3D SOUND LOCALIZATION OF BARK BEETLES WITH ACOUSTIC HOLOGRAPHY

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OPPORTUNITY STATEMENT

Bark beetle infestation of trees has the potential to devastate large areas of forests and areas[1]–[5]. Drought affected trees are particularly vulnerable to bark beetle damage as they tunnel under the bark, in particular hindering its ability to transport water[6]. In recent years, trees that are commercially and ecologically important species to the state of Arizona, are increasingly under stress due to the activity of the beetle. These infestations may cause large economic loss and infested trees need to be removed rapidly to minimize the spread of further infestation. Novel approaches have been developed to deter the beetle from entering trees, including the use of acoustics at a specific frequency range to create a deterrence sound [7], [8]. Wood-boring beetles have been examined using laser doppler vibrometry as a bio-acoustic detection tool on a localized scale[9]. To aid in the detection of bark beetles and other pest insects, transformative technologies are required which can quickly reveal their presence in trees non-invasively and in-situ.

PROPOSAL SUMMARY

Holography, formed from the Greek words Holo (whole), and graphe (write), is a 3D imaging technique that makes use of a hologram: the interference between a reference wave and a wave emanating from the specimen called the object wave[10]–[12]. It was first investigated by Dennis Gabor in 1948, while he was working to improve upon the resolution of electron microscopy. Acoustic holography is a sound wave measurement technique, which allows for the accurate 3D localization of sound emitting sources[13]–[18]. The interferogram recording of the object and reference acoustic waves in a hologram, allows one to reconstruct the entire sound field from the sample area throughout a 3D region of space. The process of reconstructing acoustic holograms is illustrated in Figure 1. An object sound wave transmitted from an object, and a reference wave produced by the microphone transducer, interfere at the surface of a N-element detector array. The holographic interference pattern formed on the array is then recorded and stored. The interference between the object wave $o(\xi,\eta)$ transmitted by the object located at the object plane and the reference wave $r(\xi,\eta)$ is recorded in the hologram plane (ξ,η). The complex amplitude of the interference pattern at the hologram plane is,

$$U(\xi,\eta) = o(\xi,\eta) + r(\xi,\eta) \quad (1)$$

These two wavefronts are recorded directly on the surface of the detector, and are expressed as,

$$h(\xi,\eta) = U(\xi,\eta).U^*(\xi,\eta) \quad (2)$$

The interference pattern is then mathematically described by,

$$h(\xi,\eta) = |o(\xi,\eta)|^2 + |r(\xi,\eta)|^2 + o^*(\xi,\eta)r(\xi,\eta) + o(\xi,\eta)r^*(\xi,\eta) \quad (3)$$

The measured signal from the detector array is connected to analog-to-digital converters (ADC) so that measurements may be recorded and stored on a computer. In acoustic holography the recorded hologram is reconstructed computationally by using numerical algorithms to backpropagate the recorded field to the original object position. The processed hologram provides high-precision acoustic phase measurements from the object as shown in the processed image in Fig. 1 which maps the contrasting vibrational modes created by the guitar. The acoustic holography technique allows for highly accurate sound maps to be made using measurements made simultaneously and at multiple points next to the object, thus allowing for high-speed imaging. This also has the advantage that one may use a hand-held microphone array as envisaged in this proposal. The use of a camera at the center of the microphone detector array, works in tandem with the microphone array holographic image and allows for the user to 3D locate the sound source position and map the sound accurately. The analyzed images show the sound levels as a color representation originating from the test object, with the sound maps overlaid with the camera images for precise association to the test object. The significant advantage of the acoustic holography technique vs. other acoustic and vibrometry measurement techniques, is that a wide range of data is available from the holography measurement, including the acoustic pressure, particle velocity and acoustic intensity, directivity, field gradient, and total power radiated, which all combined provides a much richer picture of the sample area.

Acoustic holography is carried out using one of the two primary recording methodologies. The first method is far-field acoustic holography[19], and the second technique is that of near-field acoustic holography (NAH)[13], [14], [20]. Far-field holography is performed with a relatively large distance between the originating sound area and the detector, with the resolution limited to approximately half the wavelength. Near-field on the other hand is performed much

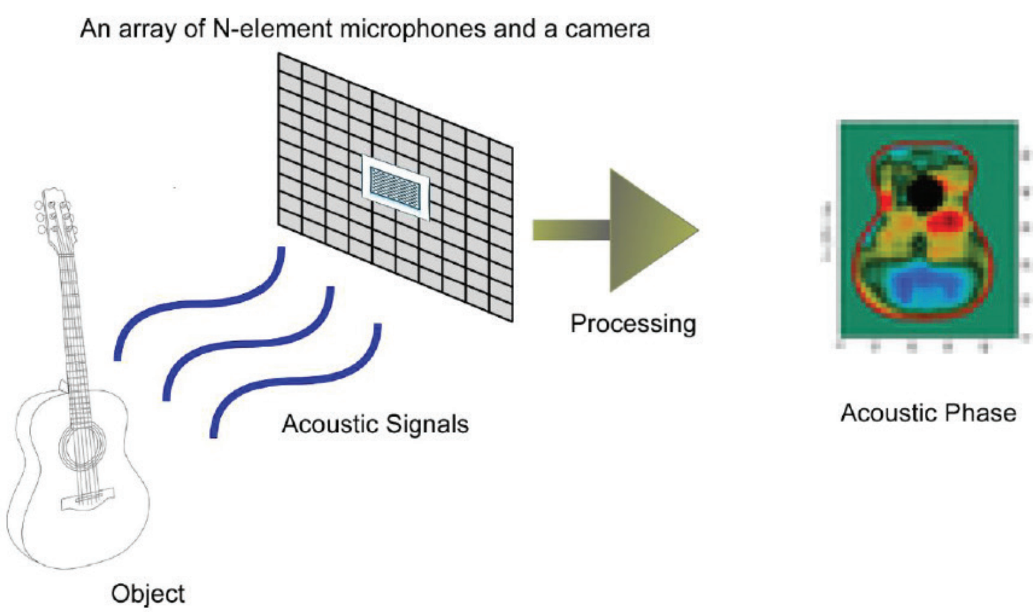


Figure 1: The process of recording and reconstructing an acoustic hologram.

closer to the object and utilizes a created evanescent wave, resulting in much higher spatial resolution. Acoustic holography has been used extensively in several industrial settings to detect noise and vibrational sound issues, including gas leakage[15], train noise[21]–[24], the automotive industry to investigate engine, interior and other vibrations and noises[25], [26], and the aircraft industry to determine the location of interior cabin noise and fuselage noise[27]–[29]. It has also been utilized for plant disease detection[30].

In this proposal we seek to develop a novel hand-held Acoustic Holography Detection System (AHDS) for the accurate 3D localization of bark beetles which exploits their various emitted acoustic sounds in the frequency range (3–12 kHz) as a detection signal[31], [32][33][34]. In addition, we plan to use the AHDS to investigate the overall health of trees. The development of the AHDS system will be carried out in the PI's metrology laboratory here at Northern Arizona University (NAU). The creation of a detection system that is capable of accurately locating bark beetles in a 3D region of space, will be critical for developing next-generation beetle and other wood-boring insect elimination strategies. The successful demonstration of the proposed system will be of interest to not only the Arizona Department of Fire and Forestry Management, but more broadly to forestry management and protection agencies across the US.

PROPOSAL ADVANTAGES

An example of the acoustic holographic 3D mapping of sound noise at 1 kHz from a single microphone array can be observed in Fig. 2 which displays the analysis results of an automotive engine. In Fig. 2 one can observe the sound wave distribution across the engine, with the red color areas corresponding to regions with a greater sound pressure intensity. High-speed recording and processing of the data allows for measurements which enable a user to monitor the shape changes of the object, with images that render 3D sound maps on a 3D model of the object. The acoustic holography technique is non-contact/non-invasive and only requires the microphone array to be placed close to the object area to record the measured signals.

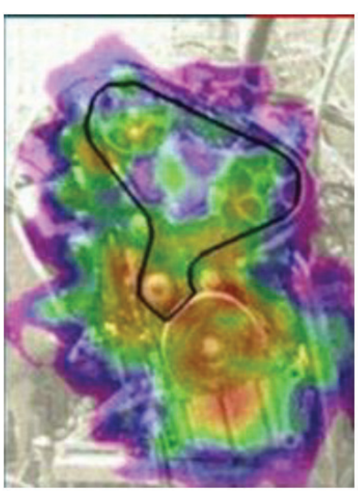


Figure 2: Acoustic holography processed image displaying 3D sound localization from an automotive engine. Sound transmission localization may be easily quantified.

We plan to build the NAH microphone detector array using 64 precision microphones (Bruel-Kjaer type 4968 microphone cost range from $120 - $200 depending on availability/vendor) which will allow us to perform high resolution near-field acoustic holography measurements. We initially will create a square shape for the detector array, using fixed 2 centimeter horizontal and vertical spacing between each microphone. There are several examples in literature of low-cost microphone arrays being developed for Near-Field Acoustic Holography[35]. This link (https://pub.dega-akustik.de/DAGA_1999-2008/data/articles/001416.pdf) for example demonstrates that an effective NAH microphone array can be built for relatively low-cost. Commercial vendors also offer microphone arrays for NAH, such as https://www.sorama.eu/blog/microphone-array for example. While the commercial route for purchasing a microphone array for NAH is simpler, and reduces complexity and time, the advantage of building the microphone array in-house is that we can specifically choose microphones with the required frequency response range, as well as be able to shape and size the area (may want to look at larger areas of trees for example) of the detector as needed to match the object under investigation. We have a long-term eye on portability and cost-effectiveness of the device for public usage. For the detector design and creation, we will consult closely with the MakerLab at NAU (https://nau.edu/library/makerlab/) to design and 3D print some of the design components. We have budgeted aluminum rods (sturdy) for the array framework, but preferably 3D printing would be more cost effective and the route we will seek.

Figure 3 shows the proposed imaging process using the mobile AHDS. The measured data from the hand-held acoustic camera is Fourier-transformed into the frequency domain, with a set of holograms for each frequency subsequently created. Each hologram is then repropagated back to the source surface by multiplication with the corresponding Point Spread Function and the field is then recomposed by superposition of all these waves. The acoustic sound map after processing reveals the sound positioning of any sound emitting sources within the sample area.

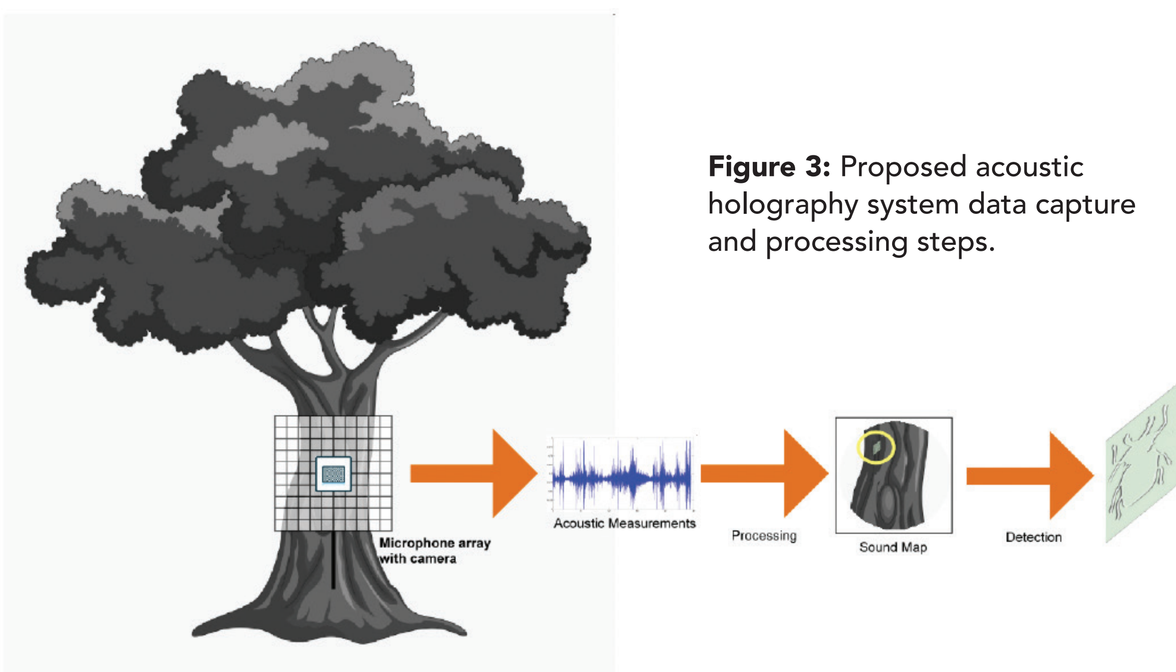


Figure 3: Proposed acoustic holography system data capture and processing steps.

SCOPE OF WORK

Specific Aim 1: Perform simulations to determine AHDS operating system parameters

- Use of Finite-Different Time Domain (FDTD) programs with the program COMSOL to simulate acoustic reflected wave from the bark/trees (including infested/non infested differences)
- Investigate the main signal differences we can expect based on the sample type and guide can we tailor the AHDS based on the simulation data.

Specific Aim 2: Construction of the Acoustic Camera

- Develop and construct the microphone array (work with the NAU Makerlab to develop the framework for the construction for the array).
- Creation and testing of the software for the processing of measured holographic acoustic data.

Specific Aim 3: Experimental testing using the AHDS instrument

- Work with AZ Department of Forestry and Fire Management Forest specialists to evaluate the acoustic holography system on selected trees in-situ and samples.
- Determine operating parameters for the tool, including ideal frequency range, field of view, detector properties, detector area, and ideal resolution requirements etc.
- Investigate microphone detector arrays that are not rectangular, which may give more flexible array options for moving objects and hard to get to areas.
- Capturing transient noise events in detail – determination of what temporal changes can be observed.
- Investigate how far we can extend the frequency range limit, allowing good sound power estimates over a broadband frequency range from a single measurement.

Specific Aim 4: Correlate measurements across a tree sample

- Generate inspection data associated with various infestation steps in trees – explore how signals changes across an infested tree or area or between different signaling emitting by the bark beetles related to them under stress or other activities.
- Correlate our data with data taken by other instruments or projects such as Laser Vibrometry – explore a combined macro-micro scale imaging approach by the combination of techniques.

Specific Aim 5: Determine how measured parameters can be used to efficiently flag detection e.g.

- Data will be correlated between different locations on the object area and in time to verify accuracy of measurements.
- Specificity - identify the presence of the bark beetle vs. other wood inhabiting insects.
- Repeatability and reliability testing will be important for the device in detecting the to be accepted widely.

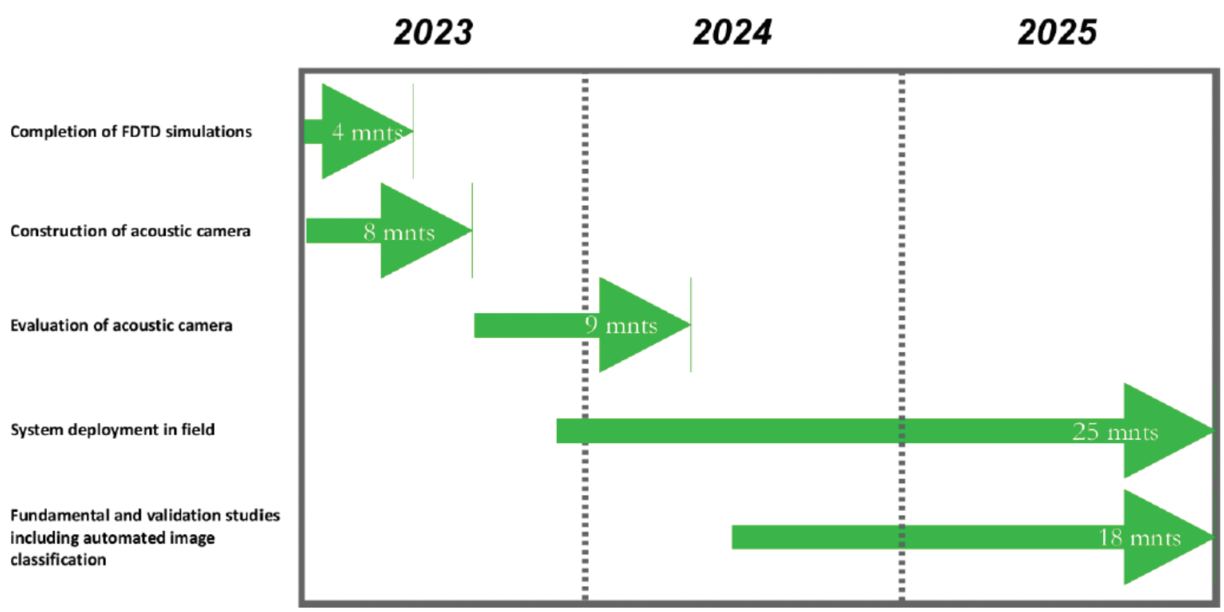
Specific Aim 6: Identify and catalogue a wide range of infestation types and trees for rapid identification in future scans.

- Pattern matching on image data will be performed by adapting existing techniques of automated defect classification to detect beetles and larvae from the acquired data.

Specific Aim 7: Investigate tools together to form an automated inspection system which can be easily integrated into outdoor and rugged environments

- Develop basic computational routines that can transmit sample data as high-speed feedback to a controller and to each instrument.
- Provide an inspection system specifically tailored to enable proficient image capture, data transfer and storage as well as high speed feedback to the user.
- Use of the electron microscope located at NAU to investigate the structure and morphological changes in infested tree samples and the bark beetle in combination with AHDS data. Investigate creating an overall assessment for the health of tree from a plurality of data.

Deliverables



Team Members

Christopher Mann (PI): Prof. Christopher Mann is an Associate Professor in the Department of Applied Physics and Materials Science. His research interests are in holography, optical metrology, interferometry, digital holography, deep learning and artificial intelligence, and remote sensing. More specifically, his focus is on developing new methods for nondestructive testing and analysis, image processing and image-based metrology using holography and interferometry. He was awarded a Eugene P. Wigner postdoctoral fellowship at Oak Ridge National Laboratory. Through his work in optical interferometry, he has made contributions in several application areas using holography, including industrial inspection, biological microscopy, for which he has 3 approved patents (with 2 currently in review). He has extensive experience in the use of optical design software such as Zemax, optical design and prototyping, and is proficient in the use of several programming languages. Dr. Mann leads the Optical Metrology Laboratory, which conducts applied optics and holographic and wavefront theory research and development addressing issues of industrial and economic competitiveness, biomedical measurement science, and national security.

Miguel Yacaman (Co-PI): Professor Miguel Jose Yacaman, is an internationally recognized expert in TEM with vast experience in running microscopy cores. Dr Jose Yacaman's research is very broad, and he has made contributions in several fields of Physics, Materials science, and Nanotechnology. The recent focus of his research has been the correlation of structure and properties in nanomaterials. He has developed Electron microscope methods to study nanoparticles and 2-D materials. He has published more than 550 papers in peer review journals. During his career he supervised around 100 graduate students and Postdoctoral fellows. His present interest is to develop the nanoscale equivalent of High Entropy Alloys and to develop new catalysts to produce cleaner fuels. For this proposal Dr. Yacaman will provide support for the electron microscopy analysis of tree samples, as well as provide mentorship for graduate student support.

Angel Martinez (Co-PI): Dr. Angel Martinez is a new Assistant Professor in the Applied Physics and Materials Science Department at NAU (started fall 2022). His research experience spans many kinds of soft matter systems, including polymers, colloids, and liquid crystals, having explored ways to shape and guide their structural self-organization using light and surface functionalization. He has extensive experience in 2D and 3D optical imaging of liquid crystals and liquid crystal colloids via techniques such as polarized optical microscopy, multi-photon nonlinear imaging and holographic particle tracking. Some of his current interests include developing machine learning algorithms to reconstruct complex 3D structures in soft materials from 2D optical data, probing the molecular dynamics and organization of the mysterious nanophases confined within liquid crystal defect cores, and studying shear-induced ordered structures in freely suspended liquid crystal thin films. For this proposal, Dr. Martinez will help with construction of the holographic detector.

Budget: 3-year budget $548,236

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