

BEYOND ROBOTICS, MATERIALS, AND SENSING: UNVEILING BIOINSPIRATION IN NONDESTRUCTIVE EVALUATION FROM "NATURE'S NDE SPECIALISTS"

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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

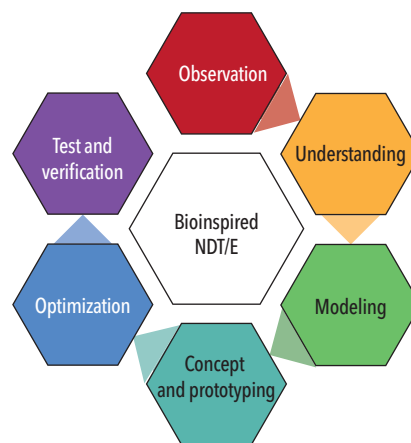


Figure 1. Key steps in transforming bioinspiration into nondestructive testing/evaluation tools and technologies.

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. 

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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

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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

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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