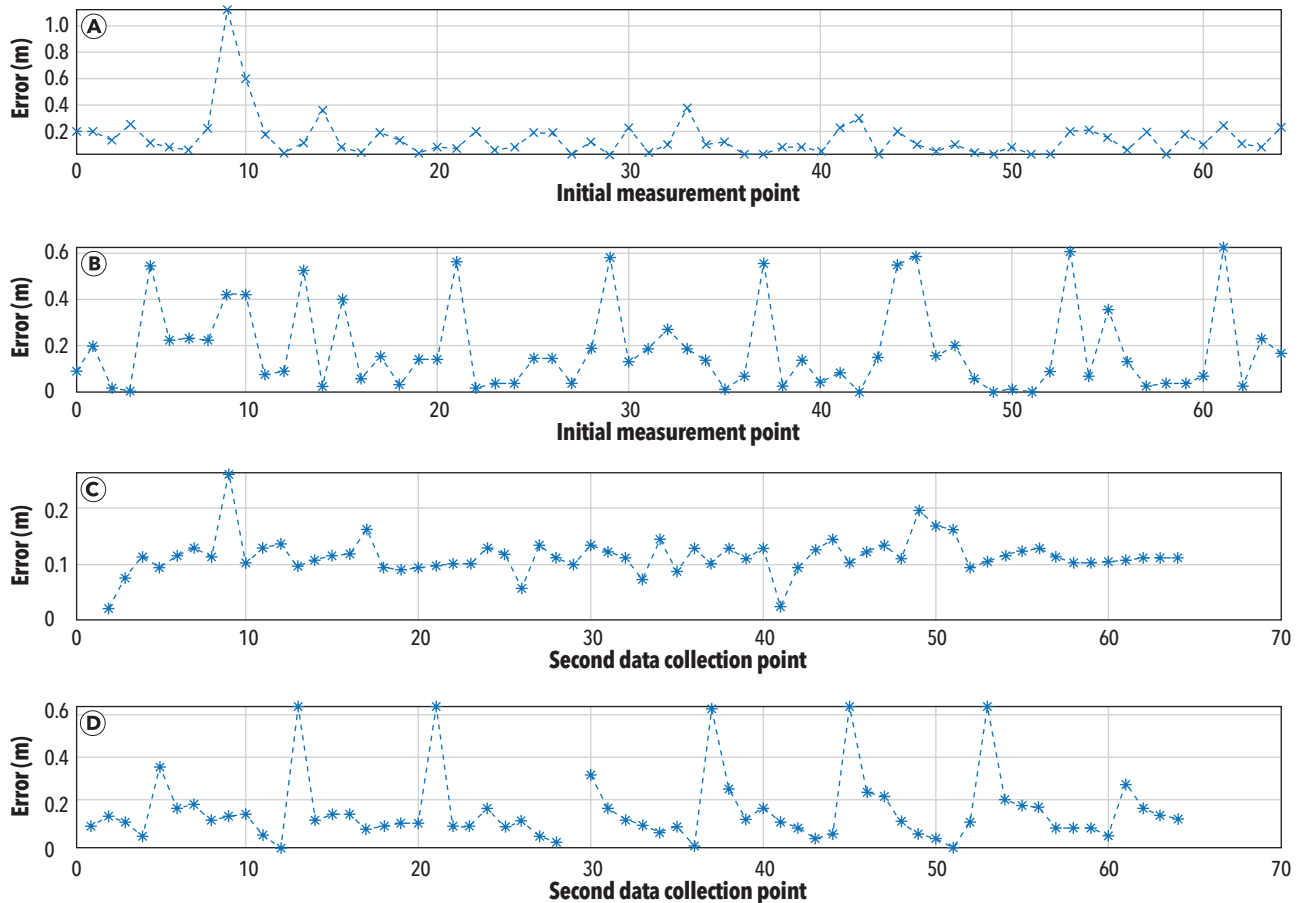


Figure 4. Minimum achievable error for each point in combination with subsequent points: (a) error in distance estimation; (b) error in direction estimation. Error distribution in leak distance estimation: Analysis based on fixing the first measurement point and its combinations with subsequent points: (c) Point 1; (d) Point 29.

Results and Discussion

The results indicate that using only two TDOAs, obtained by positioning the robotic arm at two points on the grid, the leakage direction and distance can be estimated with an error of less than 1° and 40 mm, respectively. Figure 4 illustrates the minimum achievable error when each grid point is paired with other points. One can clearly notice that not all combinations result in 40 mm distance accuracy, highlighting the importance of systematically selecting the second point for the second TDOA for distance estimation. Figure 4 explores this concept further by examining the combinations when points 1 and 29 are used as the initial measurement points. While most combinations yield good accuracy, there are certain points that the robot should avoid as the second measurement location to maintain high accuracy. Figure 5 provides color maps of the grid, where the white square indicates the first measurement point, representing the robot's initial position. By accessing the error distribution for each grid point, the robot can strategically choose the second measurement point to minimize estimation error.

Analysis of Figure 5 reveals that, in most cases, moving vertically is not a wise choice, and horizontal movement is generally more effective. This is because vertical movement often fails to provide additional information for solving the hyperbolic equations due to insufficient change of TDOA, as indicated in Figures 5c and 5d. This leads to substantial errors in source localization, as the two resulting hyperbolas tend to be nearly parallel, reducing the accuracy of the estimation.

Access to maps like those in Figure 5 can significantly aid the agent in decision-making to obtain the second TDOA. However, in real-world scenarios or with larger grids, constructing these maps and providing the agent with access becomes challenging. Therefore, we explored the range of errors the agent might encounter if it selects points randomly. As discussed earlier, relying on only two points on the grid and choosing the second location randomly is not an effective solution. Generally, increasing the number of points improves source localization accuracy. The key question is how many points the agent should randomly select to achieve reliable accuracy. To investigate this, for each fixed first location, we randomly selected two additional points 100

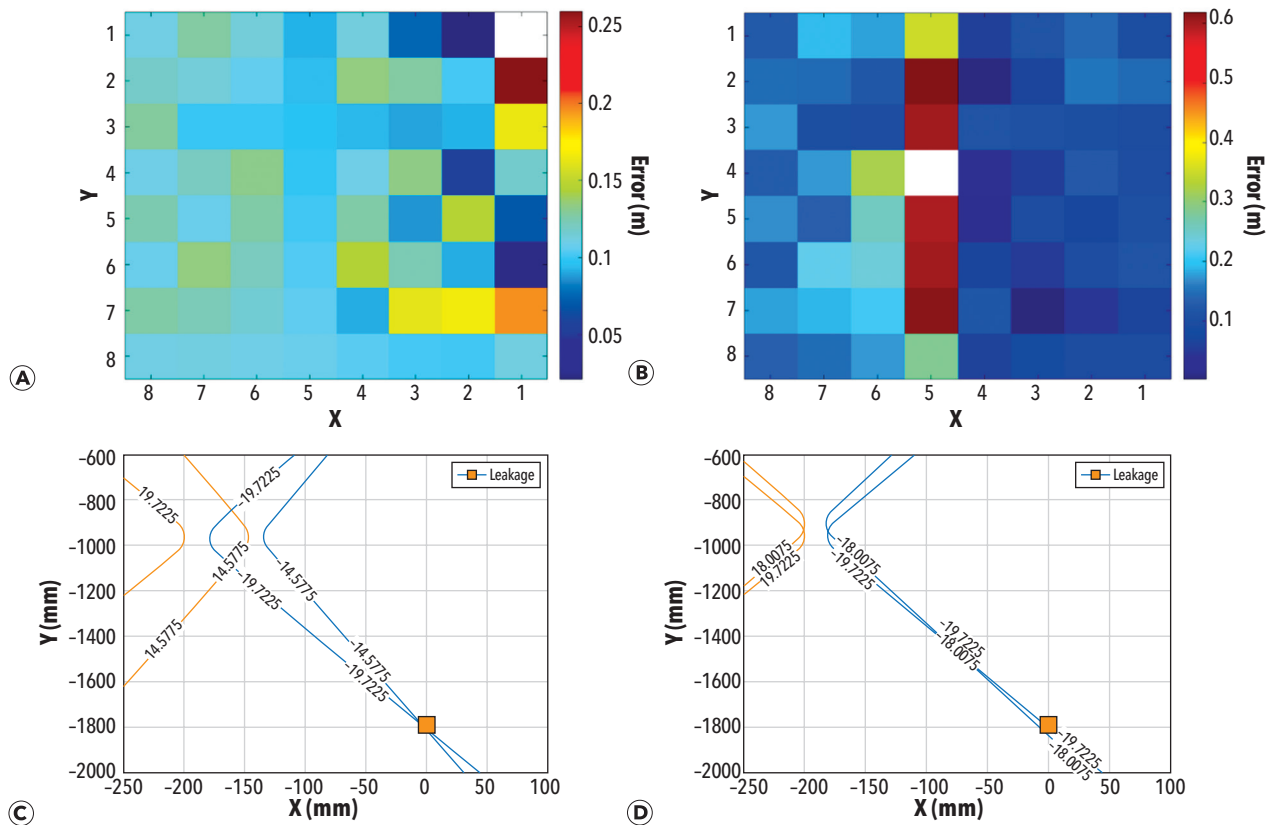


Figure 5. Distribution of error in the grid with the first location at (a) Point 1 and (b) Point 29. Intersection of hyperbolas constituted from points (c) 1 and 2, and (d) 1 and 9.

times, estimated the source location, and averaged the error in distance over these 100 trials. This approach provides a solid foundation for understanding the expected error range when the agent has data from only three locations. The same methodology was applied for scenarios with six, eight, and ten randomly chosen locations. Figure 6 illustrates the expected error an agent might encounter when starting from different grid points and selecting subsequent points at random.

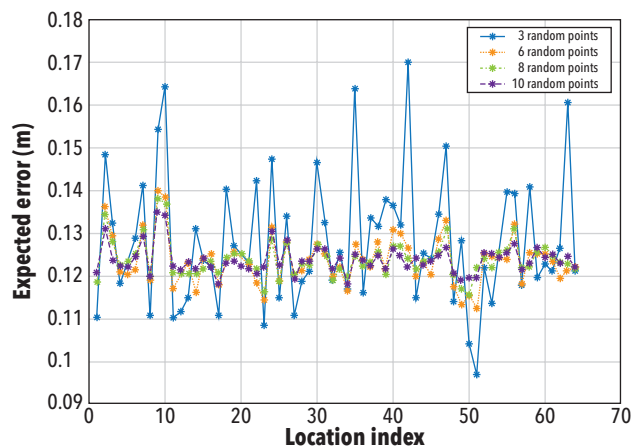


Figure 6. Expected error when the first position is fixed, and subsequent points are chosen randomly.

The expected error is significantly higher in some cases, primarily due to the agent's potential vertical movement, which increases the error. Although the expected error range becomes narrower when the number of points is increased to 10, the robot still expects a 120 mm to 140 mm error in distance.

An alternative approach involves providing the agent with additional information to enable more strategic motion planning. This additional information is obtained by rotating the microphone about the Z-axis. Figure 7 illustrates how the TDOA and amplitude change as the microphones rotate. As expected, the TDOA reaches zero when the robot is oriented directly toward the sound source (leakage). While one may expect to receive the maximum amplitude once the microphones are directed toward the leakage source, our analysis shows that the maximum amplitude slightly deviated from that direction, as depicted in Figure 7b. Consequently, starting from an initial position, the robot can rotate about the Z-axis to accurately determine the direction of the sound source (leakage) when the TDOA reaches zero. Once the direction is established, and knowing that horizontal movement is more effective, the robot can then move laterally to capture a second TDOA reading and localize the sound location. This movement strategy is tested using our robotic dog platform to replicate more realistic scenarios.

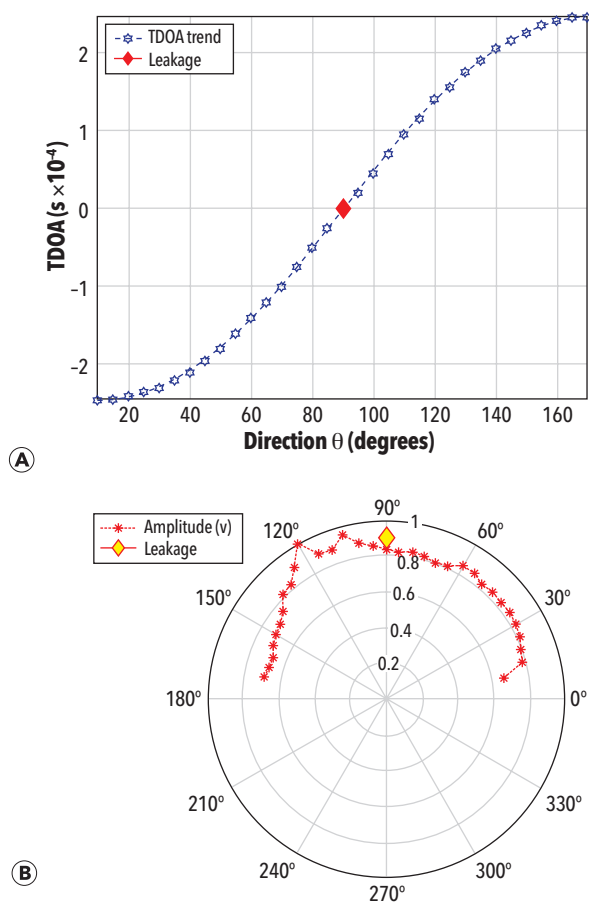


Figure 7. Angle using robotic arm versus (a) variation of time difference of arrival (TDOA) and (b) amplitude variation.

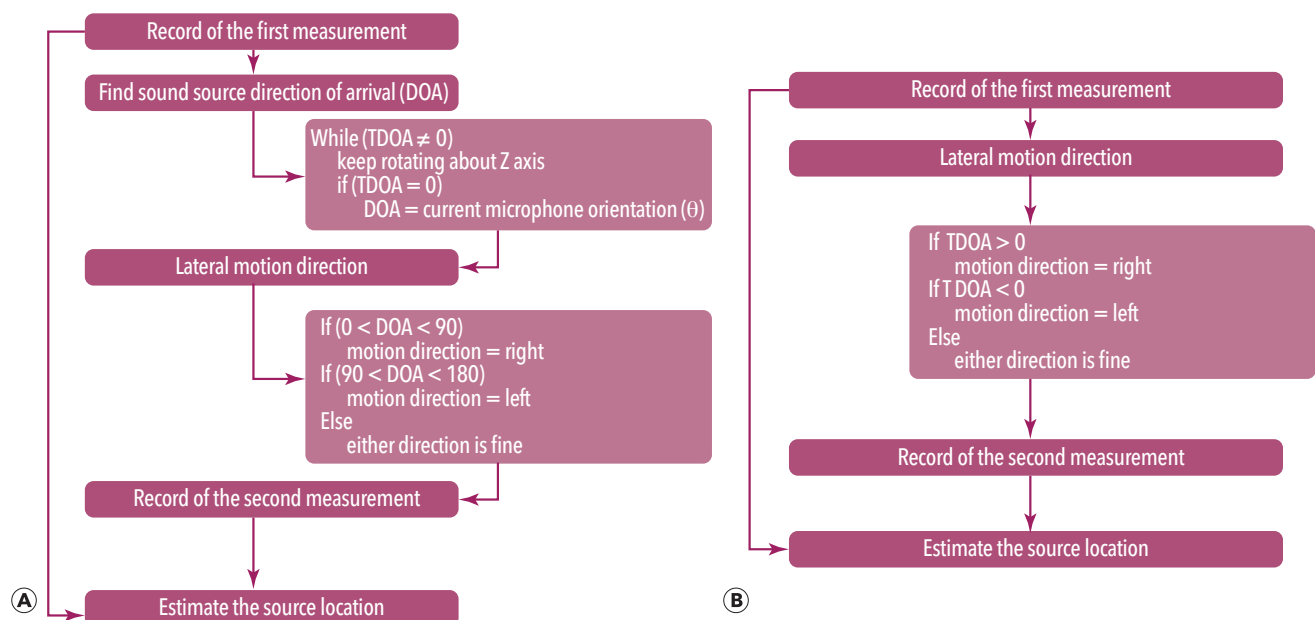


Figure 8. (a) Proposed path planning algorithm and (b) updated path planning algorithm for the robotic dog.

To integrate the source localization with this movement strategy for a mobile platform, microphones were positioned on top of the robotic dog, as shown in Figure 2b. The path planning strategy is shown in Figure 8a. Initially, the robotic dog records the first measurement at the starting point. Next, it performs a sweep of the environment by rotating around a fixed point in 15° increments to identify the direction of the source. Following this, the robotic dog moves horizontally toward the estimated source, either to the left or right. At the new position, a second data point is collected, and the source location is estimated. It is important to note that we assume the source is always in front of the robot.

To assess the effectiveness of this strategy, we conducted two experiments. In the first experiment, the robot took an initial sample at a starting point and then collected two additional samples at random locations within a grid, maintaining a consistent orientation throughout. Using the gathered data, the hyperbolic equation (Equation 7) was solved to estimate the source location.

In the second experiment, the robot first captured an initial sample and then began rotating to gather data. When the TDOA reached zero, the robot identified the source direction. With the initial sample and direction established, the robot moved horizontally to a new position to obtain a second TDOA for source location estimation. It's important to note that the robot maintained the same orientation when taking the second TDOA as it did for the first, as shown in Figure 9. Additionally, the robotic dog's rotational and translational movements were executed manually rather than autonomously, with the minimum step size for rotation being 15°. Figure 9 shows the robotic dog's motion trajectory for random and strategic walking.

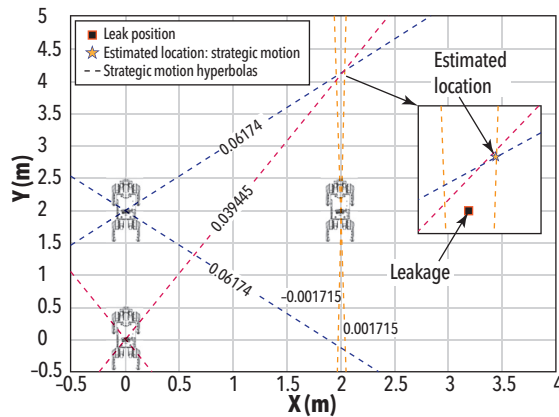
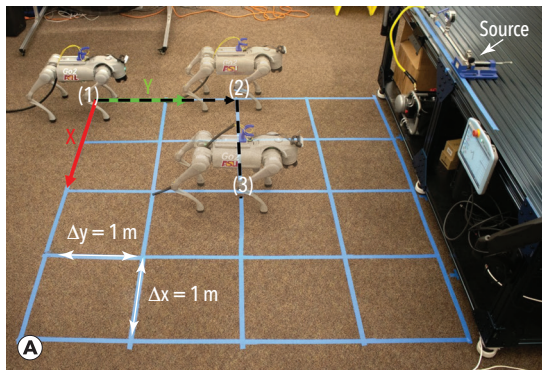


Figure 9. (a) Random walk trajectory and (b) strategic motion trajectory of the robotic dog.

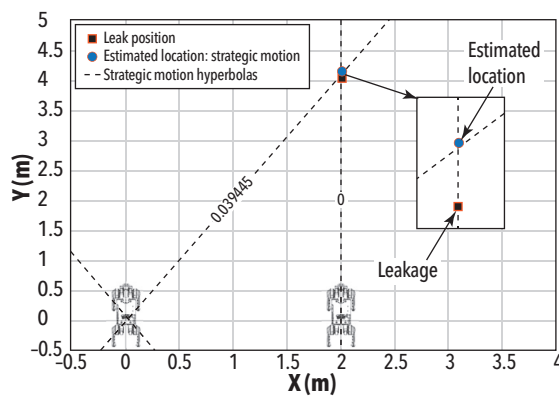
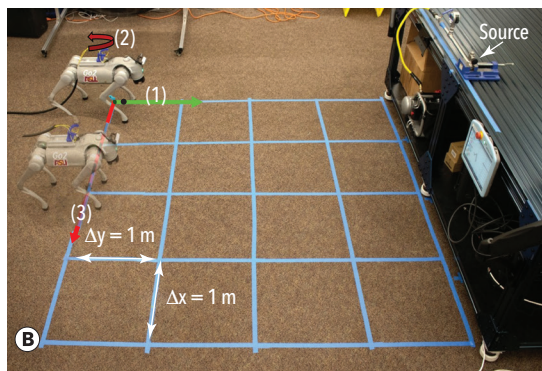


Figure 10 illustrates how the TDOA changes as the robotic dog rotates about the Z-axis from 0° to 180°, taking measurements every 15°. The expected angle for the TDOA to reach zero is 63.4°, but the results show that this occurs around 80°, with an approximate error of 15°. The authors attribute this discrepancy to several factors. Firstly, the robotic dog may not rotate exactly 15° each time, and secondly, unlike the robotic arm, the dog's axis of rotation is not fixed. As the dog rotates, it tends to shift slightly, leading to changes in its position. Therefore, the maximum obtainable resolution of 15°, combined with the rotation inaccuracies and the inability

to maintain a consistent position while rotating, results in the non-smooth behavior observed in Figure 10.

Despite the imperfect direction, the information still aids the robot in selecting the next location to obtain the second TDOA necessary for localization. With the understanding that horizontal movement is more effective, the robot correctly decides to move right rather than left to capture the second TDOA. Figure 9 compares the localization results between random walking and the proposed method.

When moving randomly and taking three measurements, the error in distance is around 17 cm, which aligns with our expectation based on the expected error when the robot takes three random positions. In contrast, the strategic movement reduces this error to ~11 cm.

While the algorithm presented in Figure 8a is functional, a closer analysis reveals that the robot does not need to rotate about the Z-axis in its initial position to determine the next location. Assuming the sound source is in front of the robot, the sign of the TDOA (positive or negative) can directly guide the robot's lateral motion. Specifically, a positive TDOA indicates the robot should move to the right, while a negative TDOA suggests moving to the left. This update simplifies the algorithm by removing the need for rotational steps, thereby reducing uncertainties related to microphone positions, robot rotation angles, and the resolution of rotation step sizes. The simplified and more efficient algorithm is presented in Figure 8b.

While the results demonstrate promising applications for mobile robots, including robotic dogs, several issues need to

Figure 10. TDOA variation as the robotic dog rotates from 0° to 180°.

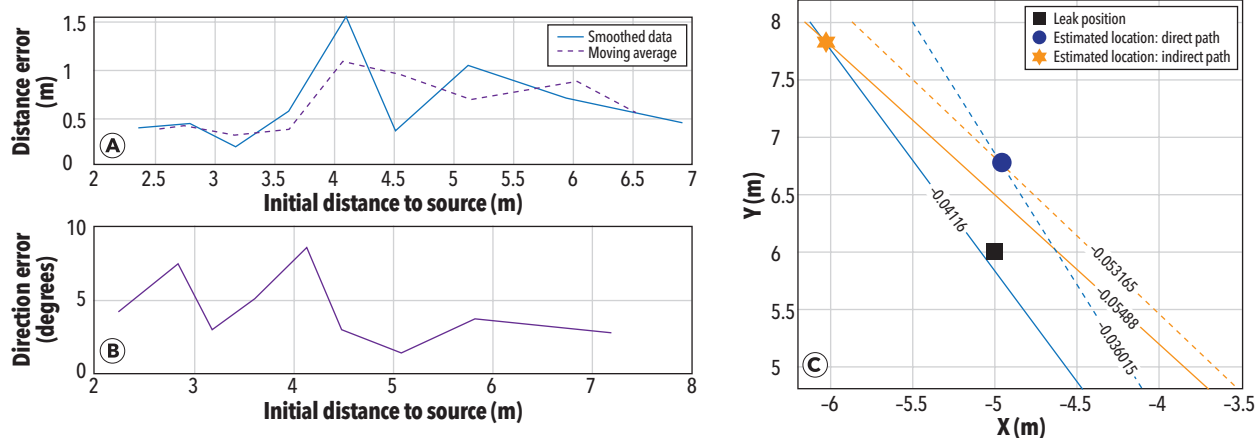


Figure 11. Sensitivity analysis on (a) distance and (b) direction; (c) comparison of localization accuracy between direct and indirect paths.

be addressed in future work. First, the assumption that the source is always in front of the robot may not hold in all scenarios. To enable the robot to discern whether the leak source is in front or behind, additional features like sound pressure levels could be beneficial. In this context, the use of pinnae or external ears may help the robot improve its sense of directionality. Moreover, to minimize noise interference and manage file sizes, the system avoids continuous recording while the robot is moving. Instead, the robot pauses briefly—less than 1 s—at each step to capture a signal. This approach ensures accurate data acquisition without the complexity of segmenting continuous recordings and mapping them to corresponding microphone positions. Furthermore, our sensitivity analysis on distance, as shown in Figure 11a, reveals that the distance estimation error generally increases as the distance to the source grows. However, as shown in Figure 11b, the direction estimation error remains relatively low compared to the distance error, aligning with the results mentioned by Rascon and Meza (2017). These findings suggest that an iterative implementation of the algorithm may be particularly beneficial in scenarios where the source is far from the robot. Additionally, iterative updates could prove advantageous in situations where the direct path to the source is blocked, forcing the robot to rely on signals arriving via indirect paths. Figure 11c illustrates such a scenario, comparing localization accuracy between direct and indirect path conditions.

On the other hand, the presence of other relatively strong sound sources may interfere with the system's performance and potentially cause confusion. While our laboratory experiment with two interfering sources—having voltage root-mean-square (RMS) ratios of 0.9 and 1.3 relative to the source at 8 m—showed no significant increase in error, the system's performance may still be affected in more complex real-world scenarios. These scenarios highlight the importance of incorporating additional features to not only determine whether the source is in front of or behind the robot, but also to guide the robot to an optimal distance from the leak for accurate

localization. Moreover, the robot should be capable of distinguishing between different sound signals, allowing it to differentiate between leakage sounds and other noise sources while moving in industrial environments. This can be implemented using supervised learning models trained on datasets such as MIMII (Purohit et al. 2019).

Future work should prioritize fully automating the processes involved in gas leak detection, including decision-making capabilities, and integrating the Z-dimension into the algorithm. This includes enhancing the robotic system to discern whether a sound source is in front or behind the robot and enabling differentiation between leakage sources and environmental noise. These improvements are crucial for autonomous navigation in industrial environments and accurate leak detection.

Environmental factors such as temperature, humidity, and obstacles significantly affect gas leak localization, emphasizing the need for robust methodologies to maintain precision (Ye et al. 2020; Zheng et al. 2021). Advanced techniques like Gaussian plume diffusion and beamforming algorithms are used to mitigate noise and adapt to varying conditions, while sensor fusion methods, such as Kalman filters and machine learning, integrate data from multiple sources to enhance reliability (Doshmanziari et al. 2020; Zhao et al. 2021). Incorporating thermal and visual data further boosts adaptability, as demonstrated by deep learning models like VideoGasNet (Zhang et al. 2022). Furthermore, real-time algorithms, such as particle swarm optimization and variational Bayesian inference, dynamically respond to environmental changes, making them indispensable for achieving precise and robust leak detection in complex scenarios (Zhang 2022; Ma et al. 2020).

Conclusion

In this study, inspired by nature, we explored the impact of rotational and translational motion on improving sound source localization (SSL) using only two microphones. Initially, we utilized the precision of the robotic arm to analyze how these

motions affect SSL estimation. Based on the insights gained, we developed a motion planning algorithm for mobile robots that optimizes movement to improve SSL accuracy. This approach was then implemented on a robotic dog to assess its effectiveness in real-world mobile robot applications. The results demonstrate that, by combining just two microphones with the proposed motion planning framework, the robot significantly improves its SSL estimation.

Future work will aim to fully automate the gas leak detection framework within the robotic system. This includes enhancing its ability to determine whether a sound source is positioned in front of or behind the robot and enabling the distinction between leakage sources and environmental noise. Additionally, the integration of multiple sensing modalities will be prioritized to improve gas leakage source localization, ensuring reliability even under varying environmental conditions.

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ADDRESSING CHALLENGES FOR AUTONOMOUS ROBOTIC FREEFORM EDDY CURRENT INSPECTION VIA COMPUTER VISION ON COMPLEX GEOMETRIES

CIARON HAMILTON^{††}, OLEKSII KARPENKO^{††}, MAHMOOD HAQ^{††§§}, AND YIMING DENG^{††§}

ABSTRACT

Eddy current inspection is a critical method for assessing the health of metallic structures, but it requires precise probe placement to avoid signal variations caused by inconsistent liftoff. Robotic systems enable scanning of complex geometries, maintaining stable liftoff and ensuring accurate data collection. This paper presents a robotic eddy current array (ECA) inspection system that operates without CAD models, using computer vision to reconstruct the part's surface for path planning. Inaccuracies in robot calibration and the reconstructed mesh can disrupt the probe's precise positioning, especially in ECA scanning, where probe tilting increases liftoff variability, particularly at greater distances from the tool's center. To address these issues, we introduce a signal processing technique that reduces the impact of mesh inaccuracies and liftoff fluctuations on the acquired ECA data. The system is validated on curved steel samples with corrosion pits, approximately 50 μm deep and ranging from 1 to 10 mm^2 in area. The results demonstrate the system's effectiveness in detecting defects and its potential for integration into the NDE 4.0 framework.

KEYWORDS: robotic NDE, eddy current array, corrosion, computer vision, part surface reconstruction, NDE 4.0

Introduction

NDE 4.0 is emerging with advancements in technology for managing and processing large datasets, which are crucial for verifying artificial intelligence (AI) systems that interpret these datasets to determine and predict damage (Savin et al. 2024). Various types of NDE robotic systems are being considered for NDE 4.0, including robotic arms and mobile platforms. Recently, several advancements have been made in autonomous scanning of complex-shaped objects using robotic arm platforms. Imaging and reconstruction methods, such as hyperspectral cameras for carbon fiber solutions (Yan et al. 2022) and X-ray for reference-free 3D scanning of defects (Kang et al. 2022; Herl et al. 2020), have been utilized in these systems. In the realm of robotic NDE data acquisition, advanced systems using in-process freeform scanning via ultrasonic testing—synchronizing NDE acquisition with path planning—have been reported (Mineo et al. 2022). Additionally, a freeform robotic arm platform for ultrasonic inspection of complex-shaped carbon fiber samples was recently developed (Hamilton et al. 2024).

Historically, techniques such as laser-based profilometry (Doyle 1995), ultrasonic profiling (Zhen et al. 2018), and physical touch-probes (Lee and Cho 2012) have been employed to assess true surface geometry and adapt scans accordingly. These methods have proven effective over decades, providing precise surface location data for applications requiring stringent geometric fidelity. However, these approaches often involve additional hardware complexity, require contact or near-contact with the surface, or are less suited for large-scale automation in NDE 4.0 applications. An example of merging robotic systems with AI technology is the use of gripper robotics for inspection, employing electromagnetic acoustic transducers (EMAT) scanning and deep learning for pipe assessment (Hespeler et al. 2024). Computer vision (CV) offers a noncontact, scalable, and hardware-efficient alternative for capturing and reconstructing part geometries, particularly for complex or variable surfaces. This makes it more adaptable to modern NDE frameworks, such as NDE 4.0, where automation, flexibility, and integration with AI-driven systems are essential.

Recent developments in eddy current array (ECA) robotic systems have introduced several innovative approaches. Many of these systems utilize a rotary axis, allowing the robot to move the ECA probe along a rotating cylindrical sample. One such system was used for inspecting nuclear assets (Foster

* Corresponding author: dengyimi@egr.msu.edu

† Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824

†† Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824

‡ ORCID: 0000-0001-9582-4843

‡‡ ORCID: 0000-0003-1146-3177

§ ORCID: 0000-0001-5958-3683

§§ ORCID: 0000-0003-2537-6015

et al. 2022). Another approach involves a robotic system with flex probes designed to inspect complex structures; however, this system is limited to movement along a single axis (Zhang et al. 2020). In a more advanced example, an aircraft wing was inspected using a CAD model for path planning (Morozov et al. 2018). However, this method often requires reverse engineering the complex structure to obtain the CAD model, which can be time-consuming and resource intensive. Mobile systems have also seen innovation, with repair and crawler robots developed for inspecting power plant boilers (Shi et al. 2021). Additionally, quadruped robotic platforms have been introduced, offering diverse inspection capabilities for energy-producing infrastructure (Tsenis et al. 2024). For in-line pipe inspections, endoscopic laser profiling combined with machine learning techniques has been used to detect deformations within pipes (Mukherjee et al. 2022).

Freeform robotic inspection methods allow for autonomous surface scanning across a wide range of components, including those with curved or complex geometries. By using a reconstruction device, path planning can be performed on a mesh within a virtual environment, eliminating the need for a CAD model. This approach supports robust scanning procedures without the need for reverse engineering components for evaluation. Additionally, it facilitates the alignment of the reconstructed scanning environment with the automated surface scanning system. With these models, a scanning path can be generated, simulated, and then implemented on the physical robot. However, challenges arise when precision scanning is required for specific NDE methods and applications.

In this work, sub-millimeter depth corrosion damage on curved steel samples is detected and characterized using eddy current testing (ECT). ECT requires maintaining a consistent liftoff between the probe and the conducting surface. A small liftoff is essential to generate sufficient eddy currents in the test sample, ensuring a high signal-to-noise ratio (SNR). Furthermore, maintaining a constant liftoff is crucial for minimizing data variability, which can introduce uncertainties and complicate data processing. These challenges are amplified when inspecting small corrosion damage, as the ECT probe must be finely calibrated for high-frequency precision scanning. The tilt of the ECT sensor can also reduce defect detectability, as the magnetic field is affected by the sensor's angle during field inspections. The worst-case scenario occurs when a collision happens due to inadequate inspection path planning for complex-shaped test samples, potentially damaging the probe immediately or through scraping along the rough or irregular surface.

Optimal NDE path planning can be developed in a virtual environment before being applied in physical space. However, discrepancies between the virtual model and the test specimen can lead to improper probe orientation relative to the scanned surface. For instance, if the model is not correctly aligned with the physical specimen, it can cause variations in probe rotation and liftoff throughout the scanning path. Additionally, geometric differences may arise between the virtual reconstruction

and the actual part. While reconstruction devices like structured light provide sub-millimeter accuracy, errors can accumulate for larger specimens. CAD models may also fail to account for small geometry variations introduced during manufacturing. Finally, errors in calibrating or mastering the robotic joints can result in misalignments in Cartesian space, affecting the positional accuracy of the scan.

This work addresses key challenges and demonstrates the capabilities of robotic ECT using array probes for surface corrosion characterization on curved steel samples. The robotic system presented here features an ECA probe that enables rapid scanning and provides expanded surface coverage through multiple coils or channels. It also employs CV-based path planning to perform inspections without relying on CAD models, representing a significant advancement in automation and digitization within NDE 4.0. Furthermore, we introduce the integration of robotic inspection with real-time data processing techniques, such as detrending algorithms and synchronization error mitigation, ensuring consistent detection of surface corrosion as shallow as 50 μm , despite challenges such as liftoff variations and probe orientation errors.

Materials and Methods

This section outlines the methodology for preparing curved corrosion samples with simulated damage and details the experimental setup for robotic ECA inspection.

Robotic Setup for NDE Using ECA and Computer Vision

A block diagram of the robotic ECA system is shown in Figure 1. The system consists of an industrial robotic arm with 6 degrees of freedom (DOF). Communication between the PC and the robot controller is established via C#, with movement

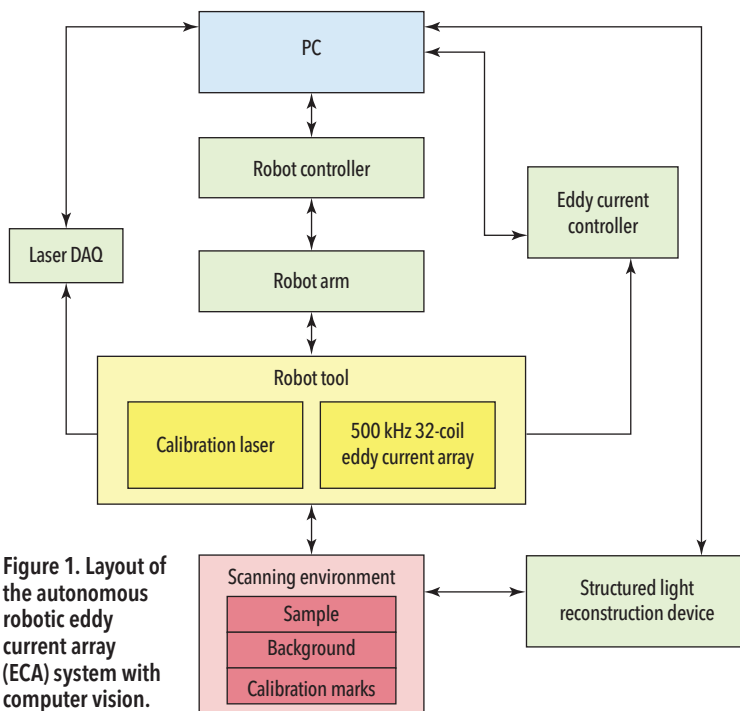


Figure 1. Layout of the autonomous robotic eddy current array (ECA) system with computer vision.

instructions issued and real-time Cartesian position and orientation data received at a frequency of approximately 70 Hz through an Ethernet connection. The system integrates three key sensors: (1) a structured-light (SL) camera, (2) a calibration laser profilometer, and (3) an eddy current array (ECA).

The structured-light camera with a reconstruction accuracy of 0.1 mm is positioned remotely from the robot as shown in Figure 2a. It captures the part's geometry, enabling precise path planning. The calibration laser profilometer is mounted in a custom 3D-printed holder, as illustrated in Figure 2b. This sensor ensures proper alignment between the reconstructed virtual model and the robot's physical workspace. Capable of measuring depths ranging from 50 mm to 150 mm with an accuracy of 4 μm , the sensor is positioned 60 mm from the calibration regions of the test specimen.

The ECA used in this system is an array of 48 pancake coils fabricated on a flexible substrate. The ECA is interfaced with the PC using the multichannel eddy current data acquisition system via a software development kit (SDK) in C#. Although the probe is a flexible array, it is mounted on a rigid fixture to ensure consistent and known coil orientations during operation. While the probe's nominal center frequency is 500 kHz, it is operated at 2 MHz to provide maximum sensitivity to surface corrosion. The array consists of 48 coils arranged in three rows of 16, with a 1.25 mm spacing between coils, offering a total coverage width of 34 mm, as shown in Figure 2c. During data acquisition, only the right two rows of 16 coils are used, resulting in a total of 32 active sensors.

In the system, the ECA supports two operational modes: impedance (absolute measurements) and reflection (pitch-catch). A differential mode is also applied during post-processing using MATLAB. The coils are driven by a 5 V AC signal, producing complex voltage outputs, with the real component used for post-processing. The robot is programmed to position the ECA probe 1 mm above the test surface, though variations in liftoff can be observed during experiments.

The laser and ECA probe integrated into the robotic setup are depicted in Figure 2b. Eddy current measurements are

acquired at an update rate of 16 kHz per coil. This configuration provides a spatial resolution of 50 μm along each raster line, ensuring sufficient detail for effective corrosion detection.

Scan Path Generation for ECA

The scan path generation procedure is adapted from the framework outlined by Hamilton et al. (2024), beginning with the virtual reconstruction of the scanning environment using a structured-light camera to create a digital model of the part. This virtual model is aligned with the physical workspace through calibration points identified by a laser calibration sensor. Accurate alignment is ensured by comparing the physical calibration points in the robot's workspace with their virtual counterparts using point-to-point projection. The reconstructed mesh is further refined by segmenting the sample from the background and applying decimation and Laplacian smoothing techniques (Sorkine et al. 2004). A zigzag raster path is then generated on the refined mesh using a ray-plane intersection array algorithm (Hamilton et al. 2024), achieving a point cloud resolution of 0.1 mm $\times$ 0.25 mm, which is interpolated to 0.2 mm $\times$ 0.2 mm for 2D processing. This path is simulated and converted into robot commands. During the scanning process, the system PC gathers data streams from the ECA, alongside real-time orientation data from the robot's tool frame. These data streams are processed to ensure accurate and reliable defect detection.

The system utilizes two types of scanning paths. The first, referred to as a "fast scan," involves the array coils scanning the region of interest without redundancy. In this method, the array probe traverses the test sample only once along its long side, minimizing scanning time in proportion to the number of coils in the array. For higher resolution, sub-scans can be performed, where the pathing distance of a coil is smaller than the spacing between adjacent coils.

The second scan type, referred to as a "full scan," introduces redundancy by using a single coil to collect data instead of the entire array, ensuring more detailed coverage at the cost of increased scanning time.

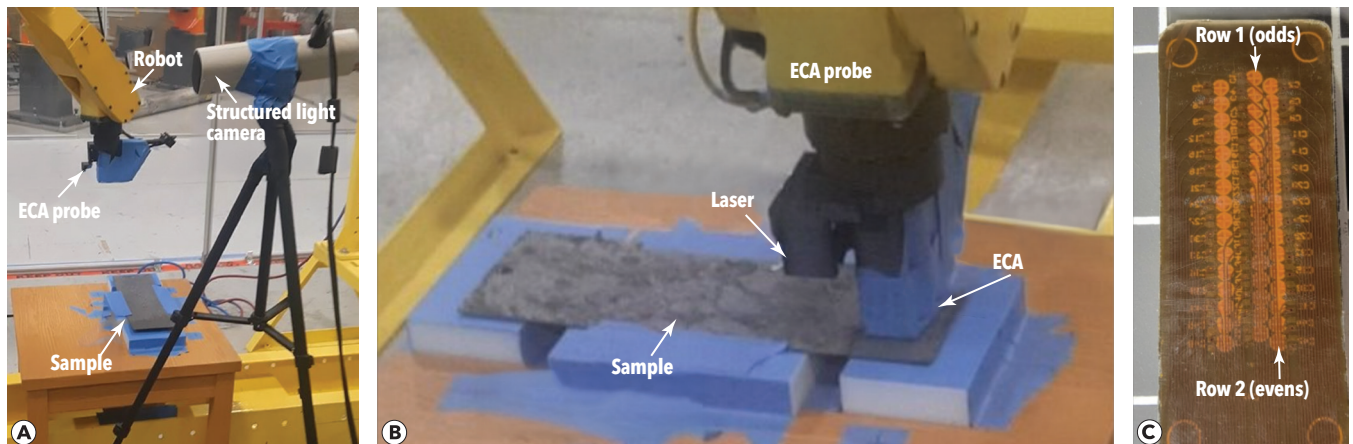


Figure 2. (a) ECA robotic setup, showing a sample, the robot tool-frame lifted away from the sample, and the structured-light camera facing the sample, outside the robot's workspace; (b) ECA robotic scan on the sample; (c) ECA probe view from below.

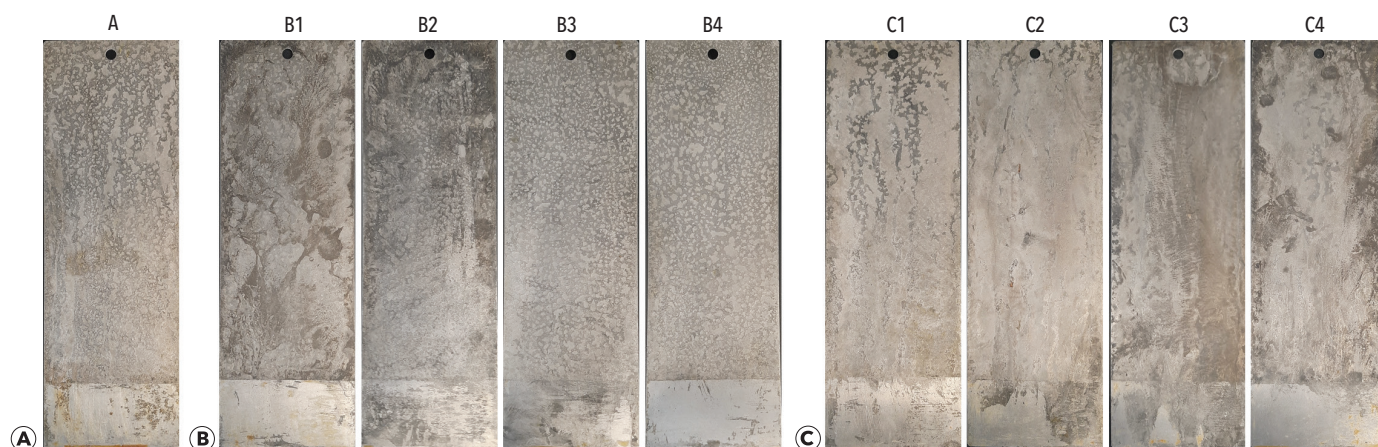


Figure 3. Steel samples with corrosion damage: (a) flat sample A; (b) concave samples B1-B4; (c) convex samples C1-C4.

TABLE 1
Curvatures of test samples with corrosion damage

Sample	A	B1	B2	B3	B4	C1	C2	C3	C4
Curvature k (1/m)	0.000	0.304	0.397	0.527	0.842	0.304	0.451	0.528	0.842

Preparation of Steel Samples with Corrosion Damage

A total of nine steel samples, each measuring 12 in. $\times$ 4 in. (30.5 cm $\times$ 10.2 cm) were prepared for corrosion inspection using the robotic ECA setup. The samples included three distinct geometries: one flat, four concave, and four convex, as shown in Figure 3. These shapes were achieved using a sheet roller, with curvatures designed according to corrosion standards detailed in Table 1. After shaping, the samples underwent a seven-day salt spray corrosion process in accordance with ASTM B117-03 (ASTM 2003). To create a calibration area for the ECA, the bottom inch (2.54 cm) of each sample was treated with a corrosion inhibitor; however, some corrosion leached into this section. Residual rust was removed using a soaking solution.

Comparison of Processed ECA Data with Microscope Depth Profiling

Ground truth volumetric data of surface corrosion were obtained using a high-resolution digital microscope for comparison with the ECA data. To locate the defects, 2D cross-correlation was applied, in which the microscope data was searched across the ECA data. The best matching pattern was indicated by the maximum correlation value between the two sets. The patterns from ECA voltages correlated well with the depths of the microscope data.

Challenges in Robotic ECA Inspection of Curved Samples

Detecting fine surface or underpaint corrosion defects (e.g., 50 μ m deep) on curved metallic surfaces using robotic arms

is challenging due to strict liftoff, tilt, and thermal stability requirements for the ECA probe. For example, ECT typically necessitates maintaining a close and constant liftoff (e.g., 1 mm) between the coil probe and the metallic surface. Small liftoff ensures a noncontact testing method, maximizing the induction of eddy currents and achieving a high signal-to-noise ratio (SNR) for the measurements. Additionally, surface corrosion detection often requires sensor coils to operate at excitation frequencies in the MHz range. As a result, probe misalignment and temperature fluctuations can introduce errors during the scanning process, affecting both defect detection and the accurate quantification of defect depth. This section explores the challenges faced during robotic ECT and presents typical experimental images obtained using the proposed robotic NDE system with computer vision.

Effect of Inconsistent Probe Liftoff and Tilt on ECA Measurements

Inconsistent liftoff typically introduces low spatial frequency trends that overlap with defect indications, complicating image processing and defect detection. Robotic manipulators can also introduce inconsistent sensor tilt, affecting the distribution of the excitation magnetic field from the coil sensor. For the rigid and linear array probe, orientation errors affect each coil as a body transformation, with coils at the edges of the array having a different liftoff compared to the coils in its center. Improper liftoff and/or tilt of the ECA probe can not only disrupt measurements but also cause collisions with the test part, potentially leading to immediate damage to the probe or long-term degradation if dragged over rough surfaces.

Liftoff and tilt inconsistencies often result from issues in the reconstruction and registration of the virtual geometry for path planning, such as misalignments between the virtual and physical surface geometries. Additional factors include limitations in the robot's hardware and the synchronization between the ECA data acquisition instrument and the robot. While post-processing methods can help mitigate these errors and improve defect detection, some defects may still be missed if the errors exceed the algorithm's corrective capacity.

Part Surface Reconstruction Error

Errors in the reconstructed surface of the test specimen can arise from several sources. One common issue is the alignment of the model, where misalignments lead to translation errors along the scan path. If the model is not properly oriented with its physical counterpart, rotation and liftoff variations will occur throughout the entire scanning process. Another challenge is the discrepancy between the virtual model and the physical surface geometry.

In this work, surface reconstruction of steel samples is achieved using structured light with a CR-01 scanner offering 0.1 mm accuracy. However, metallic surfaces can reflect light, causing inaccuracies during scanning, a problem that can be mitigated using blue-light reconstruction (Zhan et al. 2015). Additionally, errors may arise if the sample lies outside the sensor's effective range, affecting both translation and rotation. Ray-plane intersection algorithms calculate translation and rotation based on the mesh faces' normal directions (Hamilton et al. 2024).

Rotational errors between scan points can introduce discrepancies, which can be mitigated using detrending algorithms applied to the raster path. These errors arise at various stages, as illustrated in Figures 4a and 4b from a scan of flat Sample A (Figure 3a). Figure 4a depicts the delta rotation acquired from the robot alone, revealing a baseline pathing error. In raster pathing, certain scan lines shift more than others due to orientation errors on the mesh. Figure 4b highlights spatial variations in the ECA signal caused by positioning errors from pathing inaccuracies.

Mesh registration also introduces potential body transformation errors. The process, which relies on point-pair picking (PPP), aligns the mesh within the robot's reference frame. Misalignment in laser calibration or displacement of calibration marks during sample placement can introduce errors, as can human inaccuracies in selecting calibration points. To reduce these errors, the root-mean-square (RMS) error was minimized to approximately 1 mm. Although PPP provides an initial approximation, body errors were further corrected using 2D detrending. Figure 4c illustrates this correction with four calibration markers (R0–R3), whose reconstructed positions were compared to physical locations identified via laser calibration. The overall RMS error across all four points was 0.516 mm.

Robot Mastering Error

This error occurs during the calibration of a robotic arm's joints, where each joint requires precise alignment at zero degrees. While state-of-the-art robots automate this process, the robotic arm used in the presented system relies on manual measurements and markings on the robot itself. Consequently, sub-degree misalignments can occur at each joint. Although these errors may seem minor, they result in more complex orientation discrepancies within the robot's joint system,

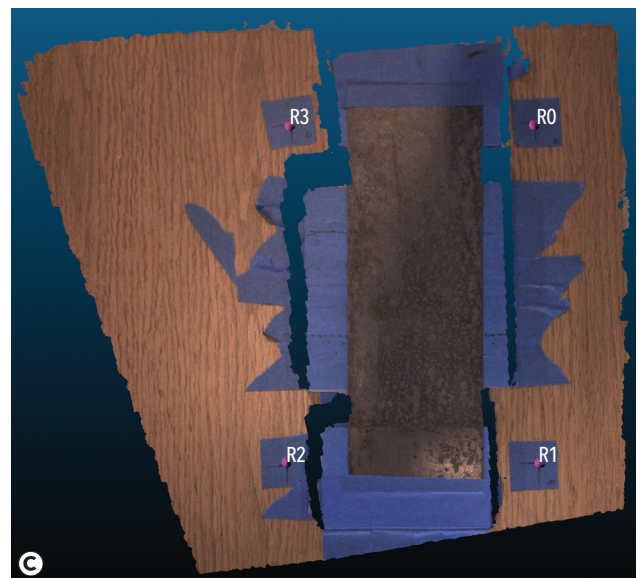
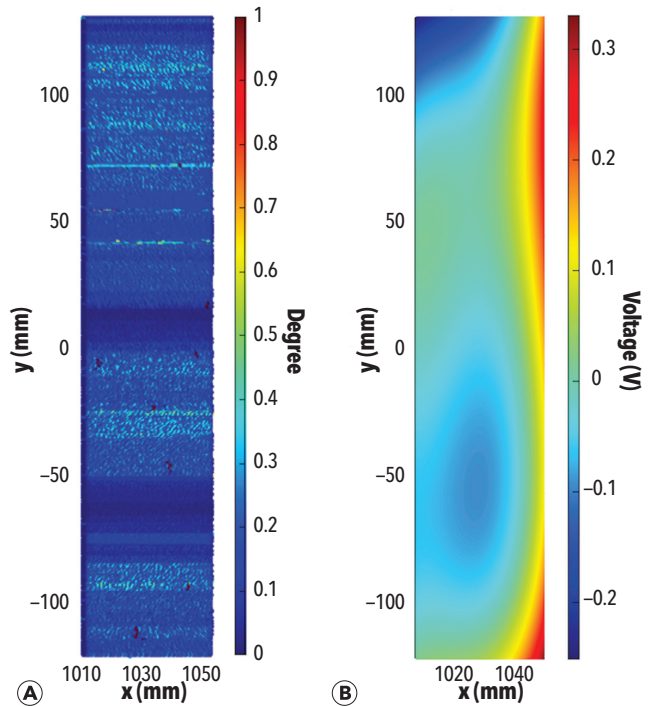


Figure 4. Effects from mesh pathing errors: (a) changes of rotation xyz of the probe during the scan of flat Sample A as provided from the robot controller; (b) corresponding voltage trend registered by the ECA; (c) aligned scanning environment from structured-light reconstruction after selecting point pairs on the flat sample.

particularly affecting the Denavit–Hartenberg (DH) parameters rather than the Cartesian coordinate system, as seen with other error types. These calibration inaccuracies manifest as “wave-like” patterns, introducing approximately 1 mm of spatial variance in the ECA scans (see Figure 6a). To mitigate this issue, a specialized post-processing method was developed.

Synchronization Error Between Eddy Current Instrument and Robot’s Controller

Errors arising from poor synchronization between the robot’s real-time orientation data and the real-time acquisition of the scanning instrument must also be considered. These synchronization issues cause smearing due to lag between the two data streams. The system managing both data flows—comprising the robot’s controller and the ECA data acquisition instrument—operates as two separate systems, leading to inevitable delays. Although timestamps are recorded alongside each data stream, a nonconstant delay persists between the two. On average, this delay was found to be approximately 50 ms. To minimize the effects of this delay, slower scan speeds of 25 mm/s were employed, reducing smearing to under 1 mm, which was adequate to detect most corrosion flaws.

Signal Fluctuation Due to Coil Heating and Environmental Effects

When performing NDE using ECT array probes in absolute mode, voltage fluctuations are occasionally observed that are unrelated to probe orientation. These fluctuations may occur even when the probe is stationary. Such behavior is typically attributed to high excitation currents in the coils or ambient temperature changes (García-Martín et al. 2011). For instance, Figure 5 illustrates a pronounced case of voltage drift in an ECA probe while it remains stationary 1 mm above the

sample. This drift occurs during the coil warm-up phase after powering on the ECA data acquisition system, prior to reaching its steady-state operating temperature. In this case, the coils were driven at twice the maximum recommended voltage, and the signals were amplified by 60 dB. Additionally, the robot, ECA probe, and steel test sample with corrosion damage were situated near a high-power air duct emitting hot air into the adjacent lab space. Once the coils reached their steady-state temperature, the ECA probe was nulled on an undamaged region of the test sample. After calibration, voltage variations were reduced to a range of -0.015 V to 0.015 V.

To mitigate environmental effects on the robotic ECA measurements, the system was programmed to null the array probe in the damage-free region at fixed intervals. Additionally, a second-order detrending process was applied to each coil signal in the time domain.

Image Processing Algorithms for Corrosion Detection

To address liftoff variations and environmental effects, the post-processing workflow incorporates a specialized array subtraction algorithm and detrending. This approach leverages the shared liftoff errors across the coils to isolate and correct these inconsistencies effectively. A simplified representation of the post-processing procedure is provided in Figure 6. A detailed description can be found in the authors’ previous work (Hamilton 2024).

Array Subtraction Algorithm

The array subtraction algorithm removes common liftoff effects across all probe channels by subtracting the mean value of the line scans, effectively eliminating identical noise and voltage variations between coils. It is applied to ECA data in the time domain to prevent spatial misalignment caused by delays

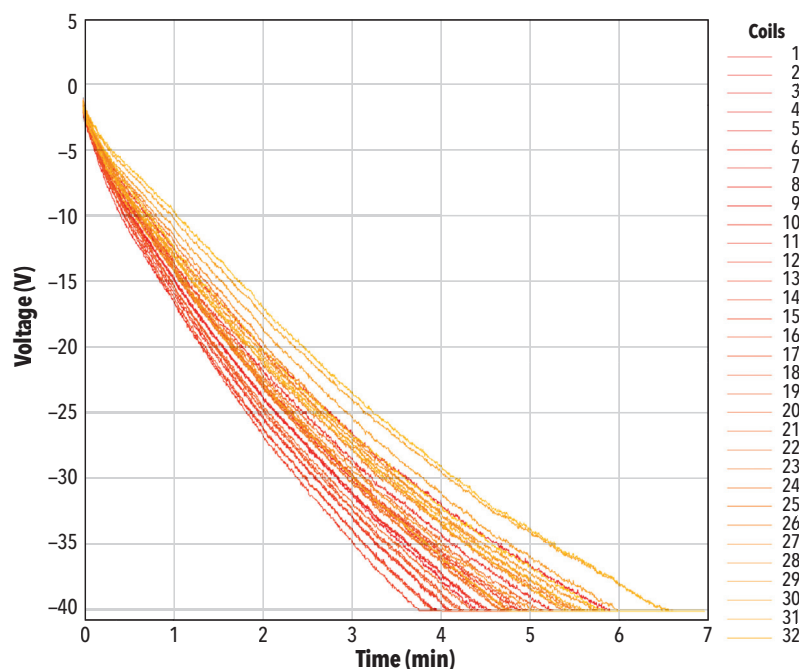


Figure 5. Voltage fluctuations in the coils (absolute mode) caused by array probe heating during warm-up and hot air circulation around the probe.

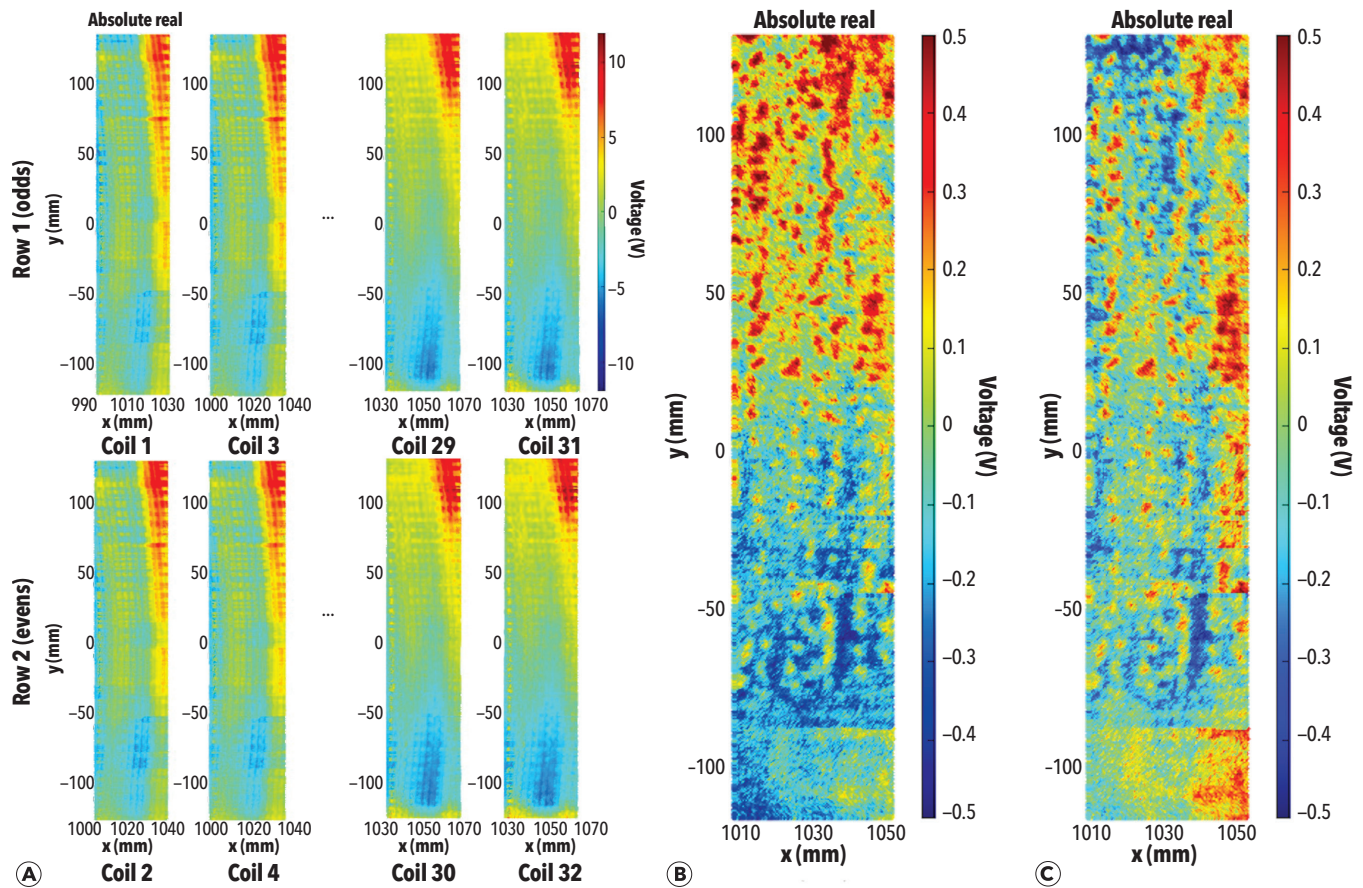


Figure 6. Post-processing of ECA image data in spatial domain: (a) raw data per each coil; (b) diagnostic image after array subtraction; (c) diagnostic image after array subtraction and detrending.

between the robot controller and the ECA data acquisition system. The process follows these steps:

1. Normalize each line scan per coil (range: 0 to 1).
2. Compute the mean voltage across all channels at each time instance.
3. Subtract the mean from the normalized voltages.
4. Convert the normalized values back to the original voltage units.

Detrending Algorithms

In addition to array subtraction, three detrending methods are applied to the ECA data. Detrending is performed across space using the x and y coordinates, while excluding the z -axis. The underlying assumption is that robot positioning errors occur at a lower spatial frequency than corrosion damage, allowing their removal through detrending. The procedures are as follows:

1. Linear detrending for signals in the time domain.
2. Planar spatial detrending (1×1 order) along x and y coordinates.
3. Higher-order spatial detrending (3×3 order) along x and y coordinates.

Experimental Validation of Robotic ECA System

This section presents the experimental validation of the robotic ECA system on curved steel samples with corrosion damage.

Additionally, we demonstrate the application of the proposed image processing algorithm for enhanced damage detection.

Acquisition and Processing of ECA Measurements

This section presents the experimental ECA measurements obtained using the developed robotic setup and their comparisons with microscopic images of corroded steel samples. Figure 6 outlines the ECA data processing workflow for flat Sample A, where all voltage processing is performed along the x and y coordinates. Figure 6a displays raw measurements from individual coils, while Figure 6b illustrates the scan using the ECA probe. The array subtraction algorithm is applied to remove common coil trends from the array image data. The final processed image, shown in Figure 6c, results from detrending to eliminate liftoff and tilt variations, with the detrend magnitude detailed in Figure 4b.

Figure 7 demonstrates the effect of processing ECA data over time. In Figure 7a, voltage spikes occur as the array probe nears the sample edge due to increased liftoff. These artifacts are largely removed in Figure 7b after processing.

Figures 8 and 9 present the results for both full and fast scans after the post-processing steps described earlier. Corrosion is visible in most datasets, though some inaccuracies persist post-processing. Full scans, acquired using Coil 16 near the center of the array, exhibit tilting effects along the x -axis in

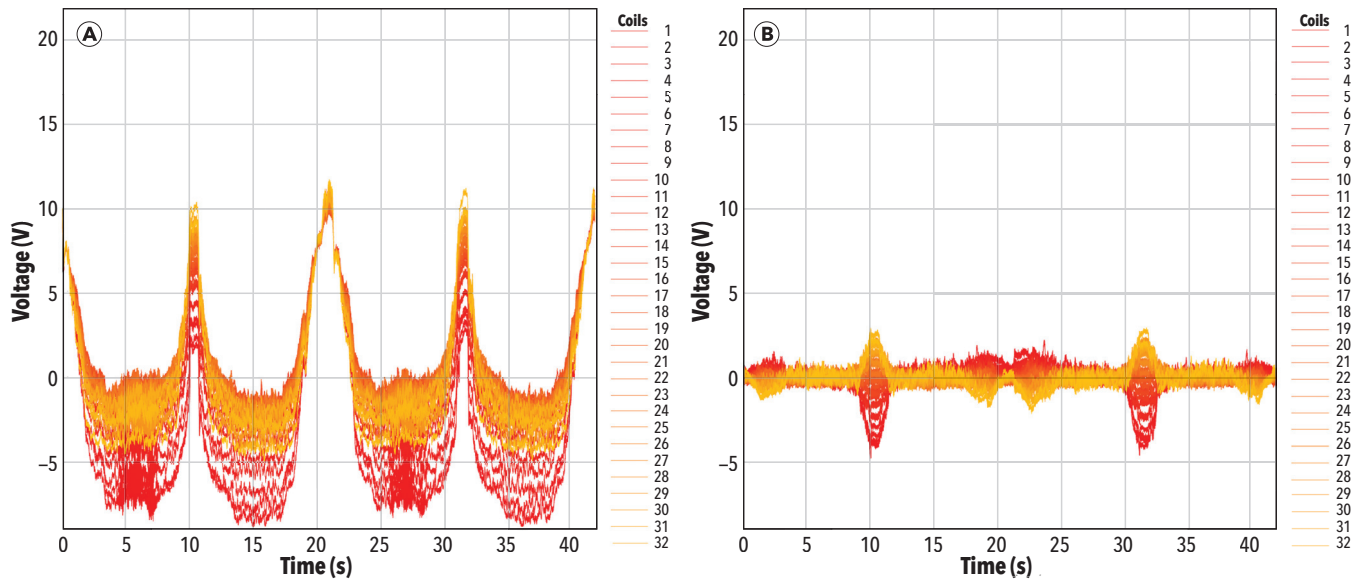


Figure 7. Post-processing of ECA line scans using array subtraction and detrending in time domain: (a) raw line scans; (b) processed line scans.

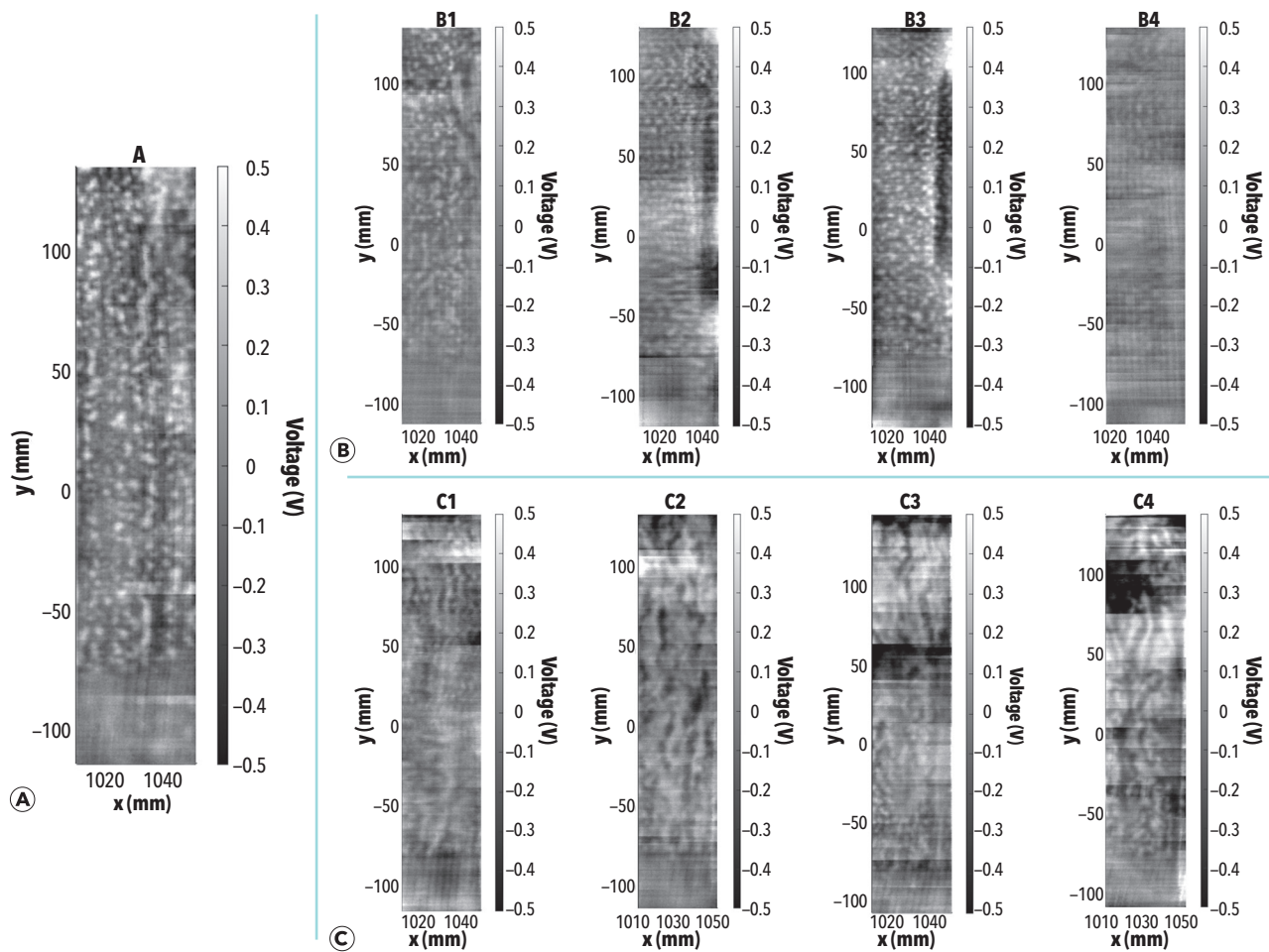


Figure 8. Full eddy current scans for steel samples: (a) flat sample A; (b) concave samples B1-B4; (c) convex samples C1-C4.

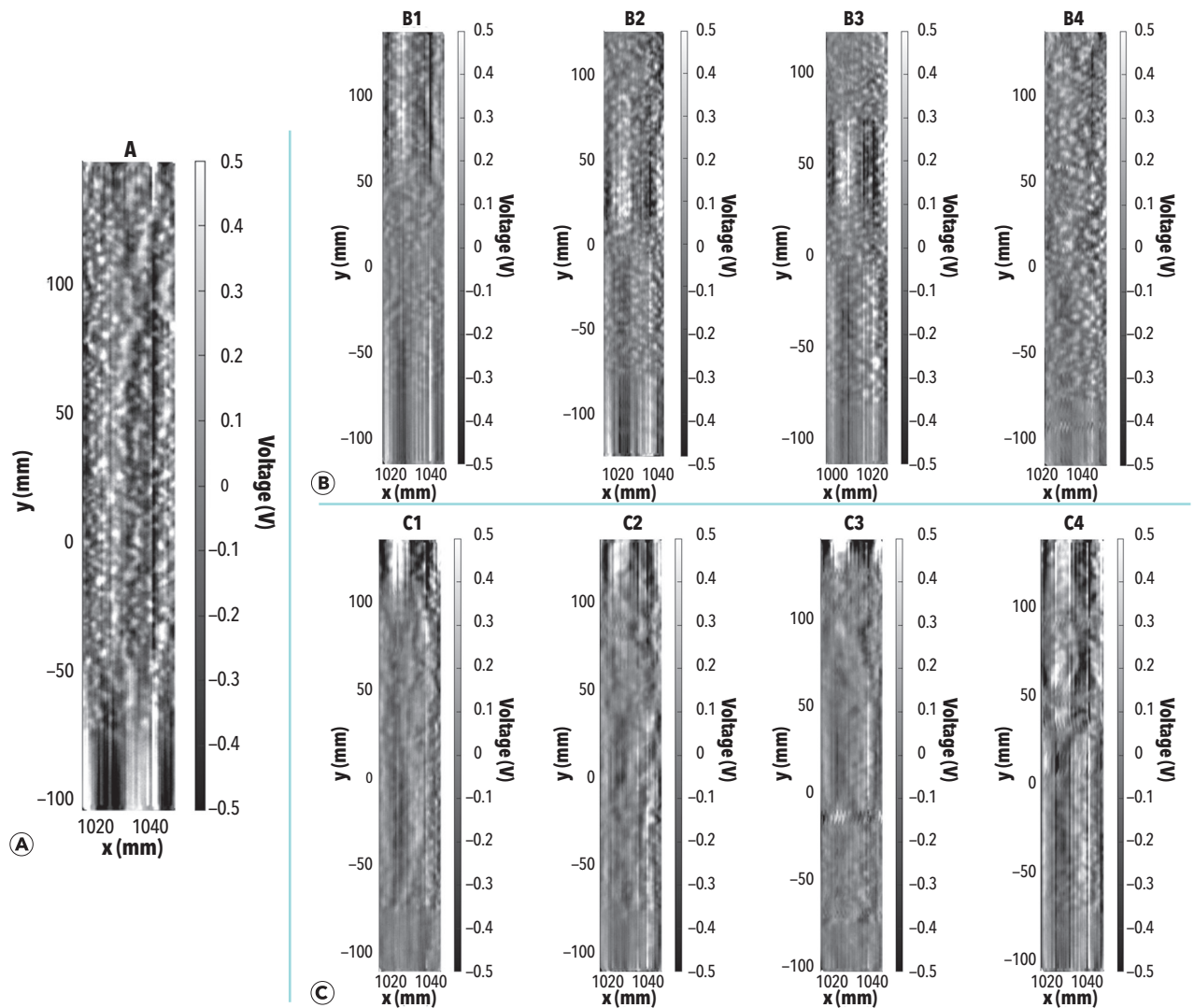


Figure 9. Fast eddy current scans for steel samples: (a) flat sample A; (b) concave samples B1–B4; (c) convex samples C1–C4.

convex sample set C. In concave sample sets B2 and B3, the right side of the scans shows saturation due to probe orientation errors, while set B4 displays desaturation across the entire scan—an issue absent in the corresponding fast scan using the same model. Fast scans experience similar tilting effects but along the y-axis.

Comparison of ECA and Microscopic Data

The validation algorithm compares ECA scans of corroded steel samples with corresponding microscopic images of corrosion depth to assess the accuracy of the robotic NDE system. Due to the time-intensive nature of microscopic imaging and reconstruction, comparisons are performed only on randomly selected regions of the test samples (D1–D4), as shown in Figure 10a. The validation process follows these steps:

- 1. Data preprocessing.** The microscopic data (Figure 10c) is downsampled to match the pixel size of the ECA image (Figure 10b), as the ECA scan covers a significantly larger area.

- 2. Alignment via cross-correlation.** A cross-correlation analysis is performed to align the datasets. The algorithm searches within the ECA data, computes the cross-correlation, and registers the location with the highest match of image patterns, as illustrated in Figure 10d.
- 3. Defect identification.** Once aligned, an intersection operation is applied to identify defect regions. The ECA data is thresholded, classifying values greater than zero as defects (coded as “1”) and background areas as “o.” In contrast, the microscopic data is thresholded such that values below zero are marked as defects (“1”), while the background remains “o.”
- 4. Final classification.** The binary masks from both datasets are combined and averaged, as shown in Figure 10e. Defect regions detected in both datasets are assigned a defect code of “1” (white), background areas remain “o” (black), and regions with no direct overlap receive an intermediate value of “o.5” (gray). The percentage of intersection is then calculated, excluding the gray areas.

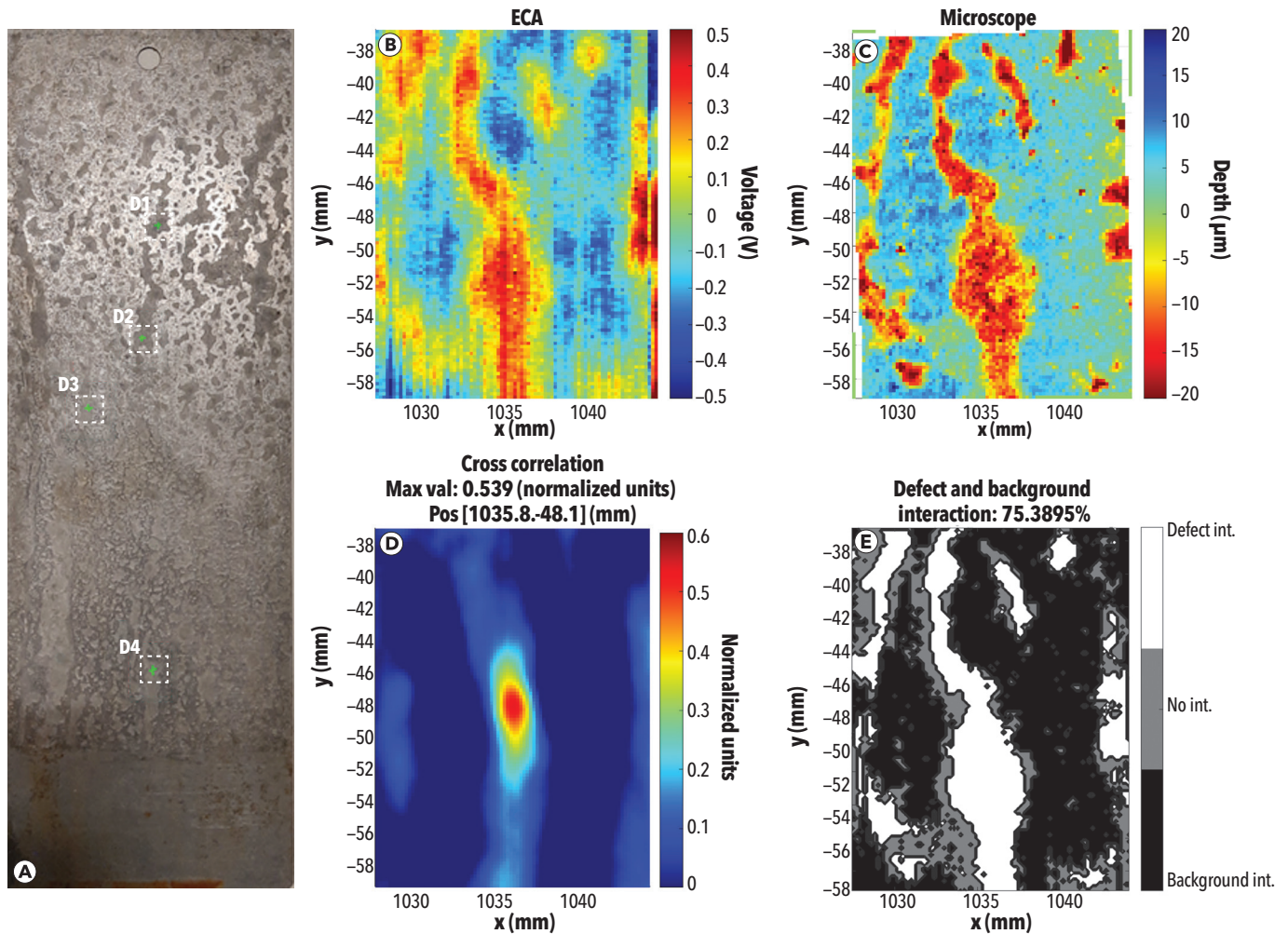


Figure 10. Experimental data for Defect D4 on corrosion Sample A: (a) locations of scanned regions D1-D4 on Sample A; (b) ECA scan of D4; (c) corrosion depth profile of D4 from the microscope; (d) the cross-correlation map between the ECA and microscopic images; (e) intersection between the ECA and microscopic images.

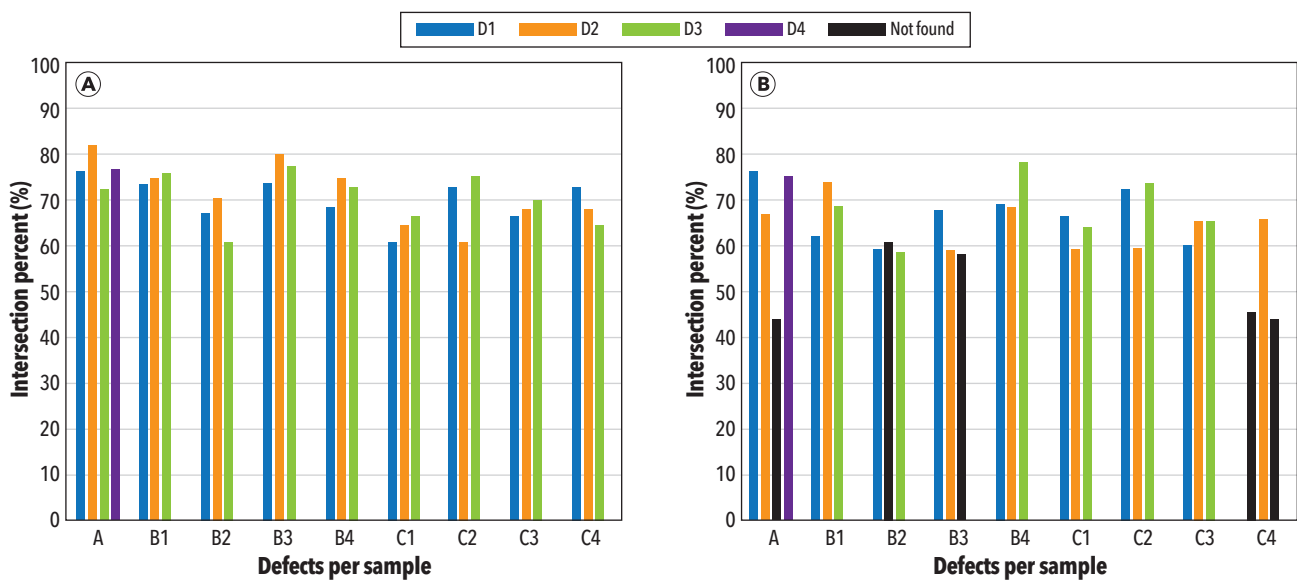


Figure 11. Intersection of the ECA and microscopic images in selected regions D1-D4 on corroded steel samples: (a) full scan results (ECA image obtained using one coil in the array); (b) fast scan results (ECA image obtained using the full array).

The gray regions in Figure 10e, indicating a lack of overlap between the ECA and microscopic datasets, result from the inherent blurriness of the ECA image compared to the high-resolution microscopic data. This blurriness occurs because the ECA sensor coils integrate magnetic field responses over their sensing area, leading to a less sharply defined defect boundary.

Figure 11 summarizes the validation of ECA results for all test samples with corrosion damage. The intersections between post-processed ECA scans and corresponding microscopic images were calculated for randomly selected regions (D1–D4) in all corroded samples, including the flat Sample A and the curved sample sets B1–B4 and C1–C4. A comparison was also made between full scans (single-coil raster scans) and fast scans (full-array, single-pass along the sample's long side).

The results showed strong agreement between ECA and microscopic images across all scans, including those on curved surfaces, highlighting the robustness of the signal processing approach used in this study. As shown in Figure 11a, full scans exhibited a high degree of intersection with microscopic data, indicating strong correlation. However, in fast scans, some randomly selected regions (D1–D4) were not effectively covered due to the single-pass nature of the scan, which followed the centerline of the sample. Consequently, for these regions, intersection evaluation was not possible. Instances where the array probe was out of bounds relative to the microscopic measurement regions are labeled as “not found” in Figures 11a and 11b.

Conclusions and Future Work

This work presents a robotic eddy current array (ECA) system developed for detecting corrosion on curved metallic surfaces, addressing key challenges such as inconsistent probe liftoff, tilt, and environmental factors. A post-processing workflow, including array subtraction and detrending techniques, was implemented to correct these errors and improve defect detection accuracy. The system showed promising results when tested on samples with varying curvatures, correlating well with ground truth data from a digital microscope. While liftoff and tilt caused some inaccuracies, the system was able to detect corrosion defects effectively. The integration of computer vision-based path planning and precise sensor alignment were essential to optimize measurements, demonstrating the system's potential for use in complex geometries and real-world scenarios.

Future work will focus on improving the robotic ECA system by addressing liftoff variations and enhancing robot calibration. More automated and accurate surface reconstruction methods, such as iterative closest point (ICP) algorithms or AprilTags (Olson 2011), will replace the current point-pair picking method. Adaptive path planning will also be explored, enabling the robot to adjust its scanning path based on real-time ECA data, which will require further development of voltage-to-depth calibration techniques. Additionally, the system will be extended to mobile and aerial platforms,

enabling autonomous inspection of large-scale or remote structures. These improvements will support NDE 4.0's goals of increasing automation, precision, and scalability in real-world inspection scenarios.

DATA AVAILABILITY

A detailed description of the post-processing procedure used in this study for the eddy current array image data is available from the corresponding author upon reasonable request.

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BECOME AN ASNT ADVOCATE!

Over my more than five years at ASNT, I have noticed some significant trends within our membership. First, you are passionate about what you do, which includes the NDT field, your respective industries, and your individual jobs. NDT is clearly important to you, and you want others to appreciate how important NDT is to your nation's health and safety, as well as the quality, reliability, and performance of your companies and employers. Second, you feel that NDT is either not well-known or it is underappreciated by your clients, stockholders, senior managers, coworkers, governments, and the public. Third, if given the opportunity to share your passion for NDT or to convince others of the importance of effective NDT, you will actively engage in such activities. This is a good thing!

ASNT recently held its first Hill Day. "Hill days" are when an association's members travel to Capitol Hill in Washington, DC, to meet with Congressional members and their staffs to discuss issues important to the association. In ASNT's case, more than 50 members and staff met with Senate and House members and their staffs to educate them about NDT and two critical issues: the workforce shortage and the need for increased government funding for NDT research. The good news is that our messages were well-received—everyone we met with appreciated learning about NDT and its indispensable role in our society. The bad news is that we have our work cut out for us to get legislation introduced in the current political climate.

I would like to extend my heartfelt thanks and appreciation to our members who took the time to travel to DC and join us on that historic day. You all made a huge impact! I would also like to thank our amazing staff team, led by Director of Public Relations and Government Affairs Garra Liming, who organized and coordinated more than 150 meetings held across two days on the Hill.



NEAL J. COUTURE,
FASAE, CAE
ASNT CEO
NCOUTURE@ASNT.ORG

**If you are
passionate about
the NDT field, if
you want the world
to recognize and
appreciate NDT, and
if you are ready to
share your passion
and our message,
then join ASNT's
advocacy team
now.**



**A group of ASNT
members and
staff gathered in
Washington, DC, for
ASNT's first Hill Day on
11 March.**

LEADERSHIP FROM P. 75

But our work has just begun. A second key initiative under development is a grassroots effort to engage members in outreach to local middle schools, high schools, trade schools, and community colleges to introduce (or reintroduce) them to NDT and the vital role we play in society. While the work-force challenges our industry faces are larger than any one organization can solve, together we can make an impact by opening doors to future generations of NDT professionals. Watch for more news on this in the coming months.

If you are passionate about the NDT field, if you want the world to recognize and appreciate NDT, and if you are ready to share your passion and our message, then join ASNT's advocacy team now. You don't need to travel to DC to participate—there will be plenty of opportunities for you locally. And you don't need to take on a leadership role—you already have a demanding job! All you have to do is care enough to pitch in. We'll prepare you with the necessary information, training, and materials, and connect you with the right offices and people. All you need to do is share your passion and our message.

To become an ASNT Advocate, go to www.asnt.org/membership/volunteer, select ASNT & NDT Advocacy, and sign up for one of several volunteer opportunities listed. I look forward to seeing you at an upcoming planning meeting where we discuss our next opportunity to advocate for NDT.

As always, if you have questions or comments, please email me at ncouture@asnt.org. ME

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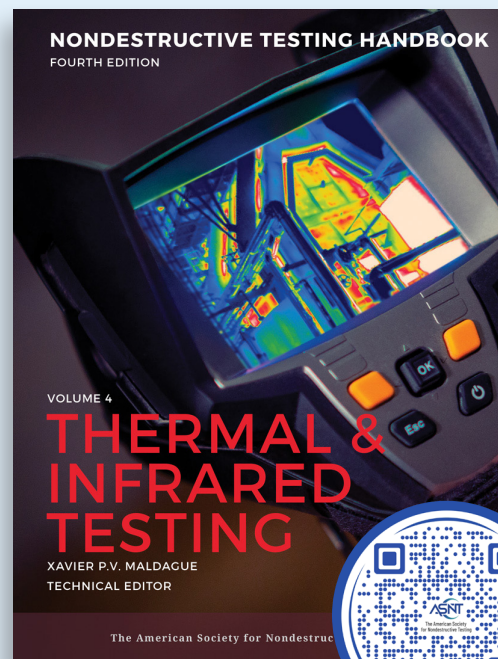


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ASNT ADVANCES GLOBAL GROWTH

In a recent interview prerecorded for ASNT Rewind, which took place on 19 March 2025, Paul Lang, ASNT Chief Global Strategy Officer and the Executive Director of ASNT Certification Services LLC, shared insight into ongoing developments in nondestructive testing (NDT) certification, training, and global outreach. These advancements reflect ASNT's commitment to aligning industry practices and standards with emerging technologies and strengthening international collaboration.

STRENGTHENING COLLABORATION WITH AWS

One of the key topics discussed was ASNT's cooperative relationship with the American Welding Society (AWS). This partnership aims to harmonize certification requirements and streamline processes for professionals in both organizations. A primary focus has been integrating AWS's Certified Welding Inspector (CWI) program into the ASNT 9712 certification framework. This effort ensures that CWIs can seamlessly transition into ASNT's certification process while meeting standardized industry requirements.

Lang emphasized the importance of this partnership, stating, "We've worked closely with AWS to identify gaps and ensure that CWIs can move smoothly into the ASNT 9712 program. This collaboration helps both organizations and, most importantly, the professionals seeking certification."

Additionally, the partnership has led to the future dual branding of AWS's Certified Radiographic Interpreter program, and other initiatives further strengthening cross-certification opportunities. With 40% of ASNT's members also holding AWS certifications, this

initiative provides professionals with greater flexibility and recognition across disciplines.

NEW AUTHORIZED TRAINING ORGANIZATION ACCREDITATION

ASNT has also launched an Authorized Training Organization (ATO) accreditation program, responding to industry concerns about training consistency and quality. Lang highlighted that training varies widely in effectiveness, and the ATO program aims to standardize instruction quality by accrediting educational institutions (such as universities, community colleges, trade schools, and other training institutions).

"The biggest issue we've seen is the wide range in training quality. Some programs are exceptional, while others fall short. With the ATO program, we're creating a consistent benchmark for training institutions to meet industry expectations," Lang explained.

The program recently completed beta testing, with the first accredited organization already listed on ASNT's website and two more nearing final approval. ASNT anticipates an official launch in

NDT CERTIFICATION WITH AND INNOVATION

the coming months, with applications opening soon. This initiative is expected to enhance training credibility and bring consistency to the NDT industry. To date, Lang said that they have received more than a hundred inquiries on the accreditation and how to go about obtaining it, indicating a high interest within the NDT community.

EXPANDING ASNT'S GLOBAL REACH

Since its establishment in 2023, ASNT India Pvt. Ltd., an entity of ASNT Inc., has been expanding its influence by offering certification exams, training programs, webinars, and industry events. ASNT Certification Services has an agreement with ASNT India to administer exams, reinforcing the organization's presence in the region.

"ASNT India has been a fantastic addition to our global strategy. It's allowing us to directly engage with professionals in the region, making certification more accessible and efficient," Lang noted.

Building on this momentum, ASNT is collaborating with AWS to open a second facility in India. This expansion aims to provide direct access to industry professionals, reducing reliance on US-based assessments and strengthening ASNT's global standing.

THE FUTURE OF NDT CERTIFICATION

Looking ahead, Lang identified technological advancements as both a challenge and an opportunity for NDT

certification. Innovations in artificial intelligence (AI), augmented reality (AR), and virtual reality (VR) are revolutionizing the industry but pose difficulties when applied to a certification framework developed over 50 years ago.

"We're at a critical point where we need to reassess how we evaluate competency. AI and AR are changing the game, and we must adapt our certification methods to reflect these advancements," Lang said.

ASNT is actively exploring ways to modernize competency assessment. Lang emphasized that the traditional Level I, II, and III certification model may need to evolve to accommodate emerging technologies and new methodologies. ASNT is committed to collaborating with industry stakeholders to develop a future-ready certification system that ensures continued excellence in NDT.

"I think in the future we will be evolving into a different type of certification system, in which we assess individuals on their competency for NDT," said Lang.

CONCLUSION

ASNT Certification Services LLC is making significant strides in enhancing certification programs, standardizing training, expanding global reach, and adapting to technological advancements. "The challenges we face today are exciting because they push us to innovate and improve," said Lang. "ASNT is dedicated to ensuring that certification evolves with the industry, and I look forward to seeing how we shape the future of NDT." **ME**

Paul Lang is ASNT Chief Global Strategy Officer and Executive Director of ASNT Certification Services LLC.



Since its establishment in 2023, ASNT India Pvt. Ltd. has offered certification exams, training programs, webinars, and industry events.

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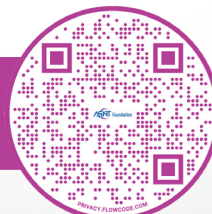
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ASNT'S VOLUNTEER SUMMIT

The Volunteer Summit, scheduled for the end of May, is designed to be a dynamic and impactful event that engages, recognizes, and inspires volunteers across all levels of the organization. Through a carefully curated selection of workshops, interactive sessions, and networking opportunities, the summit will provide volunteers with valuable insights, tools, and resources tailored to their specific roles and responsibilities.

This gathering will bring together volunteers from diverse backgrounds and experience levels, creating a collaborative space where knowledge-sharing and mentorship can flourish. By fostering meaningful connections between volunteers, staff, and leadership, the event will help strengthen relationships, encourage dialogue, and reinforce a sense of belonging within the organization.

Additionally, this event will serve as a platform to celebrate the dedication and contributions of volunteers, recognizing their efforts in driving ASNT's mission forward. Through keynote speeches and panel discussions, attendees will gain a renewed sense of purpose and motivation, leaving with a deeper understanding of how their work contributes to the Society's broader vision.

Ultimately, the Volunteer Summit will enhance volunteer engagement and cultivate a stronger, more connected community, empowering participants to continue making a meaningful impact in their respective roles. ASNT staff and seasoned volunteers will serve as facilitators.

Q: Who is invited?

A: Any member of ASNT interested in volunteering, including section leaders, those interested in committee and council work, speakers, and instructors.

Q: What is the registration fee?

A: Registration is free. However, attendees are responsible for their own transportation and hotel accommodations.

Q: Where is the Volunteer Summit being held?

A: The Volunteer Summit will be held in St. Louis, Missouri, at the Hyatt Regency St. Louis at the Arch.

Q: When is the Volunteer Summit?

A: The meeting dates are 30 May-1 June. Friday evening will kick off with a meet-and-greet, followed by a full day of workshops and learning on Saturday. ASNT will host dinner on Saturday night, followed by a half day of workshops and learning on Sunday.

Q: Where can I find out more information?

A: To register or learn more about the event, go to <https://asnt.eventsair.com/volunteer-summit-2025/>.

Q: Where can I learn more about volunteer opportunities with ASNT?

A: To learn more about available volunteer opportunities with ASNT, visit <https://www.asnt.org/membership/volunteer>. **ME**

SOCIETYNOTES

2025 ELECTION NOTICE

ASNT has partnered with Intelliscan Inc. to conduct the 2025 Board elections. On 14 March, all eligible voting members of the Society received an email with instructions and a link to vote online. The voting period will remain open through 11:59:59 p.m. (ET) on 15 April 2025. Please note that the following member categories are not eligible to vote in ASNT elections: Associate, Student, and Complimentary. To view the ballot and candidate biographies and videos, go to asnt.org/election. Do not miss your chance to have a say in the future of your Society!

SHIP FOR LESS AND SAVE BIG

FedEx and UPS raised their shipping rates by an average of 5.9% for 2025. The good news? ASNT members can save 50% on FedEx Express and 20% on FedEx Ground by enrolling in the free FedEx Advantage program through PartnerShip®, an ASNT benefit provider. PartnerShip also released a report (scan the QR code below) analyzing the rate increases, so you can see what to expect and how to manage these price hikes. Both resources are a great way to stay ahead of rising costs and keep your shipping budget in check. Find out more by visiting partnership.com/asnt.





JOHN (JACK) C. DUKE JR.

2024 50-Year Member Recognition recipient John (Jack) C. Duke Jr. joined ASNT in 1974 while pursuing his PhD at Johns Hopkins University. He served on the faculty of Virginia Tech's Engineering Science and Mechanics Department for 38 years. In 1982, Duke and five senior members of the ASME Pressure Vessels and Piping Division founded the ASME NDE Engineering Subdivision, while he was also advancing through the chairs of the ASNT Education and Qualification Council. In 1985, he became the inaugural chair of the ASME NDE Engineering Division and served on the ASNT Board of Directors. Duke is a Fellow of both ASNT and ASME and a member of the Order of the Engineer. He cofounded the National Academy of Sciences Transportation Research Board AKT40 Structure Maintenance Subcommittee, serving as its sole chair until its sunset in 2023 after completing its objectives.

In 2020, Duke received the Robert C. McMaster Gold Medal Award and the Mentoring Award from ASNT. He also received the William F. Via Jr. Bridge NDT Lifetime Service Recognition and the Robert E. Green Jr. Research Recognition for Sustained Excellence Award in 2018. He is a senior subject matter expert in NDE engineering, consulting as an external member of the NASA NESC NDE Technical Discipline Team. He is also a professor emeritus at Virginia Tech, where he is developing an online post-baccalaureate course for NDE engineering to help achieve and sustain structural integrity.



ANTHONY FANTINI

2024 50-Year Member Recognition recipient Anthony Fantini began his welding career in 1969 during his sophomore year of high school at the County Vocational Institute, where his class won a James F. Lincoln Arc Welding Award for their project work. In 1971, he became an ASME Section IX certified welder at the Materials Engineering Laboratory for a company specializing in the design, construction, inspection, and renovation of fossil and nuclear power stations worldwide.

Fantini worked for EBASCO Services Inc. for 17 years, earning multiple Level III certifications, as well as certifications from the American Welding Society and the American Petroleum Institute. Over the next 25 years, he worked for a utility, including seven years working in the Middle East's "oil patch" with Aramco and three years in China as the welding QC project manager for the ASME mechanical modular AP1000, a two-unit nuclear new-build project that was an early part of the "Nuclear Renaissance." He retired in March 2024 and has been a member of ASNT since 1974.



KURT GOTTSCHALK

2024 50-Year Member Recognition recipient Kurt Gottschalk has been in the NDT industry since he was 22, when he began working for his family's imaging production company, Warren NDT in Pittsburgh, Pennsylvania. Alongside his father, Warren, and now with his son Evan, Kurt has helped shape the company to firmly support the NDT community and manufacture X-ray imaging products of the highest quality and craftsmanship.

Under Gottschalk's leadership, Warren NDT has thrived, with a dedicated and loyal staff that has been with him for decades. Now in its 78th year of operation, the company has stayed on course while weathering economic storms under Gottschalk's valued leadership.

TIM FLAHERTY
(NOT PICTURED)

2024 50-Year Member Recognition recipient Tim Flaherty is an ASNT Fellow and a founding member and past chair of the Old Dominion Section. Flaherty is Sales Manager for Maryland-based DETEK, a nondestructive testing equipment and supplies company he joined in 1973, and is responsible for their technical support, field sales, and service.

AWARDS AND RECOGNITIONS FOR 2025

The application window for 2025 ASNT awards and recognitions is now closed. Winners will be announced soon. Watch ASNT's social media channels for updates!

ABOUT 50-YEAR MEMBER RECOGNITION

The 50-Year Member Recognition formally recognizes individuals who have been members of the Society for 50 years or longer.



JOHN T. IMAN

2024 Philip D. Johnson Honorary Member Award winner John T. Iman is Vice President of Global Sales for VMI/Varex Imaging and President of the ASNT Foundation. Iman recently ended his term on the ASNT Board of Directors

and currently serves on the Leadership Development Committee. Previously, he served as Vice Chair of the Technical and Educational (T&E) Council from 2017 to 2019 and has served on the Business and Finance Committee as well as several other ASNT committees. He was named an ASNT Fellow in 2015 and received the 2024 Advancement of Women in NDT Recognition. Additionally, he has held various roles within ASNT's Greater Houston Section.

Iman is a dedicated advocate for the NDT industry, consistently championing enhanced workforce development programs. He is the former chair of the Nondestructive Testing Management Association (NDTMA) and has served on

various American Petroleum Institute (API) committees. He is also a member of the American Welding Society (AWS) and a former committee member of Pipeline Research Council International (PRCI). Over the past decade, he has been active in international ambassadorship for both ASNT and the broader NDT industry. **ME**

ABOUT PHILIP D. JOHNSON HONORARY MEMBER AWARD

This award is the highest lifetime ASNT honor bestowed upon a longtime member of the Society, who is appreciated at the national level—and perhaps internationally—for at least 20 years of meritorious service in the technology of NDT.

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In March 2025, ASNT Director of Publications **Jill Ross** earned the Graduate Certificate in Publishing

Management (GCPM) from George Washington University in Washington, DC. Designed for experienced publishing professionals seeking to advance their leadership and management skills, the GCPM program requires 18 credit hours, including 11 credits of core coursework and 7 credits of electives. This achievement, combined with her bachelor's degree in journalism from Ohio University and numerous other industry certifications and awards, reflects Ross's dedication to professional growth and her commitment to upholding excellence in ASNT publications and journals.



In February, the Naval Welding Institute (NWI) announced the addition of ASNT member **Lawrence**

(Larry) E. Mullins Sr. as Director of Workforce Development for the New England Region. In this role, Mullins focuses on collegiate outreach, program execution and oversight, student engagement, and pipeline cultivation.

Mullins is a graduate of the University of Massachusetts with a BS in Materials. With over 50 years of experience, his career spans nondestructive testing (NDT) in shipbuilding and work with building, bridge, vessel, and piping codes. He has extensive expertise in both nuclear and conventional power generation. He has worked in quality control for a major shipbuilder, as an Authorized Nuclear Inspector and later as an NDT coordinator in the commercial nuclear sector. In the late 1980s, he returned to shipbuilding, becoming an Advisory Engineer at a Naval Nuclear Laboratory, until around 2010.

After retiring from the Naval Laboratory, Mullins founded NXTndT in 2007. He is a practicing ASNT NDT Level III and ACCP Professional Level III, involved in performance testing, evaluation, and advanced technology development, as well as codes and standards.

Mullins collaborates with organizations including ASNT, the American Society of Mechanical Engineers, the British Institute of Nondestructive Testing, and the American Welding Society. He is also a Chartered Engineer accredited by the Engineering Council in London. Currently, he works as a technical advisor and subject matter expert for NDT under contract with the US Navy.



Boeing announced **Dana Deasy** as the company's new Chief Information Digital Officer and Senior VP

of Information Technology and Data Analytics. Deasy was elected to the role, which he assumed 31 December 2024.

Deasy oversees all aspects of information technology, information security, and data analytics. He reports directly to Boeing President and CEO Kelly Ortberg and serves on the company's executive council.

"Dana is a well-respected, global technology leader who has a track record of delivering on innovative technologies across large and complex organizations," said Ortberg. "With the need to stay vigilant to protect against cyber threats, and emerging technologies like artificial intelligence playing a larger role across all industries, our IT team will have a key role as we focus on meeting our safety and quality goals, delivering reliably for our customers and positioning ourselves for the future."

Deasy has more than 40 years of technology and leadership experience, having worked across multiple industries. Most recently, he served as the Chief Information Officer at the US Department

of Defense and before that, at JPMorgan Chase, BP, and General Motors. Deasy began his career in information management at Rockwell's Space Systems Division.



Lumentum, the Silicon Valley-based optics and photonics company, appointed **Michael Hurlston**

as its new CEO, succeeding Alan Lowe, who retired after leading the company since 2015. Hurlston, previously the CEO of Synaptics, officially took over on 7 February.

Lumentum, known for its high-speed optical transceivers used in AI data centers, as well as industrial lasers and 3D sensors, has seen significant growth since its spin-off from JDS Uniphase in 2015. Lowe will remain on Lumentum's board and serve as an advisor.

Hurlston brings extensive experience in optical communications, having previously served as CEO of Finisar before its acquisition by II-VI (now Coherent). His career includes leadership roles at Broadcom, Oren Semiconductor, and other technology companies.



The Institute for Advanced Composites Manufacturing Innovation (IACMI; Knoxville, TN) named **Andrew**

Pokelwaldt as its new Director of Education and Workforce on 31 January. In this role, Pokelwaldt will lead IACMI's education and workforce team, overseeing strategic planning and the execution of key initiatives and programs.

Pokelwaldt brings significant experience in workforce development and training, including Composites Instruction Credentials (CCT-I), marine manufacturing, and technical writing for composites manufacturing. He previously served as Director of Workforce

Training and credentialing at the American Composites Manufacturing Association (ACMA) and as Training and Development Manager at Brunswick Recreational Boat Group in Knoxville, Tennessee. Most recently, he was the corporate technical training manager at Newell Brands in Maryville, overseeing workforce programs across the US, Europe, and Latin America.

Pokelwaldt holds a master's degree in Education from the University of Tennessee, Knoxville. In addition to his civilian career, he is a retired dual-career military veteran, having served 20 years in the US Marine Corps and US Army.

APPOINTMENTS

Peter Pi was appointed International Sales Manager at The Gill Corp. (El Monte, CA) in January. With more than a decade of experience in the aerospace sector, Pi brings deep knowledge and expertise that The Gill Corp. said will be instrumental in serving airlines, maintenance, repair and overhaul (MRO) companies, and OEMs throughout the China-Asia-Pacific region.

RETIREMENTS

After a decade of dedicated service, **Dale Brosius** has announced his impending retirement from the Institute for Advanced Composites Manufacturing Innovation (IACMI), effective 1 July 2025. Brosius is currently Executive VP and Chief Commercialization Officer (CCO) for IACMI.

DEATHS

Jay Kumler, President of Jenoptik's North American business and Jenoptik Optical Systems, passed away on 10 February 2025, at age 61.

Kumler served in those roles at Jenoptik for many years. As a member of the Jenoptik Executive Management Committee, he actively shaped the development of Jenoptik's photonics-based business in the US.

"Not only did Jay have a huge impact on our company, but he was also a distinguished scholar, a passionate entrepreneur, and an inspiring mentor to many startups and new talents in the entire photonics industry," said Stefan Traeger, President and CEO of Jenoptik AG.

Kumler earned a BS in Physics from Miami University (Oxford, OH) and a MS in Optics from the University of Rochester (New York). He designed optical systems for United Technologies and Bell Laboratories before founding Coastal Optical Systems in 1991, which Jenoptik acquired in 2001.

With nearly 40 years in optics and photonics, Kumler published 20 technical papers, book chapters, and patents. He was an SPIE Fellow, served on the SPIE Board of Directors, and was a founding sponsor of the SPIE Startup Challenge, which is held during the Photonics West trade fair every year. He also served on the Advisory Board of the Luminate Accelerator and loved mentoring younger optical engineers and entrepreneurs.

Kumler regularly spoke on photonics and was passionate about advancing the industry. He was especially proud of his contributions to the Hubble Space Telescope, NASA's Mars Perseverance rover, and the X Taara wireless internet terminal, which was named a *TIME* magazine "Best Invention of 2024."



NEW CERTIFICATIONS

ACCP Level II CWI

Rene Bazaldua
Isaiah Holguin
Martin Howe
Kenneth Howell
Kory Rafferty
Jason Smith
Mackenzie Smith
Roger Tarrant

ASNT 9712 Level II

Mathew Ceron
Jason Schamber

ASNT 9712 Level III

Krutik Shah

ASNT NDT Level II

Benjamin Corke

ASNT NDT Level III

Ian Ashkar
Friday Atanawhemera
Amit Balyan
Kranthi Battu
Samuel Cartozzo
Jesus Chavez
Grisell Cruz
Aynalem Getanhe
Aneesh Gopi
Timothy Harrison
Jeffery Hartman
Haris Iqbal
Rohit Kumar
Ashok Kumar Mahankali
Devin Martin
Tiju Varghese Mathew
Jack Minkler
Gourahari Nayak
Myeong Su Park
David Pirie
Anthony Quesenbury
Ajit Kumar R
Tamilselvan Seeralan
Norman Taormina
Suresh Babu V

IRRSF

Daniel Bullock
Frank DeAngelo
Jeffrey Eagen
Christopher Falls
Eddie Gentry
Kody Harlow
Michael Hodge
Matthew Lester
Kiernan Litwiler
Connor Martin
Mark Rink
Mark Roberts
Ashleigh Sloan
Cole Waxley
Kevin Wells
Isaac Young

ISQ - Oil & Gas

Lucas Barr
Majid Calil
Andrew Carpenter
Michael Devine
Rudy Espinoza
Chad Esteppe
Joseph Harris
Gregory Manbeck
Andrew Marquez
Jesus Martinez
Ryan Mouser
Paul O'Connell
Jared Raggio
Gabriel Rodriguez
Blake Rosberg
Randy Ruble-Colman
Connor Sarmiento
Tremayne Stephens
Yao Tang
Mason Unthank
James Voorhees
Micah Wilson
Grayson Wolf
Zachariah Zieke
Ruben Zuniga

Naval Shipbuilders

Richard Mills
Anthony Romano
Joe Veale

SOCIETYNOTES

NOTICE OF INTENT TO REVISE ASNT BYLAWS

In accordance with the ASNT Bylaws, Article VII: Amendments and Revisions, Section 1 - Proposals to Amend or Revise the Bylaws, this is to notify the members of ASNT's intent to revise the Bylaws as described below.

The Executive Committee proposes the following changes:

- ▶ Combine the positions of President and Chair of the Board, under the title of President.
- ▶ Change the terms of office for President and Vice President from one year each to two years each.
- ▶ Eliminate the position of Immediate Past Chair.
- ▶ Add the President of ASNT Foundation to the Executive Committee.

Members may submit questions or comments on the proposal by 16 April to Secretary Jill Ross at secretary@asnt.org. The Board will review all feedback before voting. All submissions and responses will be posted on ASNT's website. The revision will be adopted with a two-thirds vote of the Directors, excluding the CEO.

CHARLOTTE

CONCORD, NC
11 FEBRUARY 2025
15 ATTENDING

► The Charlotte Section held its January meeting at Afton Tavern in Concord. Guest speaker Carlos Rosburgh from CLR Testing delivered a presentation on Nadcap auditing.

COASTAL GEORGIA

STATESBORO, GA
27 JANUARY 2025
42 ATTENDING

► The Coastal Georgia Section held a technical meeting on the campus of Georgia Southern University. A guest presenter from the Office of Materials and Testing Technical Assistance Unit at the Georgia Department of Transportation spoke about the use of the GSSI rolling density meter for the compaction of asphalt roadways, as well as the use of nondestructive testing (NDT) for concrete pavement inspection.

GREATER HOUSTON

DEER PARK, TX
12 FEBRUARY 2025
54 ATTENDING

► The Greater Houston Section hosted its February meeting at the Republic Grill at Battleground Golf Course in Deer Park. Dinner was followed by a technical presentation on HTHA (high-temperature hydrogen attack) inspection, given by Mark Carte from Becht Engineering.

KUWAIT

FAHAHEEL, KUWAIT
18 FEBRUARY 2025
48 ATTENDING

► The Kuwait Section hosted a technical presentation and dinner at the Kohinoor Hotel in KHS-4-Souksaba, given by section officer Sangili Gunasekaran on the basics of ASNT Recommended Practice No. SNT-TC-1A (2024) and ANSI/ASNT CP-189 (2024). Included in the discussion among the members were basic NDT; 2024 changes, corrections,

and new requirements; and explanation and specific requirements of the time of flight diffraction and phased array ultrasonic testing techniques. In addition, in-line inspection, magnetic flux leakage, infrared thermography, acoustic emission testing, and guided wave techniques were discussed, as well as remote field testing and eddy current testing differences, and profile and close proximity radiographic testing techniques.

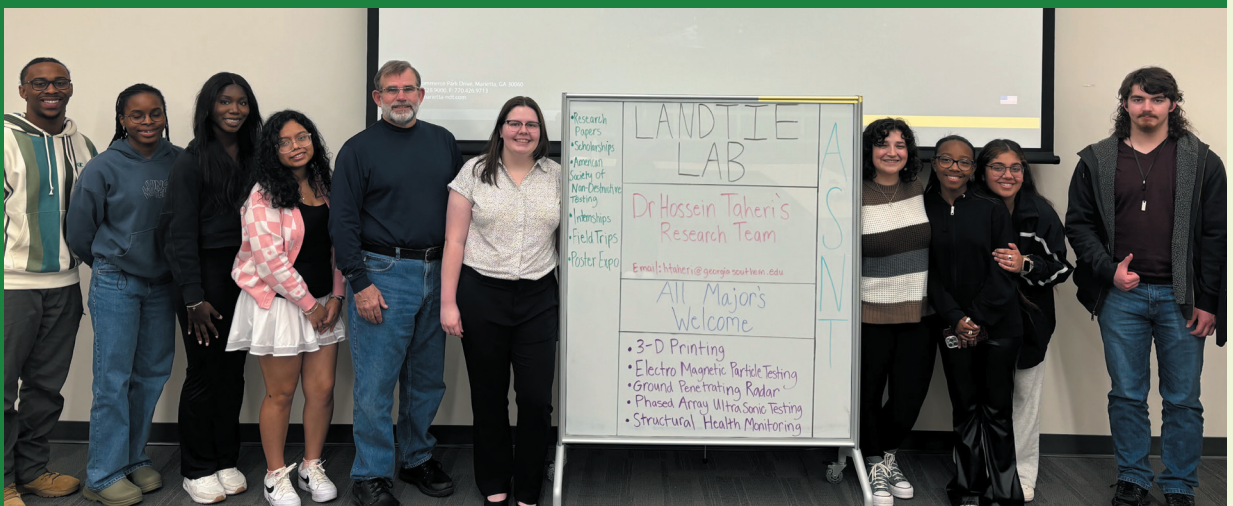
LEWIS & CLARK

PORTLAND, OR
11 FEBRUARY 2025
6 ATTENDING

► Six members of the Lewis & Clark Section met at NPI (NDE Professionals Inc.) in Portland and held a Zoom call with the Pacific Northwest Section for a discussion led by ASNT Director of Business Development Peter Roy.

ME

SPOTLIGHT COASTAL GEORGIA



Concepts of conventional ultrasonic testing, eddy current, and X-ray inspection for industry applications were discussed in a presentation given by Marietta NDT at a Coastal Georgia Section meeting held on 17 February at Georgia Southern University.

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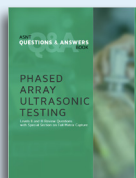


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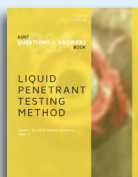
Visual Testing Method

Print 10118; ebook: 10118-e



Phased Array Ultrasonic Testing

Print 10127; ebook: 10127-e



Liquid Penetrant Testing

Print 10116; ebook: 10116-e



Magnetic Particle Testing

Print 2027; ebook: 2027-e

Also available for the following methods: Radiographic Testing, Ultrasonic Testing, Time of Flight Diffraction, Electromagnetic Testing, Thermal & Infrared Testing, Acoustic Emission Testing, Neutron Radiography, Magnetic Flux Leakage Testing, Mass Spectrometer, Halogen Diode Detector, Pressure Change Measurement, and Bubble Leak Testing.



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CALL FOR PRESENTATION PROPOSALS: ASNT 2025

Embark on a transformative journey of knowledge sharing and professional development by becoming a presenter at ASNT 2025, the premier event for the nondestructive testing (NDT) profession. This is your opportunity to contribute to a global community of peers, professionals, and influencers, shaping the future of NDT. As a presenter, you play a pivotal role in advancing the field by sharing your expertise, insights, and innovations with an engaged and diverse audience. Showcase your accomplishments, research, and projects on a prestigious platform, gaining recognition among industry leaders and experts. Beyond the honor of presenting at this esteemed event, you'll be at the forefront of meaningful discussions, networking with like-minded professionals, and influencing the direction of NDT. Join us at ASNT 2025 to be a catalyst for progress, inspire your peers, and leave an indelible mark on the NDT profession. Your voice matters, and ASNT 2025 provides the ideal stage for your knowledge to resonate globally.

Important dates:

- ▶ 25 April 2025 – Proposal submission deadline
- ▶ 30 May 2025 – Acceptance notification
- ▶ 5 September 2025 – Presenter registration deadline
- ▶ 12 September 2025 – Presenter meeting (recorded)
- ▶ 22 September 2025 – PowerPoint presentation uploads due

What ASNT 2025 looks for:

- ▶ **Content:** Proposal content should reflect cutting-edge, forward-thinking topics in the areas of NDT application, technology, or professional development
- ▶ **Topics:** NDT methods; industry applications; professional development; codes and standards
- ▶ **Innovation:** Up and coming methods, new innovations in equipment, unique ideas, and new technology presentations are encouraged
- ▶ **Formats:** Session formats that encourage attendee engagement, and adhere to adult learning styles, are given preference in the scheduling

Visit asnt.org/events to learn more.

CALL FOR PRESENTATIONS: ICPIIT 2025

Share your knowledge with the NDT global community including your peers, other professionals, and project influencers at ICPIIT 2025, the International Chemical and Petroleum Industry Inspection Technology Conference, to be held 22-24 July 2025 in Sugar Land, Texas. This conference brings together experts, innovators, and leaders to explore the evolving landscape of inspection technologies critical to the chemical and petroleum sectors. As the industry adapts to shifting energy demands and sustainability goals, ICPIIT 2025 will serve as a platform to exchange cutting-edge insights and practical solutions. Topics will include advancements in inspection for downstream refineries, midstream pipelines, and upstream production, as well as innovations in chemical plant operations, construction integrity, and workforce qualifications. Join us as we drive progress in safety, reliability, and environmental stewardship, paving the way for a resilient future. Speakers

also qualify for a significant discount on registration.

Proposal content should present new, cutting-edge, and timely content that is relevant to the NDT professional in today's workforce.

Important dates:

- ▶ 25 April 2025 – Presentation deadline
- ▶ 16 May 2025 – Acceptance notification
- ▶ 29 June 2025 – Presenter registration deadline
- ▶ 4 July 2025 – PowerPoint presentation uploads due

Visit asnt.org/events for submission information.

TECHNICAL FOCUS ISSUE: NDT/E FOR ELECTRIC VEHICLES

The rapid disruptive shift from internal combustion engine to battery electric vehicles (EVs) necessitates new nondestructive testing and evaluation (NDT/E) inspection techniques to ensure first-time quality. This special issue of *Materials Evaluation*, to be published in January 2026, aims to consolidate research activities related to EV and EV component inspection. Many EV components necessitate quality inspection techniques that must operate under a demanding set of constraints, including extremely fast cycle times, noncontact, materials with small geometric scales, and conductive materials. We invite submissions that explore advancements in NDT/E technology and methodologies for EVs and EV components, including battery cells/packs/modules, electric motors, and electric motor components. Papers focusing on inline manufacturing techniques are particularly welcome. Process monitoring techniques are also welcome. The goal is to showcase cutting-edge research that pushes the boundaries of NDT/E, ensuring first-time quality of EVs.

Each paper accepted will be assigned a DOI number. Technical Focus Issues of *Materials Evaluation* are open access, ensuring high visibility for your paper. Accepted papers are also exempt from publication fees.

Deadline: 15 June 2025

Publication Date: January 2026

Submission Process: Submitted papers should not be under consideration for publication elsewhere. Before submission, send a short abstract or tentative title to Technical Editor Megan McGovern, PhD, PE, Staff Researcher for General Motors Research and Development, mcgovern@gm.com.

CALL FOR PAPERS: ICENDE 2025

Professionals from industry, research, and academia in the fields of nondestructive testing (NDT), welding, and corrosion are invited by ASNT India to submit abstracts for paper presentations involving any of the Tracks of ICENDE 2025, the International Conference and Exhibition on Nondestructive Evaluation, to be held 20-22 August in the city of Kochi in Kerala, India. This is an excellent opportunity to showcase your research, innovations, and case studies in any of the listed topics or related subjects of interest in the following Tracks:

Track A: NDT

- ▶ Emerging techniques
- ▶ Industry applications
- ▶ Condition monitoring
- ▶ Certification and standards
- ▶ Case studies

Track B: Welding

- ▶ Advanced welding technologies
- ▶ Inspection and quality control
- ▶ Standards and certification
- ▶ Industrial applications
- ▶ Sustainability in welding

Track C: Corrosion

- ▶ Corrosion testing, inspection, and monitoring

- ▶ Corrosion mitigation
- ▶ Industrial relevance
- ▶ Challenges, failures, and case studies
- ▶ Research and development

It is mandatory for the author or co-author to attend the conference, and the presenting author must register as a delegate. This platform provides an invaluable opportunity to engage with global industry leaders, share insights, and contribute to advancements in NDT, welding, and corrosion. We look forward to your valuable contributions and participation in shaping the future of inspection, testing, and material integrity.

Important dates:

- ▶ 30 June 2025 - Abstract submissions deadline
- ▶ 3 July 2025 - Acceptance notification
- ▶ 5 July 2025 - Author delegate registration deadline
- ▶ 10 July 2025 - Full paper submissions due

Visit https://icende.in/call_for_paper for abstract submission guidelines, template, and instructions.

CALL FOR PRESENTATIONS: APCNDT 2026

Step into the spotlight as a presenter at APCNDT 2026, the premier Asia Pacific Conference on Non-destructive Testing, to be held 11-15 May 2026 in Honolulu, Hawaii. With the theme "Breaking Barriers: NDT Solutions for a Changing World - Innovate, Adapt, Transform," this international gathering provides a unique platform to showcase your expertise, share groundbreaking research, and contribute to the future of NDT on a global scale.

Proposal content should reflect cutting-edge, forward-thinking topics in the areas of NDT application, technology, or professional development. Presentations on up-and-coming methods, new innovations in equipment,

unique ideas, and new technology are encouraged.

Potential topics include:

- ▶ NDT methods
- ▶ Industry applications
- ▶ Professional development
- ▶ Codes and standards

Visit <https://www.apcndt2026.com/> present for presentation format options and submission information and portal. The proposal deadline is **31 October 2025**. Speakers will be notified of acceptance on 9 January 2026 and must register by 13 March 2026. The presentation submission deadline is 24 April 2026.

CALL FOR 2025 ASNT WEBINAR SPEAKERS

ASNT is recruiting speakers for its recurring webinar series, and we invite you to submit your topic for consideration. ASNT webinars can be hosted by one speaker or a panel of speakers depending on the topic. Webinars are 1 h long with 10 min embedded for Q&A and are typically held at 12:00 or 1:00 pm (ET) during the month. We're open to webinars hosted in English and Spanish (with a moderator provided by the speaker), and we may be open to other languages depending on topic and interest.

Potential topics may include:

- ▶ Phased array ultrasonic testing
- ▶ Time of flight diffraction
- ▶ AR/AI in NDT
- ▶ Eddy current
- ▶ Thermography
- ▶ Computed radiography
- ▶ NDT in aerospace
- ▶ Unique NDT applications
- ▶ Level I/II introductory topics
- ▶ Safety in NDT
- ▶ Business management of NDT

If you have a technical topic you'd like to submit for consideration, visit asnt.org/education/courses-by-format/webinars to complete the webinar speakers form.





SPORT FRAZIER

NDT Technical Specialist, Marmon Rail
CHARLOTTE, NC

HOW DID YOU FIRST BECOME INVOLVED IN NDT?

A friend told me about it. I was just starting at Central Piedmont Community College [CPCC] and didn't really know what I wanted to do. But once I heard about the program, it seemed perfect for me. The format was all theory one day, then the next day was

hands-on. Getting some hands-on experience using the equipment and inspecting materials really excited me.

AFTER FINISHING THE PROGRAM AT CPCC, WHAT FURTHER TRAINING AND CERTIFICATIONS DID YOU PURSUE?

After community college, I started working with Hussein Sadek, a Past President of ASNT. I did a little of everything—mag particle [MT], penetrant, visual [VT], eddy current [ECT], and ACFM [alternating current field measurement]. While working with Hussein, I earned my bachelor's degree in industrial technology with a minor in industrial engineering from East Carolina University.

I worked in project management for a while, then returned to NDT and started at Marmon Rail. There, I've completed my Level III certifications in VT, MT, and ET [electromagnetic testing]. I also have a PCN Level II in UT [ultrasonic testing] and ACFM.

CAN YOU TELL US ABOUT YOUR CURRENT ROLE?

I'm helping set up an ACFM program at Marmon Rail for tank cars. I review ACFM reports daily to make sure their data and information are correct and answer any technical questions from my Level IIs. With the ACFM units we use, I can remotely collaborate, watching technicians as they inspect. I also train technicians in our shop or at a tech center in Houston.

CAN YOU TELL ME ABOUT YOUR INVOLVEMENT WITH ASNT?

I recently joined the "Faces of NDT" program and love it.

I'm going to ASNT's Hill Day in Washington, DC, to talk to legislators about NDT. A lot of people don't know about NDT, so getting to talk about it is a cool part of being a Face of NDT. This past year, I also received the Lou DiValerio Technician of the Year award—that was pretty awesome.

WHAT WOULD YOU SAY HAS BEEN YOUR GREATEST CHALLENGE IN YOUR NDT CAREER SO FAR?

The biggest challenge is making sure you're doing your job ethically. You don't want anybody to influence your decisions. And I think that happens to a lot of people in our industry—everybody wants everything to be approved and signed off on by the technician, but you have to be able to say no, to make sure you're doing stuff ethically.

WHAT ADVICE WOULD YOU GIVE INDIVIDUALS WHO MAY BE INTERESTED IN A CAREER IN NDT?

In this industry, you can make good money, and I think a lot of people are looking to make great money as soon as they get out of community college. But somebody told me, think about the education and the training that you need. When I came out of community college, I had multiple offers to go to different places. I ended up choosing a job where I got a lot more experience than I would have if I'd picked the place offering me more money. So, I would tell anybody coming into this industry, don't always look for the money. Sometimes the experience will help you get further than looking for the money right away. **ME**





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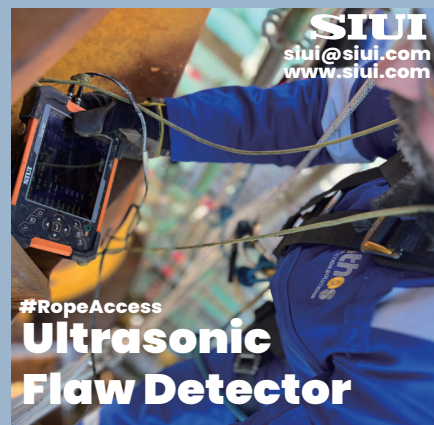
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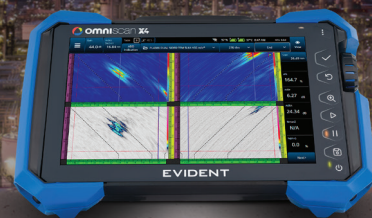
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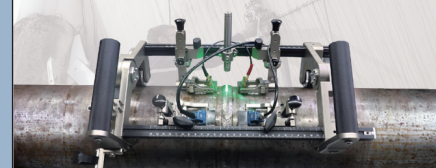


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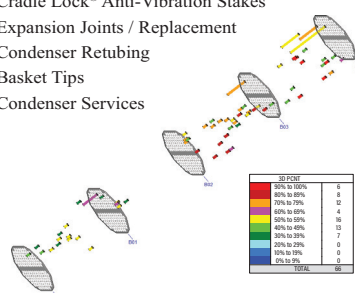
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SNACKTIME TAP-TESTING

This picture was taken during behavioral studies conducted at the Duke Lemur Center at Duke University in Durham, North Carolina. Dr. Ehsan Dehghan-Niri is feeding an aye-aye by placing its favorite food in his hand, forming a fist to resemble a cavity. The aye-aye uses its specialized middle finger, which it employs for tap-testing in the wild, to probe the hand, mimicking its natural foraging behavior. Since aye-ayes are nocturnal, the red lighting replicates their natural nighttime environment, ensuring they remain comfortable and exhibit typical behaviors.

SUBMITTED BY EHSAN DEHGHAN-NIRI, PHD, ASSOCIATE PROFESSOR, SCHOOL OF MANUFACTURING SYSTEMS AND NETWORKS, ARIZONA STATE UNIVERSITY, TEMPE, AZ

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