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Optimizing and Assessing the Performance of an Algorithm that Cross-correlates Acquired Acoustic Emissions from Internally Feeding Larvae to Count Infested Wheat Kernels in Grain Samples

D. K. Weaver, D. Shuman and R. W. Mankin

US Department of Agriculture, Agricultural Research Service, Center for Medical, Agricultural and Veterinary Entomology, 1700 SW 23rd Drive, P.O. Box 14565, Gainesville, FL 32604, USA

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ABSTRACT

An algorithm was developed with optimizable parameters to match sounds from individual insects in grain by cross-correlating signals from an acoustic sensor array. The algorithm was optimized in a series of trials conducted in the sample chamber of an Acoustic Location 'Fingerprinting' Insect Detector (ALFID). The sample chamber was filled with uninfested wheat, except for a single kernel, which was infested with an immature rice weevil. This kernel was placed at a known location in the sample chamber. With analysis parameters optimized, the algorithm successfully detected the single insect in 100% of the trials. The algorithm's capability to count multiple insects was assessed by combining signals in data files collected from single insects into a set that represented sounds from a pair of insects. In these analyses, the algorithm correctly detected the two insects in 100% of combinations three sensor spacings apart, 100% of combinations two sensor spacings apart, and 70% of combinations one sensor spacing apart. Based on these results and the dimensions of the ALFID sampling chamber, the algorithm has a 90% probability of identifying two randomly located insects producing sounds in a wheat sample. Published by Elsevier Science Ltd

Keywords: Quantitation, algorithm, hidden larvae, grain samples, inspection.

INTRODUCTION

Current grain inspection practices focus on the presence of insects in determining the quality of a particular shipment. This is accomplished by sieving and visually inspecting a sample (1 kg) to see if it contains an unacceptable number of insects. The US Grain Inspection Service, Packers, and Stockyard Administration (GISPSA) guidelines currently classify samples with less than two insects per sample as 'clean' grain and samples with greater than one insect per sample as 'infested'. Larvae of most of the severe stored-product pests must feed and develop within kernels. Thus, infested grain may appear clean if adults are not yet present or if they have been removed by mechanical cleaning. Laboratory methods available for detecting internally feeding larvae involve the measurement of carbon dioxide evolved, resonance spectroscopy, or X-rays. These technologies are not widely implemented because they are costly, time consuming, of limited practicality, or are not accurate enough for reliable use. There is a strong need to develop methods to overcome these listed limitations and implement a method for rapid, accurate detection of internally feeding insects in stored grain.

A significant amount of scientific research has been conducted on acoustical phenomena involving insect pests of stored grain. The research is directed at two separate areas: monitoring of insect populations and detection of insects in a sample for regulatory purposes. Most of the monitoring research initially involved correlation of the numbers or occurrence of sound spikes per unit time to the numbers of insects in discrete samples (for example, see Hagstrum *et al.*[1]). Recently, an automated system was developed to acoustically monitor for increases in the number of sound spikes at particular locations in a grain mass.[2] Increases in the occurrence of sound spikes per sensor during a 5-day sample interval were correlated with increases in the number of insects in a grain trier sample taken near the sensor. The relationship between continuously collected sounds, discrete numbers of insects in a grain sample, and the actual population size in the grain mass is not clearly understood, primarily due to uncertainty associated with relating the number of insects in a grain sample to the size of the insect population in the grain bulk. The actual size of the population, if known, is the best criteria for grain managers to use to make decisions about possible control or intervention strategies. However, automated acoustic monitoring of sounds in bulk storage is valuable because increases in acoustic phenomena occur as populations grow, thus providing a direct warning of a potential problem for managers. In addition, an automated system with distributed sensors also gives location information, so hotspots may be effectively pinpointed and treated before the pest population migrates throughout the grain mass.

The problem of quantification is also very important in grain inspection. When grain is in transportation channels, a limited time is available to accurately detect the exact number of insects in a collected sample. The number of such samples is limited and certainly not representative, but the few that are taken are diagnostic, so it is important that any quantitative information about the presence of insects be accurate. A system called ALFID (Acoustic Location Fixing Insect Detector) was developed to determine the number of loci from which sounds are originating in a grain sample.[3] This initial version of ALFID (ALFID 1) performed well in determining when grain was 'clean' by GISPSA standards, and performed adequately when determining if the grain was 'infested'. However, the exact counting of insects in 'infested' grain was less precise, which was in part due to irresolvable data from closely spaced insects.[3]

A new acoustic insect detection system with the same acronym, ALFID, but a different name, the 'Acoustic Location "Fingerprinting" Insect Detector' (which will be referred to as ALFID 2) has been developed using a novel design and more sensitive detectors. The design and operation of the new system is described in detail in Shuman *et al.*[4] Briefly, grain samples (1 kg) are placed in the ALFID 2 grain container, and signals are acquired from an array of acoustic sensors on the sides of the container whenever any one sensor detects a sound emanating from within the grain mass. Waveforms acquired from contiguous sensors are cross-correlated for each detected sound, and the locations of cross-correlation peaks are identified. The peak locations, which depend on the differences in the arrival time of the sound at the two sensors, are closely aligned for multiple sounds produced from the same location, for example those produced by a larva feeding within a grain kernel. The locations of cross-correlation peaks from sounds acquired during a test of a grain sample can be represented as a distribution in multi-dimensional space with a different axis for each sensor pair that is cross-correlated. The distribution of these peak locations is smoothed by deriving a potential field contour based on the empirically measured variability of peak locations. Clusters of peak locations can be identified on this contour based on the ratio of peak to valley heights. Broad clusters are truncated to an established maximum window width positioned to encompass the greatest number of peak locations. Clusters are retained for fingerprinting if they contain a minimum number of cross-correlation peaks. The fingerprints of any pair of sounds have a matching value that is the number of clusters that have common cross-correlation peaks. Sounds that match well are considered to have a common source and are therefore grouped together. A sufficiently large group of matched sounds indicates the presence of an insect. Here we report the results of tests using single late-instar larvae of the rice weevil, *Sitophilus oryzae* (L.), to evaluate the performance of ALFID 2 and the efficiency and accuracy of the algorithm.

MATERIALS AND METHODS

Kernels of wheat from a laboratory stock culture containing active late-instar (20–25-day-old) larvae of the rice weevil, *Sitophilus oryzae* (L.), were selected for use in tests by individually placing putative infested kernels on a piezoelectric microphone and verifying that they were producing sounds. This was undertaken because the larvae are occasionally quiescent and we did not wish to be inefficient by recording an inactive insect. The culture was maintained on soft white wheat in an incubator that was operating at 26 ± 1°C and 65 ± 5% relative humidity with a 14:10 h (L:D) photoperiod. An infested kernel was placed at one of several positions in the ALFID 2 system[3] as the unit was filled with 1 kg of wheat.

Before testing, the wheat was frozen (−20°C) for 1 week to ensure that it was free from insects. The grain was then warmed in an insect-proof container and inspected to ensure it was free from insects before testing. Positions tested were: (A) at the midpoint between directly opposing sensors; (B) at the tube wall, midway between two directly opposing sensors; (C) offset from a sensor but within 1 cm of it; (D) directly in front of a sensor, within 1 cm; and (E) halfway between position (A) and one of the directly opposing sensors, effectively one-quarter of the distance between the two facing sensors and displaced at the midpoint between two adjacent sensors (Fig. 1). Infested kernels were placed in several different regions of the grain container to achieve each of these positions, but these trials did not include the regions at the ends of the tube. Data were recorded from tests run for 30 min in an anechoic chamber at 20–23°C and 50–65% ambient relative humidity. Eighteen trials were conducted without insects in the ALFID grain container, while 15 were conducted with single insects at one of the locations described

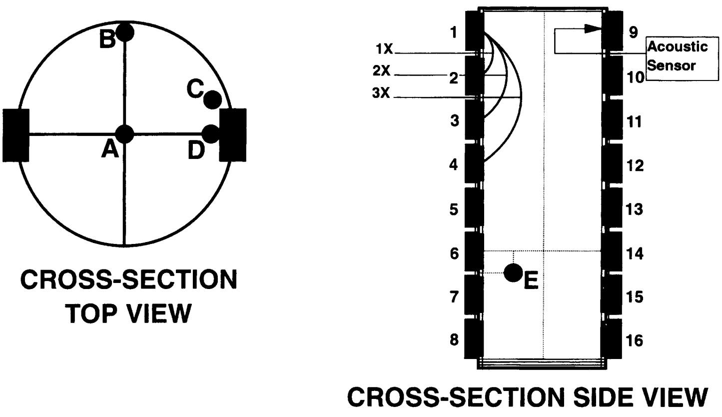

Fig. 1. Placement of infested kernels in ALFID (A–E) and illustration of sensor spacing intervals (1×–3×) for the combined data sets.

above. Trials with insects generally substituted a different insect for each new trial, but several insects were used more than once, in the interest of efficiency.

Evaluations of the accuracy of the algorithm in scoring two insects were conducted using data sets created by combining two data files from individual insects that were spaced at locations equivalent to one or more sensor positions apart. The data files were concatenated after cross-correlation and before clustering. This facilitated determining whether tests that counted the number of insects properly used the correct, known sound groupings to do so. Briefly, the sounds associated with one insect will all be numbered less than or equal to the total number of sounds in its data file and all of the sounds associated with the second insect will be numbered greater than any of those associated with the first insect. This assumes no interactions between the acoustic emissions of the insects, but even if there were such interactions, these would only increase or decrease the numbers of sounds produced. This would not impact the time-delay locations. Thirty such files were tested, 10 of which were approximately one sensor spacing apart (Fig. 1–1×), 10 of which were approximately two sensor spacings apart (Fig. 1–2×), and the last 10 were approximately three sensor spacings apart (Fig. 1–3×).

The algorithm[4] contains several analysis parameters, which can be set at default values, listed in Table 1, that maximize the probability of detecting weak insect sounds, based on empirical data collected from a series of

TABLE 1

Default and optimized signal analysis parameters for the current ALFID algorithm

Parameter name	*Magnitude*		*Unit*
	Default	*Optimized*	
RMS ratio threshold	1.3	1.4	—
Cross-correlation			
Peak threshold			
Relative	0.10	0.15	—
Absolute	5	110	10^4 AU[a]
Time-delay threshold			
Adjacent sensors	245[b]	245[b]	μs
Opposing sensors	360[b]	360[b]	μs
Diagonal sensors	512[b]	512[b]	μs
Maximum number of cross-correlation peaks	—	5	—
Cluster width	128	64	μs
Number of peaks/cluster	3	4	—
Valley/peak ratio	0.7	0.7	—
Matching value threshold	3	3	—
Minimum group size	3	3	—

[a] For the relationship between Amplitude Units (AU) and Sound Pressure Level, see text.
[b] The maximum calculated cross-correlation time delay shift.

individual insects feeding within grain kernels. These low-level insect sounds are not readily separated from random grain or system noise. These parameters can be optimized to retain an adequate number of louder insect sounds for analysis, while culling cross-correlation peaks, channel outputs and/or low-level spurious background noises. Optimization to the present values was possible after repeated analyses of many trials using either clean or infested grain.

RESULTS AND DISCUSSION

We compared the performance of the algorithm using optimized parameters (ALFID 2-O) to the performance using the default parameters (ALFID 2-D). The ALFID 2-D RMS ratio threshold[4] of 1.3 retained low-level sounds but passed too many spurious system and grain settling noises into further analysis. Resetting this threshold to 1.4 in ALFID 2-O discarded some of the weakest insect sounds, but deleted even more of the random noises. Increasing the cross-correlation peak absolute threshold[4] from 5×10^4 in ALFID 2-D to 1.1×10^6 amplitude units in ALFID 2-O had the same effect. To relate the cross-correlation amplitude units to sound pressure level, we calibrated the sensitivity of the sensor/amplifier unit (in mV/Pa) by reference to a B&K Model 4145 microphone/Model 2610 amplifier system (Brüel and Kjær, Nærum, Denmark) and calculated the cross-correlation amplitude for 2-ms sine wave bursts between 3 and 4 kHz, emitted from a source equidistant from the two sensors. If the gain of the sensor/amplifier unit is assumed constant (at its average value) over this frequency range, the ALFID 2-O threshold corresponds to a signal of 15 dB *re* 20 μPa, while the ALFID 2-D absolute cross-correlation peak threshold corresponded to approximately 2 dB *re* 20 μPa. The relative cross-correlation threshold[4] in ALFID 2-O includes peaks that are $\geq$15% (ALFID 2-D $\geq$10%) of the largest cross-correlogram peak amplitude acquired with that sound. In addition, ALFID 2-O discards cross-correlograms that have more than five peaks, because this is a good indicator of noise in at least one of the sensor channel outputs.

The clustering and grouping parameters[4] are also optimizable and have been considerably modified from those used in default testing of the system.[6] The ALFID 2-D value for cluster width is nine time samples or 128 μs. Trials with ALFID 2-O indicated that a cluster width of five time samples (64 μs) was a more accurate indicator of the central tendency of the data, reducing both false positive and false negative counts. In addition, ALFID 2-O indicated higher accuracy when a cluster had to contain peaks representative of at least four sounds rather than at least three sounds in ALFID 2-D, during a test of 30 min duration. The following parameters were found to be suitable for both settings: the ratio for the cross-correlation valley amplitude relative to the smallest of the pair of adjacent peak amplitudes was 0.7; the matching value threshold and the minimum group size were set at 3, primarily because the previous parameters adequately culled spurious sounds that could result in false positives before these final 'counting' portions of the algorithm; and time-delay thresholds of 245, 360 and 512 μs for culling cross-correlation peaks with physically impossible time delays were determined by calculating the maximum possible time delay between adjacent, opposed, or diagonal sensors, respectively, using 240 m/s as the mean speed of sound in grain.[5]

The optimized (ALFID 2-O) parameter settings counted insects more accurately than the default (ALFID 2-D) parameter settings. ALFID 2-O correctly counted single insects in 100% of the tests ($n = 15$) (Fig. 2). The initial version of ALFID[3] (ALFID 1) was accurate in 70% of the tests, with 11% counted as two (Fig. 2), and 19% counted as zero. The ALFID 2-D settings[6] were accurate in 86% of the tests, with all errors being overcounts. Overcounts with single insects are important because they represent false scoring as 'infested' for GISPSA standards. In tests using data combined

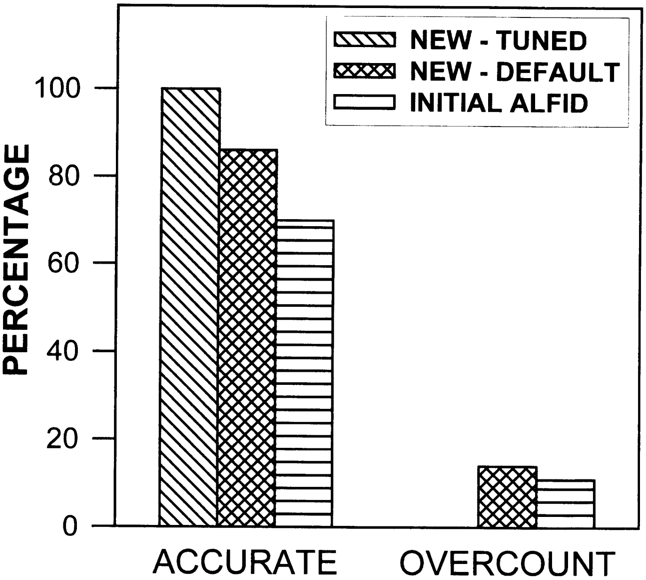

Fig. 2. Performance of the tuned or optimized current version (ALFID 2-O), default current version (ALFID 2-D), and initial version of ALFID (ALFID 1) in counting a 1-kg sample of grain infested with a single late-instar larva of the rice weevil, *Sitophilus oryzae* (L.), developing within a wheat kernel. Percentage of accurate counts is the number of trials in which the insect was counted correctly over the number of trials conducted, multiplied by 100. Overcount percentage is the number of trials where the system counted more than one insect over the total number of trials, multiplied by 100.

from two individual insects, ALFID 2-O counted correctly in 90% of the combinations overall ($n = 30$), with all miscounts being counted as one. The ALFID 2-D settings counted correctly in 62% of the combinations overall, again with all miscounts being counted as one. ALFID 1 counted correctly in 55% of the trials with two insects and undercounted in 42% of the tests.[3] This enhanced performance is significant because ALFID 1 could not resolve data for insects less than 1.75 sensor spacings apart, while ALFID 2-O is 70% accurate at approximately one sensor spacing interval for combined data ($n = 10$), with 30% undercounting (Fig. 3). The ALFID 2-D settings resulted in only 21% accuracy at one sensor spacing interval, with all errors being undercounts. ALFID 2-O scored correctly for all combinations with two insects approximately two sensor spacings apart ($n = 10$) and counted two insects correctly in all combinations with the insects approximately three sensor spacings apart ($n = 10$) (Fig. 3). The ALFID 2-D settings resulted in only 64% accuracy at two sensor spacings and 100% at three sensor spacings (Fig. 3). When sensor spacings were two or greater, ALFID 1 counted correctly only 72% of the time. Therefore, ALFID 2-O is approximately 30–70% more accurate than its predecessor when counting one or two insects in a grain sample. For the trials using 'insect pairs' created from

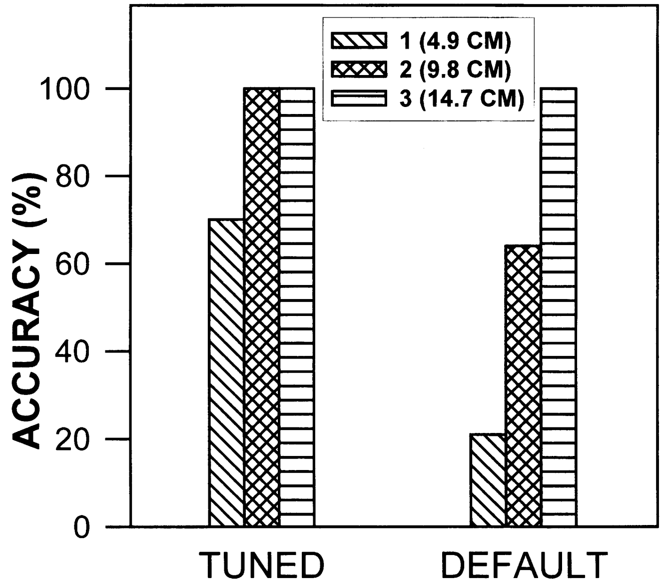

Fig. 3. Performance of the current version of ALFID with the tuned or optimized (ALFID 2-O) or default (ALFID 2-D) parameter settings in counting paired combinations of sound data from single insects (late-instar larvae of the rice weevil, *Sitophilus oryzae* (L.) developing within wheat kernels) as two insects in a 1-kg sample of grain. The insects were located at approximately one, two, or three sensor spacing intervals apart.

single insect data files the results were independent of the position within the grain container. The accuracy relative to ALFID 1 increases primarily as the distance between pairs of insects decreases. The increased sensitivity of the new detectors, combined with optimized parameters designed to minimize the overlap between insect sounds and those resulting from grain or electronic noise results in increased accuracy in scoring grain containing no insects. The ALFID 2-O settings had an accuracy of 100% ($n = 18$), compared to 90% for those with ALFID 1 (Fig. 4).

The observed fraction of correct counts of insect pairs at different spacings allows for approximation of the overall probability of the current ALFID correctly counting a random sample of two insects in the test chamber. The probability of correctly counting two insects decreases from 1 at two or more sensor spacings, to 0.70 at one sensor spacing, and to 0 at zero sensor spacings. Such a relationship can be expressed approximately as $\rho(r) = r/R$, where $\rho(r)$ is the probability of a correct count when a pair is separated by distance r, and R (equal to two sensor spacings in this case) is the critical distance at which the probability of a correct count becomes 1. The overall probability of a correct count within a sphere of radius R is the normalized integral of $\rho(r)$ over the total volume, or $P = 3/4$ (see Appendix). So, we estimate that any two insects will be scored correctly in 75% of trials where they are within a sphere of $R =$ two sensor spacings, and in 100% of trials where their spacing is greater than R, for a cumulative probability of 90%

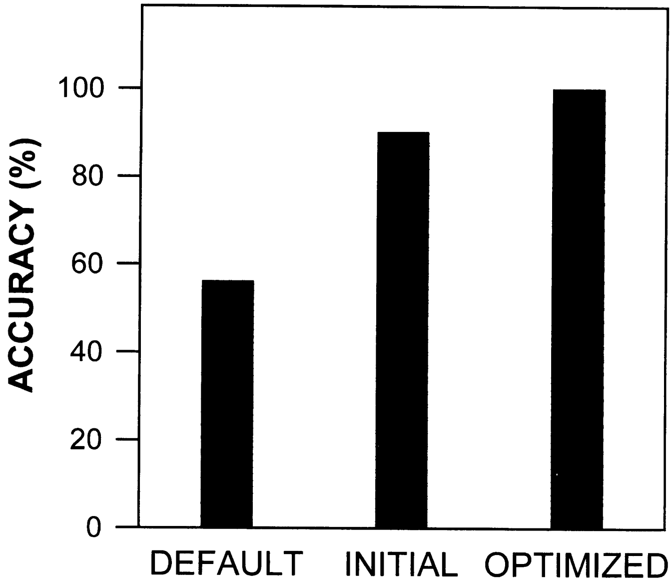

Fig. 4. Performance of the optimized current version (ALFID 2-O), default current version (ALFID 2-D), and the initial version of ALFID (ALFID 1) in counting uninfested samples.

for any trial with two randomly distributed insects (see Appendix). Note that this cumulative probability could actually be greater because the true critical sphere was probably achieved before reaching two sensor spacings (this was the distance at which we first recorded 100% accuracy, and is probably not the distance at which it first occurred).

In summary, with the algorithm parameters optimized (ALFID 2-O), we have a higher level of accuracy with both infested grain and uninfested grain for this new system than was possible with the earlier version of ALFID (ALFID 1). It was our intent to develop the algorithm with the optimized parameters to ensure that enough insect sounds will be retained for correct scoring, while eliminating most of the random noises that result from grain movement and those that are electronic in origin. Such noise 'culling' parameters reduce the number of insect sounds available for analysis compared to that in the default (ALFID 2-D) settings, but subsequent optimization of 'clustering' parameters in ALFID 2-O serves to better separate insects that are located within two sensor spacing intervals of each other. Thus, we have demonstrated that this system is highly accurate for detecting insects in grain samples and that it clearly performs better than its predecessor. Subsequent extensive laboratory tests and field trials, using a custom-designed sound-insulated enclosure,[7] will rigorously elucidate the overall accuracy of this system in counting infested kernels under conditions typically encountered during sample inspection.

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APPENDIX

Calculations for the probability of correctly counting two late-instar larvae in a 1 kg sample of grain in ALFID.

The observed probability of correctly counting two insects separated by distance, r, is approximately

$$\rho(r) = r/R|r < R \tag{A1.1}$$

where $\rho(r)$ is the probability of a correct count and R is the critical distance at which the probability of a correct count becomes 1 (about two sensor spacings). The overall probability of a correct count within a sphere of radius R is the normalized integral of $\rho(r)$ over the total volume

$$P = (4\pi R^3/3)^{-1} \int_0^R \rho(r)\mathrm{d}v \tag{A1.2}$$

where $\mathrm{d}v = 4 \cdot \pi \cdot r^2 \mathrm{d}r$ is an infinitestimal volume element, and $\mathrm{d}r$ is an infinitestimal length element. Combining eqn A1.1 eqn A1.2 yields

$$P = (4\pi R^3/3)^{-1} \int_0^R (4\pi/R) r^3 \mathrm{d}r \tag{A1.3}$$

$$= (4\pi R^3/3)^{-1} \pi R^3 = 3/4$$

Thus we have an overall probability of accuracy of 0.75 for counting two insects correctly within a critical sphere.

To consider the probability of correct counting over the entire sampling chamber, we used Monte-Carlo methods to determine the probability of two insects that were randomly placed within the ALFID chamber being within the critical radius, *R*, or two sensor spacing intervals of each other. The simulations were run 100 000 times. Based on these simulations, there is a 41.7% probability that the insects will be located at or within the length of the critical sphere (two sensor spacings) of each other. Therefore, the overall probability of accuracy within the chamber is $(0.75\times0.417)+(1.0\times0.583)=0.896\approx90\%$.

Note

The actual probability is probably higher than 90% because the critical radius is probably shorter than when first detected at two sensor spacings.