Enhancing Biomimetic Design of Tap Scanning Sensors through High-Resolution Thermal Camera-Based Behavioral Studies

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ABSTRACT

Researchers conventionally employ thermal imaging to monitor the health of animals, observe their habitat utilization, and track their activity patterns. These non-invasive methods can generate detailed images and offer valuable insights into behavior, movements, and environmental interactions. The aye-aye *(Daubentonia madagascariensis)*, a rare and endangered lemur from Madagascar, possesses a uniquely slender third finger evolved for tapping surfaces at relatively high frequencies. The adaptation enables acoustic-based sensing to locate cavities with prey in trees to enhance their foraging abilities. The authors' previous studies have demonstrated some descent simulating dynamic models of the aye-aye's third digit referenced from limited data collected with monocular cameras, which can be challenging due to noisy and distorted images, impacting motion analysis adversely. In this proposed research, high-speed thermal cameras are employed to capture detailed finger position and orientation, providing a clearer understanding of the overall dynamic range. The improved biomimetic model aims to enhance tap-testing strategies in nondestructive evaluation for various inspection applications.

Keywords: aye-aye, thermal imaging, tap-testing, nondestructive evaluation, biomimetic modeling

1. INTRODUCTION

Bio-inspired design, also known as biomimicry, is an innovative approach that draws inspiration from nature's time-tested solutions to complex challenges. Engineers, designers, and researchers aim to create more efficient, sustainable, and resilient technologies by emulating biological strategies, structures, processes, and systems in the natural world. This interdisciplinary field encompasses various disciplines, including biology, engineering, materials science, and design, and it seeks to harness the wealth of knowledge accumulated through billions of years of evolution. Through bio-inspired design, solutions to human problems can be developed by understanding, imitating, and adapting the ingenious designs and processes found in living organisms. From Velcro inspired by burdock burrs[1] to high-efficiency wind turbine blades inspired by humpback whale flippers,[2] the applications of bio-inspired design are diverse and continually expanding, offering innovative solutions across industries such as transportation, architecture, robotics, and medicine. Numerous research endeavors have affirmed the viability of incorporating biological inspiration in the initial design phases to foster innovative solutions,[3,4] which has documented a rise in the uniqueness of conceived concepts compared to traditional brainstorming methods.

Different animals exhibit unique adaptations that have evolved in response to their habitats. One such species that has gained significant attention over the years is the aye-aye, a nocturnal lemur native to Madagascar. Aye-ayes have a distinctive appearance, including large ears, rodent-like teeth, and an elongated middle finger for extracting insects from tree bark[5] as seen in Figure 1. They employ percussive foraging methods, tapping on the wood surface to locate cavities containing insect larvae.[6] This tapping behavior, facilitated by their specialized finger, highlights their exceptional adaptation to their habitat, setting them apart from other species in their environment. Using multiple sensory modalities, such as visual, olfactory, and acoustical hearing, aye-ayes detect

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and identify the location of larvae worms inside trees.[7] Through detailed studies of their tapping behavior and the morphology of their specialized finger, researchers seek to unravel the intricacies of aye-aye biology and gain insights into the adaptive mechanisms that have shaped their evolutionary trajectory.[8–10]

Tap-testing sensors have diverse applications across industries, playing vital roles in structural health monitoring, non-destructive testing, material characterization, and quality control. Furthermore, tap-testing sensors contribute significantly to characterizing the mechanical properties of materials, identifying damage in composite structures, and advancing research and development endeavors in engineering and materials science. Their capability to analyze acoustic responses to tapping facilitates accurate evaluation of structural integrity, defect identification, and optimization of material performance, thereby enhancing safety, reliability, and efficiency in various applications. However, despite their countless capabilities and advantages, tap testing may encounter challenges in certain scenarios. One common issue is interpreting the results, especially when analyzing complex structures or materials with varying properties. Another challenge is the need for skilled operators to accurately interpret the acoustic responses and distinguish between normal and abnormal tapping sounds. Without proper training and expertise, there is a risk of misinterpreting the results and overlooking potential defects.[11] To address this limitation, an alternative approach inspired by nature's efficiency and objectivity in signal analysis could offer a promising solution. By drawing inspiration from biological systems and their innate ability to discern subtle cues and patterns, a bio-inspired tap testing method could enhance the objectivity of signal analysis, mitigating the challenges associated with traditional approaches.[12,13]

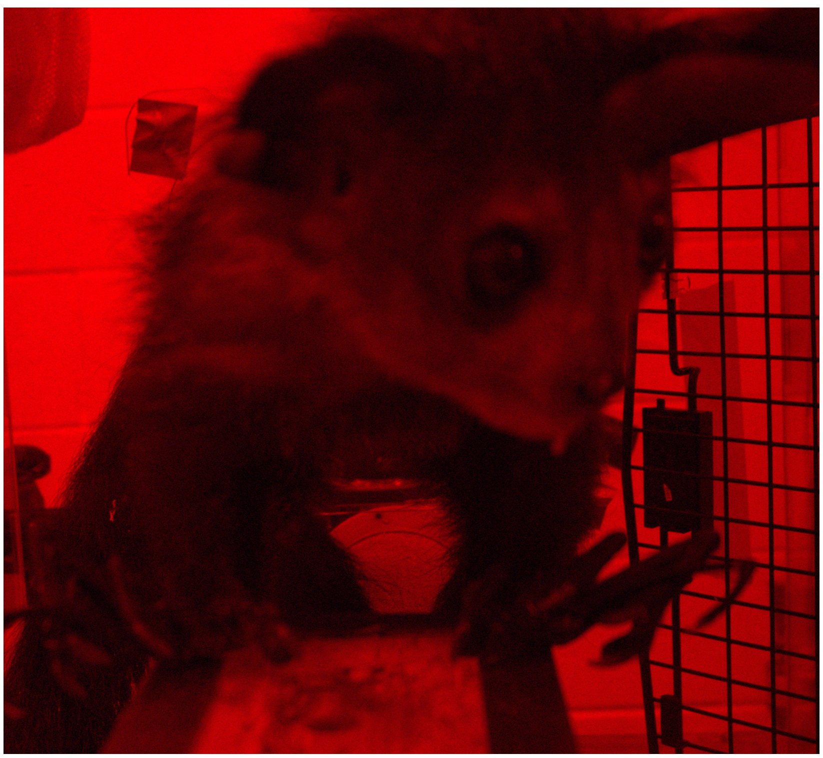


Figure 1. An aye-aye interacting with a customized wooden foraging box in a scaled-down version of their home enclosure.

This research aims to advance behavioral studies to refine the methods used to develop a bio-mimetic tap-testing sensor.[9,10] To achieve this goal, a specialized enclosure with an attached foraging box was designed to facilitate interaction and tapping behavior by the aye-aye, thereby aiding in cavity localization. The study was conducted under low-light/red-light conditions to mimic the preferred nocturnal environment of these primates. Multiple camera systems were used to capture the tapping behavior of aye-aye's middle finger. Utilizing a motion tracking algorithm, Kinovea, the motion trajectory of the middle digit was analyzed and compared to data obtained from previous color camera recordings. For further elaboration, readers are directed to Sections Methods and Experimental Setup, where comprehensive details regarding the research methodology and experimental configuration are provided. Then, the article delves into some concise discussions, offering interpretation of the obtained results. Lastly, the conclusions section summarizes this investigation's significant findings and insights, emphasizing the potential advantages of high-speed thermal imaging for motion analysis.

2. METHODS

Animal motion capture studies traditionally involve precisely recording and analyzing their movements to understand their biomechanics, behavior, and locomotion patterns. By employing specialized equipment such as cameras, sensors, and markers, researchers can track the motion of animals in various environments and contexts. These studies provide valuable insights into the capabilities and adaptations of different species, shedding light on evolutionary, ecological, and physiological aspects. Motion capture technology allows for the detailed examination of animal movements, facilitating research in biology, biomechanics, ethology, and robotics. These studies use markerless 3D motion capture techniques for studying animal locomotion. One of the main challenges of traditional marker-based methods presents a novel approach using computer vision algorithms to track and analyze movements without the use of physical markers[14] and also on its application to understanding animal locomotion, particularly in the context of biomechanics and behavior research. It evaluates the effectiveness of the markerless system in capturing various types of movements and discusses its potential for providing valuable insights into animal locomotion patterns. Overall, the paper highlights the advancements in motion capture technology and its significance in advancing our understanding of animal behavior and biomechanics.

Thermal imaging has become essential for investigating animal behavior, offering valuable insights into physiological responses and thermal dynamics.[15] By capturing thermal radiation emitted by animals, thermal cameras can detect alterations in surface temperature, providing indications of key physiological processes such as metabolism, circulation, and thermoregulation. In animal behavioral research, thermal imaging enables researchers to non-invasively monitor temperature fluctuations across various body regions, uncovering patterns linked to stress, activity levels, and social interactions.[16] For example, researchers have employed thermal imaging to assess the influence of environmental factors on animal well-being, including evaluating thermal comfort in livestock under diverse housing conditions and studying the physiological stress response in wild animals subjected to human disturbances.[17] Additionally, thermal imaging yields valuable insights into animal locomotion and energetics, as temperature gradients can reveal areas of heat generation or dissipation during movement. Another significant benefit of thermal imaging is its capability to observe animals and their activities in challenging environments, such as low-light conditions or underwater.[18]

Several research teams have initiated behavioral investigations to gain an understanding of different aspects of the motion dynamics displayed by the middle finger of the aye-aye while tapping.[9,10] Given the predominantly nocturnal nature of this creature, many of these experiments are conducted in environments characterized by low-light or red-light conditions, utilizing standard or high-frame-rate cameras. While this approach is effective for observing animals' behavior and their interactions with objects in their surroundings, the resulting images often suffer from noise and distortion due to the low-light conditions. This limitation hinders gathering additional information about muscle excitation or heat generation induced by tapping behavior. Moreover, it can pose challenges in understanding the tapping process itself. Therefore, there is a need for techniques that provide a deeper understanding of how the animal interacts with wooden blocks and taps the surface to locate mealworm-loaded cavities, as depicted in Figure 2(b).

2.1 EXPERIMENTAL SETUP

To examine the dynamic movement of the aye-aye's middle finger, a customized plexiglass enclosure was constructed, aiming to recreate their natural habitat, illustrated in Figure 2(a). This enclosure replicated its surroundings by integrating a plastic pipe coated with fine granular sand to emulate the rough texture of a tree branch. Moreover, a foraging block filled with mealworms was strategically positioned at the pipe's center to entice the aye-aye, as depicted in Figure 2(b). The foraging box comprises a single channel with attached lures and various adjustments in channel depth (D) and width (W) to examine the finger's motion dynamics across different D and W parameters.

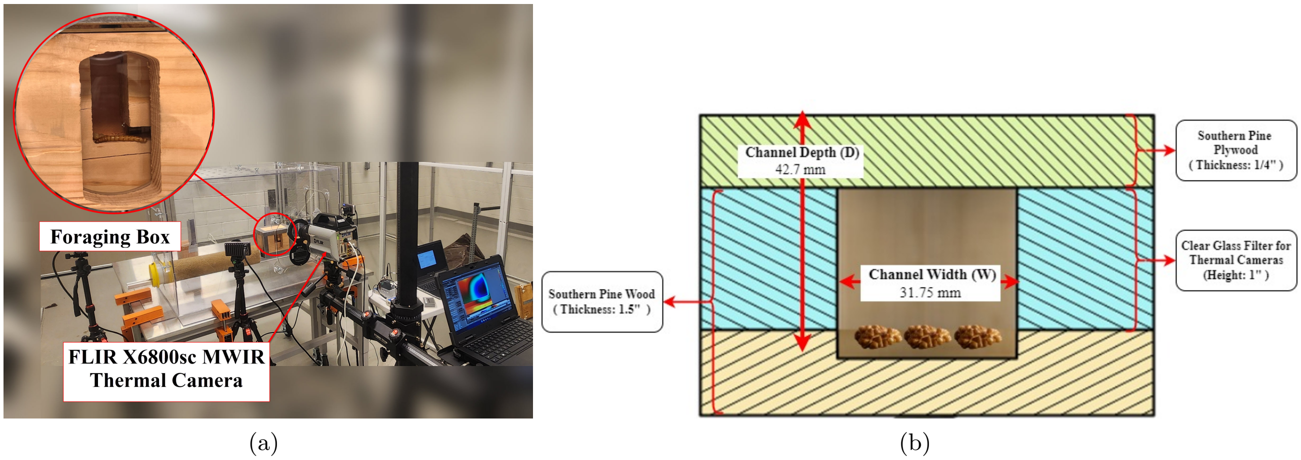


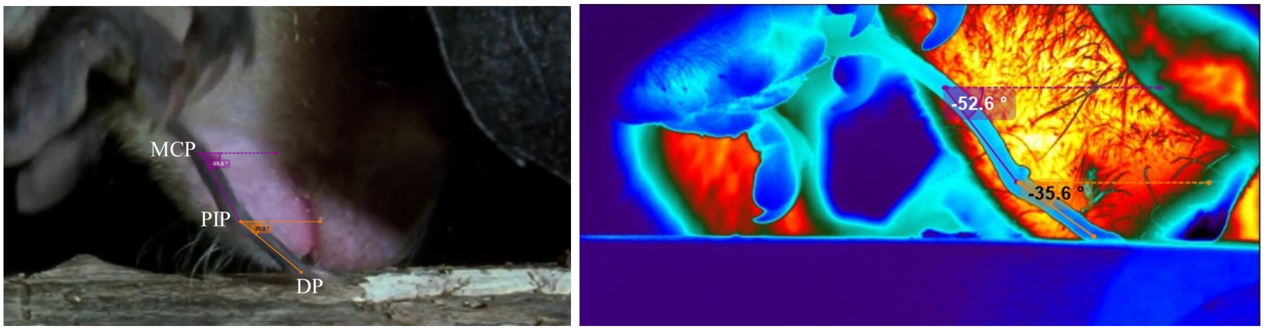
Figure 2. Experimental setup employed for the behavioral study at Duke Lemur Center consisted of (a) a plexiglass enclosure with a centrally positioned foraging box and (b) a cross-sectional CAD representation of the foraging box.

To monitor the finger's dynamic movement, a FLIR X6800sc thermal camera is utilized, which can provide valuable insights into the temperature variations associated with the tapping behavior of the aye-aye. This camera is known for its high-speed capabilities, recording up to 520 frames per second (FPS) at a resolution of 640 × 512 pixels. It enables precise tracking and analysis of such rapid movements under low-light conditions. By capturing these thermal images at such high speeds, researchers can visualize the rapid tapping movement as well as observe subtle changes in the temperature distribution across the middle finger, which can also provide information that can indicate physiological responses, thermal dissipation during exertion, or even detect anomalies such as inflammation or injury. Moreover, comparing the finger tracking analysis using the FLIR X6800sc thermal camera with high-speed conventional cameras offers a comprehensive perspective on finger movement dynamics. While conventional cameras provide visual data, thermal cameras provide additional information based on temperature changes. This dual approach enhances the understanding of how fingers move in response to stimuli or activities, facilitating advancements in biomechanics, human-computer interaction, and medical diagnostics.

The data collected from this experimental configuration is processed using Kinovea, a markerless motion-tracking software. Puig-Divi et al. assert Kinovea's reliability, precision, and validity in extracting angle and distance data from coordinates.[19] Their study illustrates the software's consistency across different raters and within the same rater, thus bolstering its credibility. Moreover, Shishov et al.'s investigation underscores Kinovea's proficiency in capturing whole-body kinematics from real-world video footage.[20] Some preliminary results are obtained from the experimental setup discussed in this section.

3. DISCUSSION

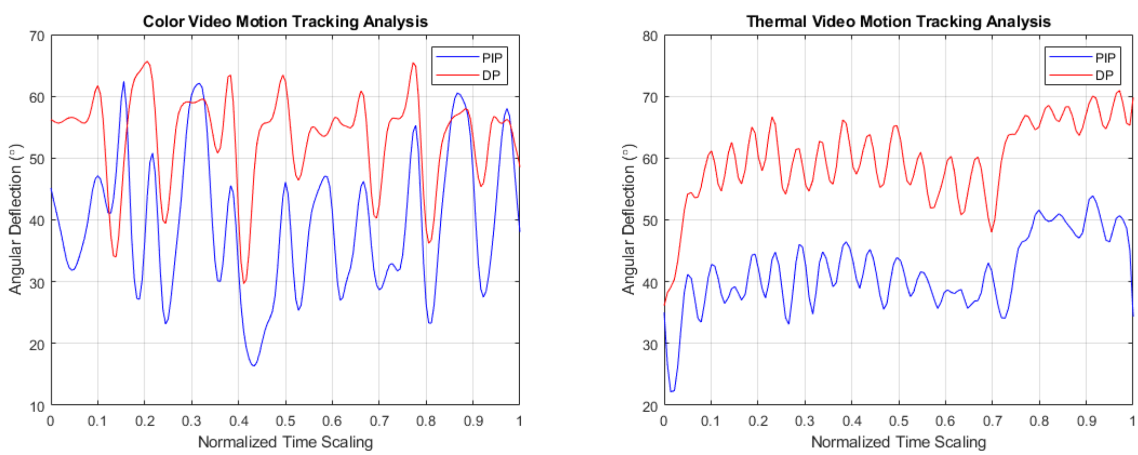
To track and analyze the dynamic movement of the middle finger, researchers often employ a methodical approach involving the placement of minimal markers on the video frame at their respective locations to monitor the movement of the metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP), and distal interphalangeal joint (DP) (see Figure 3). While analyzing the motion path of the entire finger, it is common to simplify the analysis by positioning each marker along the center of the respective joint. This simplification facilitates a more focused examination of joint movements and allows for a clearer understanding of overall finger motion patterns. However, it is important to note that while this approach provides valuable insights, the motion of each joint may not be uniform throughout different experiments as the aye-aye's tapping behavior is completely randomized. The PIP and DP joints are crucial components of the aye-ayes finger anatomy, and their flexion (bending) motion plays a significant role in shaping overall tapping behavior. By understanding how these joints contribute to finger movement dynamics, researchers can better comprehend the underlying mechanisms involved in their process of percussive foraging.



(a) (b)

Figure 3. An aye-aye tapping on a wooden surface is depicted in the following images: (a) captured by a standard color video camera and (b) captured by a FLIR thermal camera.

The comprehensive angular flexion of both joints was monitored using footage obtained from a standard color camera and a thermal camera. As these cameras operate on different time scales and the recorded videos are not synchronized due to the unpredictable tapping behaviors of the aye-aye, the signals from both sources are aligned on a simplified time scale ranging from 0 to 1 for normalization. As depicted in Figure 4(a), it is quite apparent that motion tracking conducted with standard color cameras yields noisy outcomes, posing challenges for accurately tracking these markers and potentially resulting in inconsistencies. This was compared with the results obtained from previous studies.[9] However, the motion tracked by thermal imaging cameras is notably more precise, attributed to the detailed visual data acquired from temperature variations. Thermal imaging captures nuanced temperature differences, allowing for enhanced accuracy in motion tracking compared to standard color cameras, as shown in Figure 4(b).



(a) (b)

Figure 4. Motion Tracking analysis done to depict the angular deflection of the PIP and DP joint (a) Video obtained from a color camera (b) Video obtained from a thermal imaging camera.

While comparing these two graphs, it is crucial to acknowledge that both sets of analyzed data exhibit a consistent trend in motion for each joint. Despite potential differences in the precision and accuracy of motion tracking between the standard color and thermal imaging cameras, both datasets demonstrate a parallel movement pattern for each joint. This consistency suggests that the overall motion characteristics remain comparable across the two imaging modalities despite any variations due to the image quality or the noise levels of the captured data.

4. CONCLUSION

The setup outlined in this study aims to experimentally explore the tapping behavior of aye-ayes by introducing a lure placed within a foraging box inside a controlled environment. This unique foraging behavior, known as tap scanning' or 'percussive foraging,' enables the animal to differentiate between the distinct tones emitted by different types of wood during tapping. Subsequently, data from these behaviors is captured using a high-speed thermal camera and processed through a markerless motion tracking algorithm to analyze the various movements of each joint. The results obtained from the thermal camera motion analysis method are then compared with previous findings to assess the effectiveness of employing such techniques for analyzing the motion of nocturnal animals. Ongoing research focuses on investigating the overall temperature fluctuations of the finger and their impact on finger motion dynamics. The proposed setup could be simulated as the next step to calculate temperature variations and observe their effects on motion trajectories. These findings could then be implemented into the existing hardware model to enhance its tapping capabilities and further utilized for testing structural defects in composite materials.

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