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Screening for scorpions: A non-invasive approach to tracking the movements of arachnids in sand

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Summary

Piezoelectric materials are highly sensitive devices capable of transducing mechanical energy into electric voltage. They find application as sensors in a wide variety of commercial and academic fields. Borrowing from the use of these materials in geophysics to measure the transmittance of a wave front through a substrate, and the principles used to locate the epicenter of an earthquake, we used an array of piezoelectric transducers on a much smaller scale to triangulate the position of a scorpion, in sand, as it leaves its burrow to hunt. Such an approach relies on the ability to resolve the surface waves created by a scorpion's footsteps and uniquely identify them against a background of other such waves. Such a passive form of measurement has the benefit of eliminating environmental factors associated with other monitoring systems, such as camera lights, that could change the scorpion's behavior. The work to date has yet to yield a fully functional tracking system but has identified the major obstacles that, when resolved, should yield a sensitive, accurate, and dependable technique. Much progress has been made in resolving issues of sensitivity and reproducibility of signal measurement with the piezoelectric materials currently in use.

Introduction

Scorpions are well suited for scientific study. Their relatively clear ancestral origin makes them ideal for comparative studies, and their unique physiology offers an exceptional platform for investigating the "broader questions of organismal biology" (Brownell, 2001). One of the very interesting aspects of scorpion sensory biology, seemingly unique among terrestrial animals, is their use of vibration-sensitive structures for hunting. These structures, called the basitarsal slit sensilla, are located near the tarsal joint on each of the scorpion's eight legs and can sense the mechanical waves generated by the movements of its prey (Brownell, 2001). In the 1970s and 1980s, Philip Brownell published a series of papers detailing this sensitivity to vibration and how such information is vital to the way scorpions hunt (Brownell, 1977, 1984). Scorpions can determine with remarkable accuracy both the direction of and distance to the origin of a set of waves. Brownell reports that within a distance of 20 cm these estimates are reliable enough to capture a prey item in a single movement, and that signals generated from as far away as 50 cm can be sensed and used for hunting (Brownell, 1977).

This ability is made possible by the wave conduction properties of sand. Unlike many other solids, where seismic velocities are typically on the order of several kilometers per second (Manghnani & Ramananantoandro, 1974), measured velocities in unconsolidated sand are closer to 40–120 m/s (Brownell, 1977) with a theoretical minimum of 13 m/s, as reported by Bachrach et al. (1998). Nervous systems were once thought to be too insensitive to discern the differences in arrival times of waves with the greater velocities measured in solids (Brownell, 1984). Accordingly, when an earthquake strikes, a human can tell when the seismic waves have passed by feeling the "shaking" of the ground, but cannot determine which leg felt the wave first. No known example exists of an organism with sufficient resolution to use mechanical vibrations in a solid substrate to orient itself. In sand, however, the lessened velocity of the waves allows the scorpion to judge the passing of the wave front across each of its legs, making sand a plausible medium for transmitting a biologically useful and unique sensory cue.

Inspired by the ability of a scorpion to triangulate the position of an object of interest based on vibration, we became interested in devising a method of tracking the scorpion itself in a similar manner—a case of hunting the hunter, so to speak. With an array of sensors sufficiently sensitive to resolve the seismic waves generated by a scorpion's footsteps, it seems possible that one could track the movements of a scorpion in a non-invasive way. Traditional approaches to monitoring such movements use a low-light or IR camera for filming. With such methods, however, a certain amount of light is necessarily introduced into the environment. In experiments where total darkness may be desired to limit the scorpion's reliance on visual cues, no completely satisfactory method exists for determining the position and movement of the study organism. With vibration sensors buried within the substrate, measurements would be taken in a passive way, eliminating the need for light sources or other behavior-altering stimuli. It has been the focus of this project to determine if such a technique can be developed, based on preliminary experimentation with inexpensive materials.

Piezoelectric materials

Piezoelectric crystals are transducers that convert mechanical energy into a voltage and vice versa (Mason, 1950). As such, they can be used as sensors by producing a voltage proportional to the amount of strain applied or, with applied voltages they can be used as micromanipulators or motors. The major characteristic common to all materials exhibiting the piezoelectric effect is the lack of a center of symmetry in the crystal structure (Mason, 1950).

These materials are quite common, being used in such varied applications as crash sensors in automobiles, micromanipulators, "key finders" activated by whistling, and in electronic circuitry as filters for eliminating extraneous signals (Mason, 1950; Anonymous, 2004). For our purposes, the most appealing characteristic of these materials is their acute sensitivity, which makes them a candidate for the sensors required to register the very low energy waves that will be produced by a scorpions footsteps.

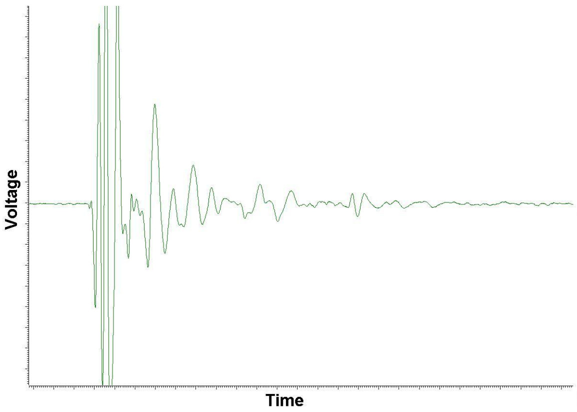
Piezoelectric materials can be specially manufactured to suit a particular application. As an inexpensive alternative, we have been using materials harvested from pre-existing commercial sources (see Methods).

Theory of triangulation

Theoretically, to determine the position of a scorpion, one needs at least three transducers arrayed so as to measure the passing waves from three different positions. The transducers are only able to measure the difference in arrival times of various waves, but from this information two methods for determining the position of the scorpion are available.

The first takes advantage of the fact that packets of waves are typically produced when the surface of the substrate is disturbed. Traditionally, these packets are referred to as primary, secondary, and long waves. Each has a characteristic transmission velocity and thus the tranducer will register their passage at different times—first the primary wavefront, then the secondary, and finally the long waves. If the waves have traveled any appreciable distance, the temporal separation between the arrivals of the various waves should be measurable. The farther the waves have had to travel, the greater the separation in time between their respective arrivals. This separation is predicted to vary linearly with distance traveled, but can appear nonlinear if the distances and depths of transmission are great. The latter factor involves the increasing velocity of the waves with depth, due to the increased compression of the substrate (Longwell & Flint, 1955).

A typical signal from a piezoelectric transducer registering surface waves is pictured below:



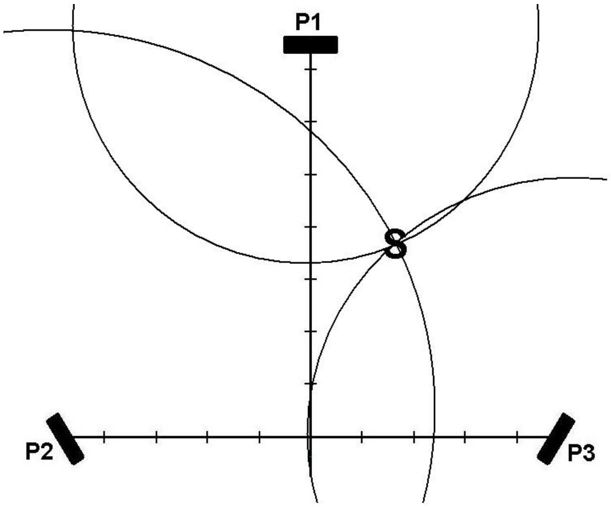
Here, the first few spikes likely represent the passage of compression waves, whereas those that follow are probably due to Rayleigh waves (Mason, 1950). Assuming one can accurately determine the difference in arrival times of these two sets of waves, one can calculate the total distance they have traveled.

Assuming that the increase in separation of the wave fronts is linear with respect to the distance the waves have traveled, one can calculate the distance from their origin to the receiver by solving the following equation for X:

$$X / V_s - X / V_p = t$$

where X = *the distance from the origin to the receiver*
Vs = *the velocity of the second wave to arrive*
Vp = *the velocity of the first wave to arrive*
t = *the time between the arrival of the two waves*

This distance can be represented graphically by a circle of radius X that is centered on the receiver, signifying that the origin of the waves could have been anywhere a radial distance of X from the receiver. If three receivers are used, and three such distances are derived, one can triangulate the position of the scorpion by determining the intersection of the three circles:



Where:

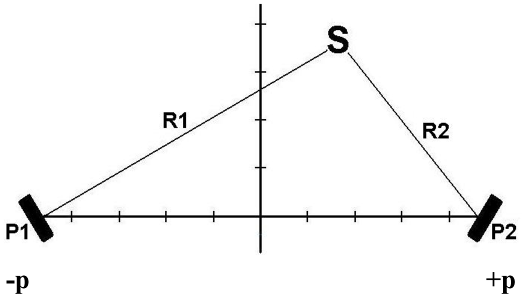
P1, P2, P3 = *Piezoelectric receivers 1, 2, and 3*
S = *Source of the disturbance*

We did not explore this approach for two reasons. First, it relies on the ability to precisely identify the arrival of at least two separate wave types. As will be discussed, one of the greatest difficulties encountered thus far is judging precisely the arrival of a single wavefront. Making two of these judgments for each measurement compounds the difficulty. Second, this approach will require that, beyond the use of surface waves, the more ephemeral compression waves be used. Compression waves spread in three dimensions, as opposed to surface waves that are largely two dimensional, and thus suffer from geometrical spreading to a greater degree than their surface counterparts. Essentially, the energy that interacts with a given receiver diminishes far more quickly with compression waves, making them hard to measure except at close range.

The second approach that can be used to determine the scorpion's position involves looking at the time difference of arrival of the same wave packet at each of the three receivers. One might, therefore, track the arrival of the Rayleigh wave front as it passes across each of the receivers.

If, for example, the source of the waves is equidistant from two receivers, the waves should arrive at the same time. If the source is closer to one receiver than the other, the wave packets will arrive first at the nearer of the two. More quantitatively, for receivers called "1" and "2," placed at "**p**" and "**-p**" on the x-axis respectively, the radial distance from any point in the x-y plane to the first receiver can be expressed as:

$$R1 = SQRT\ [(x-p)^2 + y^2]$$



Where:

R1 = *the radial distance between the source and the first receiver (P1)*
x = *the Cartesian coordinate of the scorpion on the x-axis*
p = *the known position of the receiver (P1 or P2) on the x-axis*
y = *the Cartesian coordinate of the scorpion on the y-axis*

The distance to the second receiver is thus

$$R2 = SQRT\ [(x+p)2 + y2]$$

The difference in the distances is

$$R2 - R1 = SQRT\ [(x+p)2 + y2] - SQRT\ [(x-p)2 + y2]$$

This represents the extra distance the waves must travel to reach the second receiver after contacting the first. This distance can also be expressed as

$$V * t = R2 - R1 = SQRT\ [(x+p)^2 + y^2] - SQRT\ [(x-p)^2 + y^2]$$

Where

V = *the velocity of the wave used for the calculation*
t = *the time difference between the arrivals at the two receivers*

This yields a relationship between the arrival time difference and the x and y position of the scorpion. The equation itself is that of one-half of a hyperbola, as is more easily seen when rewritten in the more familiar form :

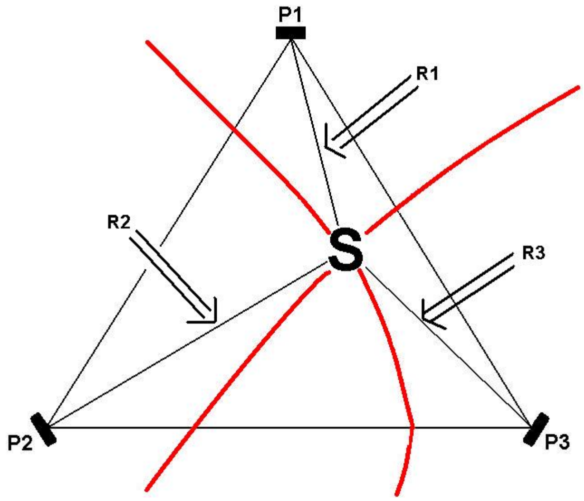
$$\frac{x^2}{t * v/2} - \frac{y^2}{p^2 - t * v/2} = 1$$

Where

t, **p**, *and* **v** *are constant*

A hyperbola describes the set of points for which the absolute value of R2 - R1 is constant (Demana & Waits, 1990). In our case, we are not concerned with the absolute value of R2 - R1 but rather the true value. A positive value for this difference indicates that the scorpion is closer to P1, whereas a negative value indicates the scorpion is closer to P2. Thus, when plotting the graph of the hyperbola, only half of the points are included; those on the side of the conjugate axis shared with the closest receiver.

For any given time difference between the arrivals at two receivers, a series of possible origination points are found by plotting the half of the hyperbola that used the nearest receiver as a focal point. If three receivers are used and the time differences are found between two pairs, two hyperbolas can be plotted. The intersection of these hyperbolas is the origin of the wave fronts.



Representation of the intersection of two hyperbolas generated by the time differences between P1 - P3 and P2 - P3 (the third possible hyperbola is not pictured). Here,

S = *Position of the scorpion*
P1 = *Receiver 1*
P2 = *Receiver 2*
P3 = *Receiver 3*
R1 = *Distance between S and P1*
R2 = *Distance between S and P2*
R3 = *Distance between S and P3*

Assuming that sensors are sensitive and precise enough to register the vibrations produced by the walking of a scorpion, a series of equations similar to those above could be solved to arrive at a position in the defined Cartesian coordinate system that represents the origin of the waves and thus the position of the scorpion at that moment.

Methods

To develop a reliable system of triangulation for tracking a scorpion, the piezoelectric receivers must be both sensitive and reproducible. Various inexpensive commercial sources of piezoelectric materials were explored including those harvested from an antiquated brand of phonograph cartridge from the Astatic company, and those taken from two brands of electric lighters. Other sources have been examined but not tested to this date.

Each transducer was assessed for sensitivity and reproducibility to a signal generated by disturbing the surface of the sand. As this project is still in its trial stages, no single rigorous assay has been developed for comparing the performance of the various piezoelectric materials or determining the effect of the various alterations made to improve the setup. Most of the "data" to this date are either qualitative or based on simple voltage or signal-to-noise ratio comparisons.

The outputs of the transducers were amplified by an AM Systems differential AC Amplifier (Model 1700) and converted to a digital signal by a 1401-plus Analog to Digital Converter (CED, Cambridge, England). Spike II (CED) was used as the data acquisition and analysis software package.

Sand used in these experiments was collected from sandy regions of the Northern Chihuahuan Desert near Kermit, Texas, from areas with healthy populations of sand scorpions (*Paruroctonus utahensis,* in particular). Several small containers for this sand were experimented with, and the best results were achieved in a thick (approximately 2.5 cm) Styrofoam container, with a square internal diameter of 35 cm, filled with sand to an average depth of 20 cm. Good results were also achieved in an electrically grounded metal cookie tin of about 30 cm circular diameter and an average sand depth of 15 cm.

Several methods were used to disturb the surface of the sand, ranging from driving the tip of a pen into the surface, to dropping a small weight from a known height, to allowing a scorpion to walk across the surface.

To test the characteristics of each piezoelectric material, some effort was required to standardize the measurements and to improve the between-trial reproducibility. Steps were taken to filter out extraneous noise, adjust amplification parameters, and improve the sensitivity of the transducers themselves.

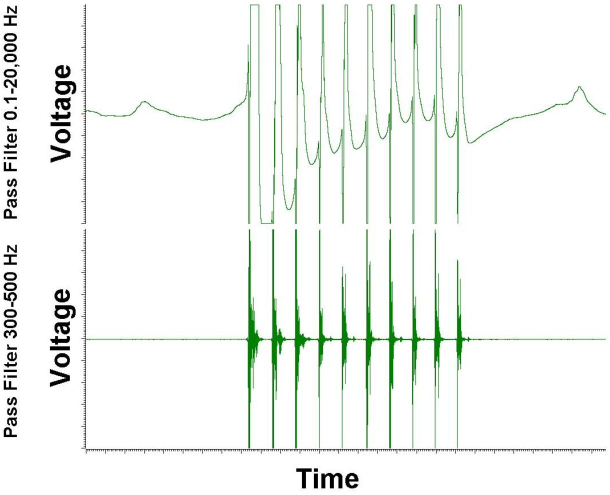
Results & Discussion

The following factors had the most significant effects on the sensitivity and reproducibility of measurement:

- Bandpass filter of the signal from 300–500 Hz to capture the major frequency bandwidth for compression and Rayleigh waves in sand.
- Further insulation of the sandbox from extraneous vibrations.
- Use of a resistor/capacitor (RC) filter to attenuate unwanted frequencies.
- Elimination of unnecessary electromagnetic field effects from the environment.
- Reduction of amplification of the signal to prevent saturation of the amplifier.
- Increasing of the exposed area of the piezoelectric receiving element to improve sensitivity.

Bandpass filtering

The greatest improvement to the signal came by limiting the frequency bandwidth used for amplification. For the AM Systems amplifier, the high pass filter ranges from 0.1 Hz to 300 Hz, and the low pass filter ranges from 500 Hz to 20,000 Hz. With the high pass filter set at 0.1 Hz and the low pass filter set at 20,000 Hz, the signal drifts over a wide range, and distinct wave pulses attributable to a stimulus cannot be identified. Brownell (2001) states that in sand the majority of the signal strength for compression and Rayleigh waves lies in the 300–500 Hz range for distances greater than 10 cm and up to 5000 Hz for lesser distances. On the assumption that either compression or Rayleigh waves would be valuable for triangulation purposes, the signals from the receivers were band passed filtered between 300 to 500 Hz. The result was immediately apparent, yielding a vastly improved signal. It was noted, by independently varying the high and low pass filters, that most of the noise and "drift" was a result of low frequencies. Thus, a high pass filter setting of 300 Hz was necessary, while filtering above 500 Hz was less important. The figure below shows an example of signal improvement with filtering:



Insulation of the apparatus

Most measurements were taken with the sandbox atop a thick foam insulation pad. This reduced the effects of building vibrations but did not completely eliminate them.

To further improve insulation from vibration, the apparatus was placed atop an inertial mass (a very heavy metal sheet) supported by four rubber racquet balls. Theoretically, this should eliminate high frequency noise as the inertial mass will resist high frequency oscillation. The effect of this step was not apparent and not seemingly worth the effort of involving the awkward inertial mass. This follows along with the observations made during bandpass filtering, that the lower frequencies had a greater effect on signal quality and that high-frequency noise is either not present, is attenuated by the sand, or does not seem to effect measurements.

RC filtering

Several trials were conducted using an RC filter as a low and a high pass pre-filter. Unfortunately, during these measurements, the between-trial reproducibility remained poor. Thus, measurements could not be compared for a single piezoelectric receiver with and without filtering, but rather simultaneous measurements between two receivers (one with an RC filter and the other without) were made. Afterward, the filter was switched between the receivers to control for effects other than the filtering.

Following up on similar experiments previously conducted by Stephens & Gaffin (2000), a 99 kohm resistor and a 0.01 microfarad capacitor were used for the filter. For the simple setup we used, frequencies above or below the time constant, or "break point" of the RC circuit will be attenuated. The break point for this RC pair is 1010.1 Hz. Given the preferred frequency bandwidth of 300–500 Hz, this filter will likely work best as a low pass filter. This is confirmed by cursory examination of the effects seen when the filter was used as a high-pass filter; signal quality was either reduced or seemingly unaffected. However, rigorous testing using the device as a low pass filter has not been completed. It may also be desirable to adjust the resistance and capacitance values to better reflect the desired bandwidth of 300-500Hz.

Electromagnetic field effects

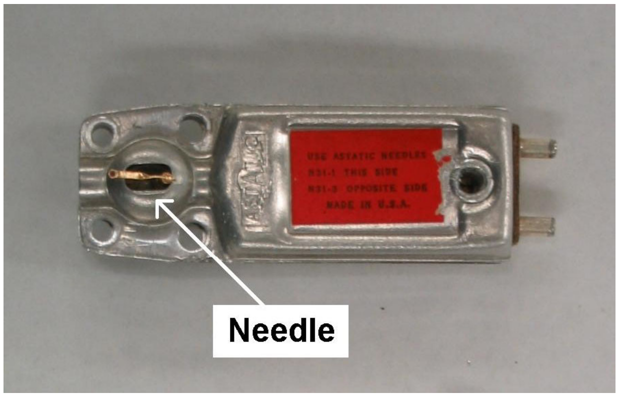
Cables and wiring not associated with the triangulation apparatus may interfere with the measurements. The signal-to-noise ratio improved when all wires near the triangulation apparatus were disconnected and removed. The use of a loosely constructed Faraday cage using window screens and aluminum foil has a yet uncertain effect.

Amplification

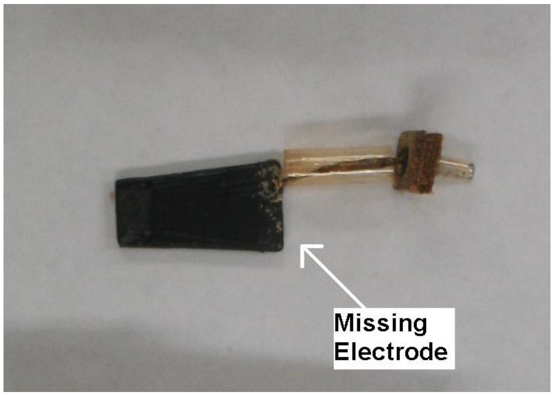
In each of the previous trials, results were often qualitative or inconclusive. This is largely the effect of the inability to reproduce a given trial. Signal intensity would often change by an order of magnitude or more on separate days, given seemingly identical circumstances and setup. More problematic was the periodic loss of signal, even in the middle of a trial, when the spikes representing the stimuli would suddenly fail to register regardless of how hard the sand was disturbed. This loss of signal could be due to saturation of the amplifier. The amplification setting was subsequently reduced from 10,000X to 1,000X or 100X. This seems to largely correct the problem.

Choice of piezoelectric material and exposed surface area of the receiver

Experimentation with the three sources of piezoelectric material used thus far indicates that highest sensitivity was achieved with the Astatic phonograph cartridge. Piezoelectric materials were also harvested from two brands of electric lighters: one purchased from the local supermarket and labeled only as a piezoelectric lighter, and the other a Scripto® brand utility lighter. These two brands of electric lighters contained transducers that were sensitive to the type of vibrations being used to a distance of approximately 20 cm. These have therefore been abandoned without further attempts to improve their sensitivity. The phonograph cartridges, as the more sensitive receivers, have been subject to several modifications to further improve their functionality. Originally, they were employed using their full casing, with the needle arm acting as the receptor and applying pressure directly to the transducer.



After testing, the cartridges were pried open and the transducer itself was used as the receptive element. This approach benefited from the increased surface area for receiving the waves, but suffered due to the fragility of pre-attached electrodes. Several electrodes were torn during handling.



Finally, the cartridge was altered by cutting away part of one of the sides, exposing the transducer but allowing it to remain within the stable casing. This seems to maximize the performance of the receivers while protecting the electrodes.

The best signals produced are sufficient to resolve a clear signal of a pencil driven into the sand at distance of more than 0.5 m. Unfortunately, they cannot, except in the very near field, resolve the footsteps of a scorpion above the baseline of background noise. For now, triangulation of a more robust signal (pencil tap) is being pursued to determine how accurately the triangulation can be performed assuming a sufficient signal. Once the technique is perfected, new sources of piezoelectrics will be sought. It may prove necessary to buy directly from a manufacturing company to achieve the necessary sensitivity.

Remaining obstacles

Having resolved a majority of the problems involved in achieving a clear signal, the greatest remaining problem is interpreting these signals. The signal is assumed to be composed of several different wave types, however, the beginnings and ends of each are difficult to precisely identify. Attempts to determine, by hand, the velocity of the respective waves based on time-of-arrival measurements failed to achieve a precision of even tens of meters per second. The principal error was the identification of the arrival of the wave front. Techniques for such identification must be well known, as seismologists routinely make such determinations (Longwell & Flint, 1955). Once we are able to better estimate the time of arrival of the waves, we will be able to begin manual triangulation. When the technique proves reliable and accurate, the system can be automated and put into practice.

Acknowledgments

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