Computerized monitoring of stored-product insect populations

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Abstract

Insect infestations in stored agricultural commodities result in annual losses of millions of dollars. Traditional stored-product infestation monitoring by sampling or trapping can alert managers to initiate an insect control tactic. These monitoring schemes are laboring intensive and thus not performed frequently. Computerized monitoring can automatically display real-time data indicative of stored-product insect populations throughout a storage facility at a central console Data acquired from arrays of sensors can be input to spatial analysis programs for generating contour maps of insect distributions. These sensors respond to some component of insects' biological activity. Locomotion and feeding activity of insects in stored-products can be quantified with acoustic sensors An electronic sensor can also count insects when they enter a trap The Electronic Grain Probe Insect Counter (EGPIC) System counts insects falling through and partially masking an infrared-beam incorporated in a modified grain probe trap. The sensor output signal is proportional to the size of the insect, providing some identification information Counted insects can be released at a distance from the sensor to reduce the need for probe maintenance and to not alter the local population density. For large-scale implementations, a tree-structured (distributed multiplexing) network enables computer acquisition of insect count data from up to a million addressable probes with a minimal amount of cable.

Introduction

Protection of bulk-stored agricultural commodities from insect infestations and the direct loss caused by insects are costly Monitoring of insects to estimate population density is essential in an integrated pest management system for postharvest commodities. This can reduce the amount of insecticide needed for control based on economic threshold analysis and eliminate unnecessary 'scheduled' insect-control treatments Many alternatives to chemical applications will be financially attractive only with early warning of emerging infestation problems. Sustained monitoring also provides a means for measuring the effectiveness of control strategies.

The traditional practice for detecting and quantifying infestations in stored-products is the visual inspection of samples for live insects. However, sampling does not provide thorough or continuous monitoring. Low insect populations are difficult to detect in small samples and sampling is expensive because it is labor intensive. Therefore sampling may be performed infrequently even though an infestation can grow from undetectable to damaging levels in weeks (Hagstrum et al., 1995). As an alternative to sampling, insect traps can be more sensitive to low insect densities because they monitor continuously and can be enhanced with chemical attractants. Although trap catches do not provide exact assessments of insect populations due to the influence of insect behavior and other parameters (Fargo et al., 1989), they can be effective indicators of population changes, especially if some of these other parameters are also monitored and factored into the interpretation of the trap catches However, traps must be inspected periodically which is also labor intensive, limits the temporal availability of data, and restricts placement to easily accessible locations.

Knowledge of the spatial distributions of populations can further reduce the amount of insect control needed. Arrays of sampling sites or insect traps can provide input data to spatial analysis methods for generating contour maps of insect distributions. Control methods can then be targeted to high density regions where the economic threshold has been exceeded and/or to infestation source locations. Targeted control also allows natural enemies to survive and exert more influence in untreated regions. Once again a practical limitation is the time and effort required for collecting samples or accessing traps, manually inspecting samples or trap contents, and accurately entering the insect numbers into a spatial analysis database.

Automated monitoring

Automated insect monitoring systems involving computer acquisition of data from sensors distributed throughout stored commodities can eliminate the need for scheduling costly manual inspections by remotely displaying the data in real-time from all storage regions. These data can alert

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personnel to the need for a manual inspection or to initiate control measures and can be input directly to spatial analysis programs, expert management decision support systems, and computer-controlled automatic insect deterrent systems. During and after control measures are taken, the incoming sensor data can provide spatial maps of control efficacy. Whereas the information acquired from a sample is like an instantaneous snapshot of a small fraction of the stored-product and that acquired with a passive trap is like a snapshot integrated over time (from when the trap was deployed), the information acquired with an automated monitoring system is dynamic like a moving picture This dynamic picture provides greater time resolution, which permits discernment of the interplay between spatial and temporal population trends As a practical matter, the fine time resolution can also reveal abrupt changes in sensor data that would be physically preposterous and thus indicative of an error condition.

The most crucial component of an electronic monitoring system, and the one necessitating the greatest research and development effort, is the insect sensor. It is the point where the biology meets the technology and therefore requires an interdisciplinary approach. The sensor output data need to be indicative of the presence or numbers of insects in the vicinity of each sensor. This is attainable by measuring some parameter related to the insects' biological activity. The primary activities of insects are locomotion, feeding, reproduction, and respiration. Since the magnitude of insects' activities are also affected by some environmental parameters (e. g., temperature, and possibly humidity, ambient light and time of day), sensor data used to estimate populations may need to be adjusted by the outputs of other sensors measuring those parameters

The only commercial automated monitoring systems currently available for grain measure temperature. These consist of embedded cables with distributed thermocouples connected back to a central computer and are used in grain elevators to detect 'hot spots' that can occur due to moisture and mold growth, and which may also correlate to high insect populations. Their use demonstrates the practicality of hanging sensor cables from the roofs of storage bins and having the cables and bins survive the tremendous forces exerted by the loading and unloading of grain.

A more direct method of detecting insects can be achieved with acoustic sensors that can 'hear' movement and feeding activity. The sounds, generated by the insects' interactions with their substrate (usually the agricultural commodity), are detected when they exceed some specified amplitude threshold. Accordingly, the sound spectra are often more indicative of the commodity ('the drum') than of the insect species ('the drummer'). However, specific temporal patterns of sound activity may still be a marker to the unique biological activity of a particular species. False detection resulting from ambient noise can be prevented by raising the amplitude threshold level (effectively lowering the sensor sensitivity or its range of delectability), attenuating the noise (with external shielding or by being deep enough within the commodity), selective frequency filtering (when sounds and noise have different spectra), temporal pattern analysis, and masking (inhibiting sensor output when excessive ambient noise is detected). Population estimates based on quantification of acoustic activity are possible (Hagstrum et al , 1996) although there are many auxiliary factors that are currently being explored. These include species dependence (size and behavioral characteristics), environmental influences, sensor range, the method of quantifying the acoustic activity (what aspect of the sensor output signal is measured), and ensuring that the acoustic activity measurement varies with population density over the range of population densities of interest

Insects in or around a commodity can also be counted as they pass by electronic sensors. It is preferable to count each insect only once when estimating populations or detecting population changes, which can be accomplished by trapping or killing the insect when counting occurs. Presently available commercial traps rely on baits, pheromones, or behavioral characteristics to ensnare insects and the inclusion of electronic sensors can capitalize on this proven and accepted monitoring technology. The partial masking of an single infrared-beam by a falling insect in a pitfall trap has been used for counting insects in stored grain (Shuman et al., 1996) and is discussed in more detail later. In other contexts, multiple infrared-beams can also be used to resolve direction of motion, avoid multiple counts of a single insect, and also provide insect size information for species discrimination Other possible sensors for detecting insects are capacitive (an insect between two parallel plates alters their capacitance) and mechanical contact with a piezoelectric material. Flying insects can be monitored using an electrocuting grid outfitted with an inductive sensor to count the number of electrical discharges.

Once an insect-induced sensor output is generated, additional circuitry may be needed to extract the essential information from the raw sensor signal and put it into a form suitable for transmission to the central computer. This conditioning and processing of the raw signal can involve amplification, spectral filtering, threshold detection, timing, accumulation, conversion, etc The processed signal from each sensor can be a directly connected to the computer via its own transmission pathway so that the computer continuously monitors each sensor. This method is only suitable for small applications and involves the use of a parallel port for digital signals or an installed multichannel analog to digital converter computer board for analog signals However, having an individual computer connection

for each sensor is physically unwieldy and economically impractical when hundreds or thousands of sensors are involved and the computer is thousands of meters away. In fact, the major cost in large-scale automated monitoring systems may not be for the remote sensor hardware but rather for the means of getting the data back into a computer at a central location

Time division multiplexing can be used in two different ways for enabling data from multiple sensors to share a common pathway into a computer The first uses a multiplexer to sequentially connect each sensor for a small time interval However, this is not always suitable for insuring detection of insect activity, which can be erratic in nature. However, continuous monitoring can be achieved by having each sensor's data being quantified, accumulated, and stored in memory at or near that sensor Then the central computer can use a multiplexer to sequentially download the data from each sensor's memory several times a day. This second method is appropriate since significant changes in insect populations typically occur over days rather than within seconds. With either of these methods, each sensor must still have its own pathway to a multiplexer, which would involve an excessive amount of cabling if there are a large number of spatially divergent sensors and a single multiplexer is used. A custom-designed transmission facility the Serial Multiplexing Addressable Register Transmission System or SMARTS (United States patent pending) has been developed (Shuman and Nasah-Lima, 1996) to address this problem in implementations of the second method. It uses an array of spatially distributed small multiplexing modules arranged in a tree network to efficiently transfer data from up to a million sensor memories to the serial port of a central computer with a minimal amount of cable. An example of such a network with four levels of multiplexing is shown in Figure 1.

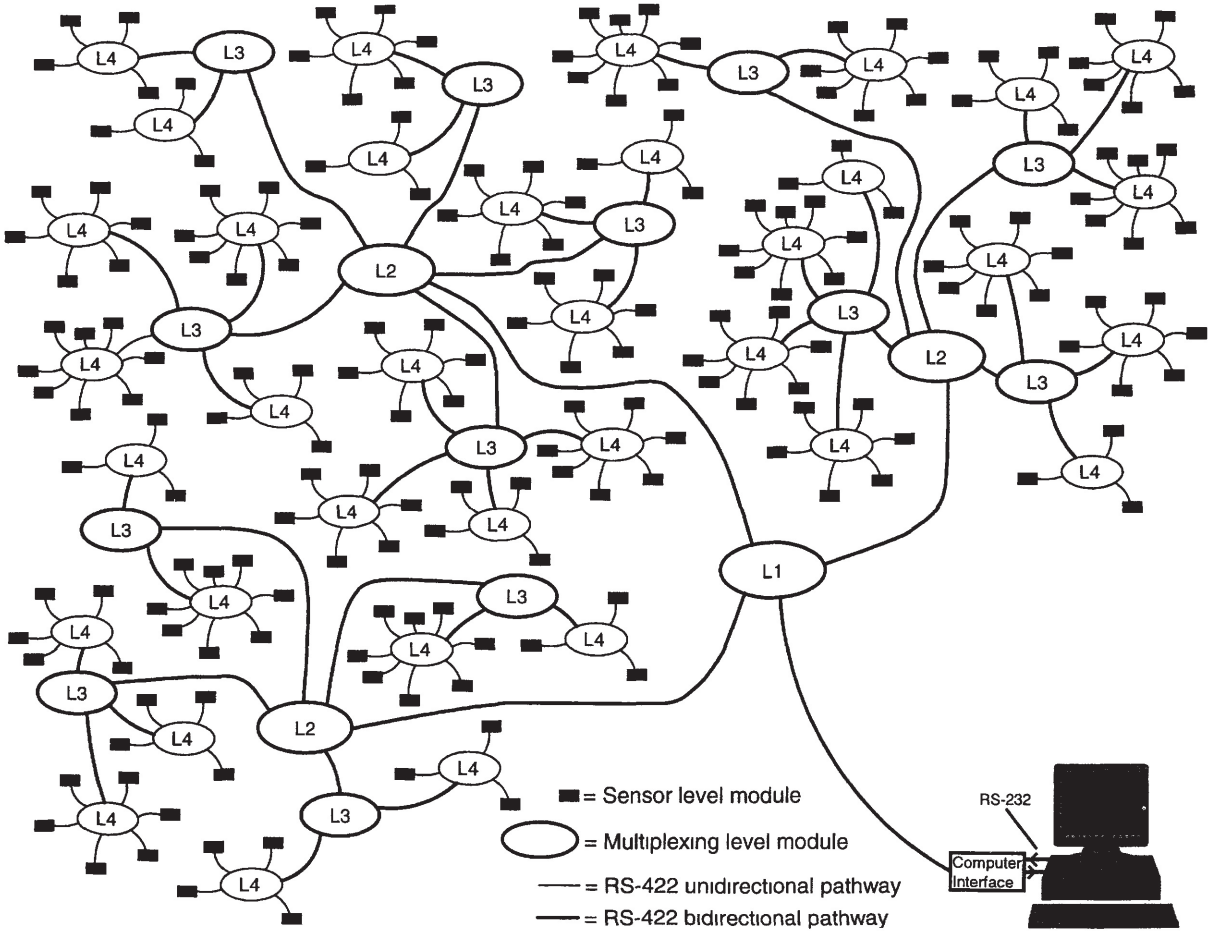

Fig. 1. SMARTS tree structure topology example with 4 levels of multiplexing Each sensor level module's internal memory can be addressed and read by the computer All digital pathways (RS-422 protocol) are single twisted wire pairs and the bidirectional pathways have address data and sensor data traveling in apposite directions on the same twisted pair

The electronic grain probe insect counter system

The Electronic Grain Probe Insect Counter (EGPIC) System (United States Patent No 5,646,404) is an example of automated monitoring using sensors to count the numbers of insects entering traps. Shuman et al (1996) described the initial design of the system which uses infrared-beam transducers to count insects that crawl into and drop through perforated cylindrical tubes (modified commercial grain probe traps). Although they performed very well in laboratory tests, a first field test of this system, conducted in a flat storage of corn in Wisconsin (1993), revealed some deficiencies in the sensor probe design that affected its counting accuracy. This paper will now discuss the design of a new sensor probe, present some performance data, and indicate current EGPIC research activities. As alluded to previously, the sensor probes have been the critical components in determining the system's performance. Presently, they are part of an eight-probe EGPIC System implementation as described in detail by Shuman et al. (1996). However, these sensor probes can be interfaced with SMARTS for large-scale commercial applications.

The sensor head, attached to the bottom of a grain probe trap body, detects insects as they drop through the head's channel and pass through a light beam projected by a light-emitting diode (LED) and received by a phototransistor The selected transducers are infrared to avoid interference by ambient light and were selected for their narrow beam divergence The range of sizes for the stored-product insect species of concern 1.5 mm by 0.4 mm for the flat grain beetle, *Cryptolestes pusillus* (Schoenherr) to 4.5 mm by 1.1 mm for red flour beetle, *Tribolium castaneum* (Herbst) are smaller than the transducers' diameters (5 mm) and so the passage of an insect through the head only partially masks the beam. Also, the phototransistor is biased in its linear region in order to produce an output signal proportional to irradiance. This results in output signals that vary with insect size and allows the minimum detectable object size to be set by means of an adjustable threshold voltage. In early laboratory tests of the prototype sensor head (Shuman et al., 1996) shown that some species e.g , the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L) and the rice weevil, *Sitophilus oryzae* (L.) could grab onto the infrared-beam transducers and produce multiple counts This was successfully remedied in the laboratory by the inclusion of a clear acetate insert partially coated (to not obscure the beam) with liquid Teflon (DuPont, Wilmington, DE, and USA). However, field testing in Wisconsin (1993) of the EGPIC System with this sensor head revealed a susceptibility to grain dust adhering to the insert, thus masking the beam and providing a foothold for insects. A second-generation sensor head design (Fig. 2) addresses this problem by recessing the infrared-beam transducers back from the narrow downward path (through the top funnel) of dust and insects. Several design features help keep insects from remaining in the vicinity of the infrared-beam and producing erroneous insect counts. The surface of the top funnel is sufficiently steep so that all insect species landing on it continue to fall through. The aperture at the bottom of this funnel is made smaller than the beam width to insure that falling insects do not miss the beam. The bottom edge of the funnel is positioned a small distance (2 mm) above the top of the beam so that if any insect inadvertently manages to hang from the bottom of the funnel, it would not intersect the beam and cause multiple insect counts The sharp acute angle of the bottom edge also keeps such insects from crawling around the edge and up the outside surface of the funnel (and then down to the infrared-beam transducers). The function of the lower funnel (also with a sharp acute angle bottom edge) similarly is to prevent insects from crawling up from the bottom of the sensor head to the infrared-beam transducers. The lower funnel's bottom aperture is wide enough so those insects falling through the top funnel pass through without contacting it. For additional protection against insect encroachment, sensor head surfaces above and below the infrared-beam are coated with liquid Teflon. Fig. 3 shown a red flour beetle falling through an operational (cross-sectioned) sensor head. This stop-action photograph was produced by using the phototransistor (seen across from the LED, both as a round dark objects) output to trigger an electronic flash.

In the first field test in Wisconsin (1993), grain particles entered through the holes in the originally used probe body (Storgard WB Probe II, Trécé Inc., Salinas, CA, USA) which resulted in high probe count errors. Grain particles do not lead to erroneous insect data when passive traps are inspected visually, however the infrared-beam sensors of the EGPIC electronic probes cannot distinguish between insects and grain particles similar in size. To reduce the number of grain particles entering the probes, a different probe body design (Trappit Insect Probe Trap, AgriSense-BCS Ltd., UK) consisting of an acrylic tube with downward slanted drilled holes for the insects to enter was selected. By using this body upside down with the holes slanted upward, gravity tends to keep grain particles out while not affecting the entry of insects (Subramanyam et al., 1989). A tubular plastic outer sleeve covers the holes during insertion of the probe into the grain to prevent particles from entering the probe, after which the sleeve is pulled up

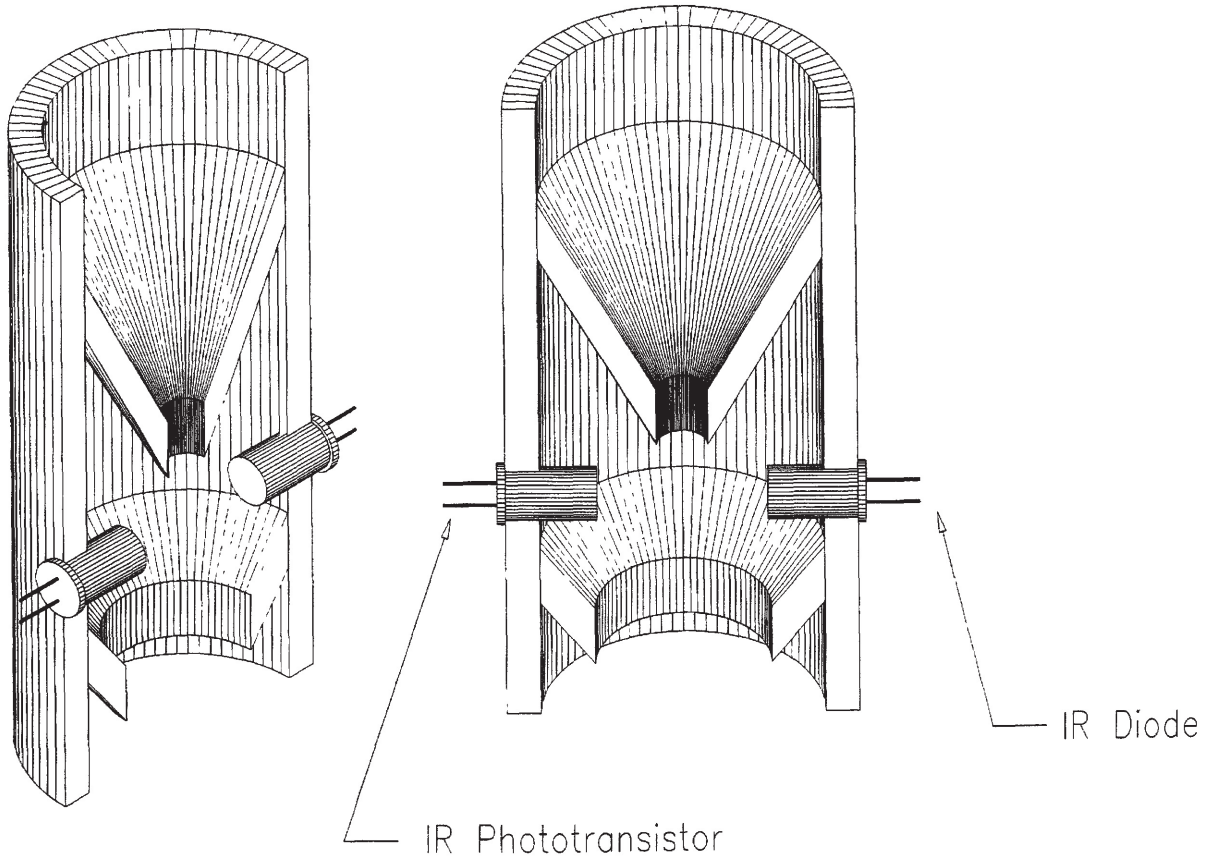

Fig. 2. Three-dimensional rendering of the new machined sensor head

For system performance accuracy testing, a removable insect trap receptacle (a part of the Storgard WB Probe II, Trécé Inc., Salinas, CA) is mounted underneath the sensor head so that the total numbers of EGPIC System insect counts can be compared with the numbers of insects trapped over a time period. However, for actual monitoring implementations, an extension tube with insect exit holes at the bottom could be mounted underneath the sensor head. This would allow the probes to be left in stored-products for extended periods of time without creating large accumulations of dead insects. Future research will determine a suitable extension tube length to keep insects from looping around and getting counted multiple times. However, it might also be possible to factor such looping around into subsequent insect count to population density analyses. Another use for such extension tubes could be in maintaining constant population densities (rather than having reduction by capture) within closed containers during laboratory tests.

Accuracy of the sensor probes was determined in laboratory trials using 2 – 3 week old adults of the flat grain beetle, the sawtoothed grain beetle, the rice weevil and the red flour beetle. Tests were conducted in polyvinyl chloride (PVC) cylinders (10 cm diam by 50 cm tall) that contained a single probe placed in the center and in larger PVC cylinders (15.2 cm diam by 45.6 cm tall) that contained four equally spaced probes. The cylinders with a single probe held 2 kg of wheat, the cylinders with the four probes held 4.5 kg of wheat. Tests were conducted with 44 – 88 insects per kg, and the grain was pre-sieved to remove broken pieces. Insects were either mixed with the grain by sequentially adding small amounts of both in a separate container before adding to the cylinder or were added to the top of the grain after the cylinder was filled. A trap receptacle was attached to each probe at the same time that its sensor circuit was activated. Number of insects captured was determined by emptying the trap receptacle at the end of a 24-h test and this number was compared with the EGPIC System insect count. Percent accuracy was determined by dividing the EGPIC System insect count by the number of insects that were captured. There were eight replicates of tests with red flour beetles, 16 replicates of tests with flat grain beetles and with sawtoothed grain beetles, and 24 replicates of tests with rice weevils. The tests show the distribution of the accuracy data obtained for each species. Median accuracy ranged from 100% in tests with flat grain beetles to 96.5% in tests with rice weevils. The lower accuracy with the rice weevils was observed to be due to their occasional clinging

together while falling through the probe (producing only a single insect count). Data from one replicate of each test with red flour beetles, sawtoothed grain beetles and rice weevils using the single probe cylinders were plotted in Figure 4 as an example of using the EGPIC time-stamped insect counts to view the capture of insects over time.

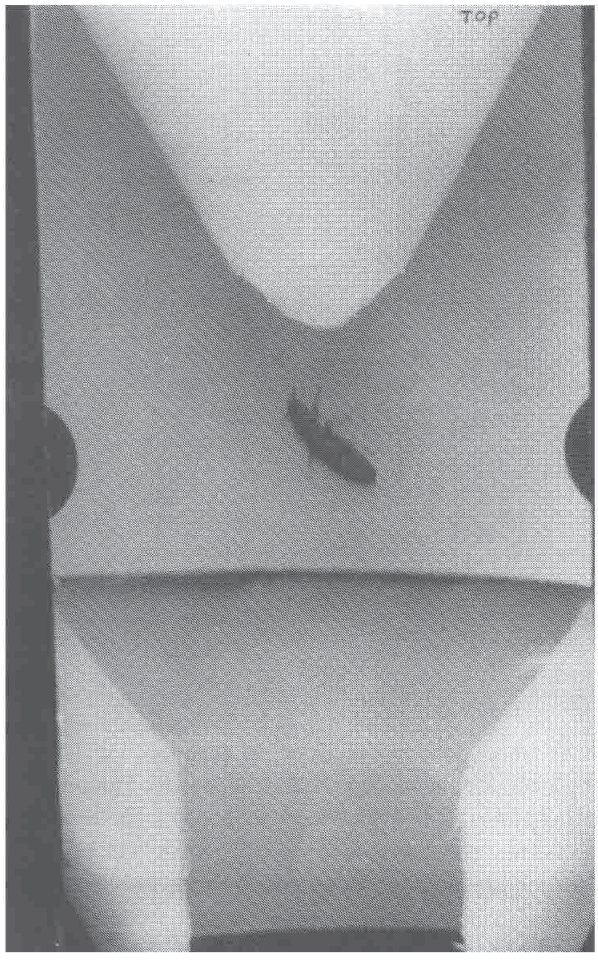

Fig. 3. Stop-action photograph of a red flour beetle falling through the (invisible) infrared-beam.

An eight-probe EGPIC System was tested at a commercial facility 3 km southwest of Williston, Florida during the summer of 1996 in a bin 5.5 m high by 5.5 m diameter and 3/4 filled with newly-harvested oats. The system sensitivity was adjusted to not count very small arthropods such as mites but to accurately count the small flat grain beetles. The probes were manually inspected weekly and EGPIC System data file counts were compared to insect numbers trapped in the probes as above. The deployment of the probes in the bin with the EGPIC System counts and the accuracy for each probe during a one week period (October 1 – 8). The EGPIC System average accuracy during this field test was 85%.

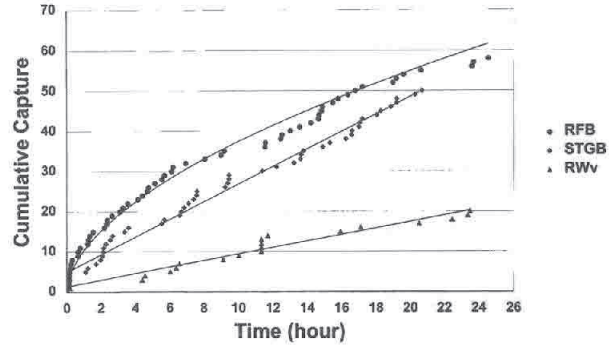

Fig. 4. Insects captured by an EGPIC probe over time. The graph is plotted directly from the EGPIC time stamped data file. Insect species: RFB-red flour beetle, STGB-sawtoothed grain beetle, RWv-rice weevil.

As an example of using spatial analysis methods. Figure 2 shows a spatial distribution map based on the EGPIC System insects counts for September 5 – 12. It was generated by posting the insect counts to a map of the bin surface and constructing contour plots of the insect distribution using Surfer 6.02 (Golden Software, Golden, Colorado). The spatial analysis was conducted using a 75 × 75 grid with interpolation by kriging (options = linear variogram model, no drift, zero nugget effect). The contours are then displayed on a three-dimensional surface map. A volume can be calculated for such a map, in units of (insects · m^2), to give a simple measure of infestation.

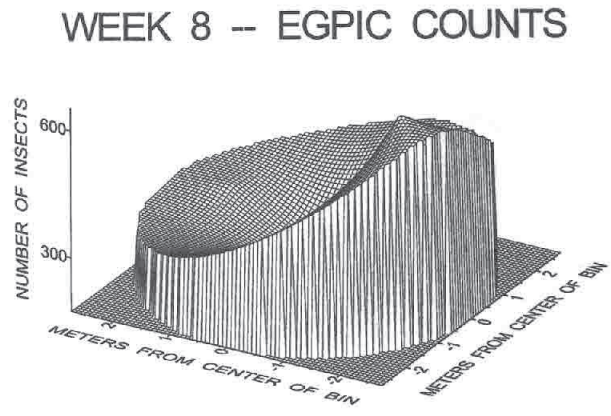

Fig. 5. A three-dimensional surface plot of the EGPIC system counts for the September 5 – September 12, 1996.

Figure 5 clearly portrays a very large insect population which (by trap catch inspection) was found to be dominated by a large concentration of proceeds in one region and relatively large numbers of foreign grain beetles, *Ahasverus advena* (Waltl), throughout. testing was halted and the probes were removed (to prevent corrosion) when the commodity was fumigated with phosphine on September

14 (enacted by the manager of the facility based on the insect population growth data supplied by the researchers). After blower venting and insuring that the bin was safe for reentry, the probes were reinstalled on September 24 and the three-dimensional spatial distribution for the week of September 24 – October 1 is shown in Figure 6 for comparison. The fumigation clearly suppressed the insect population but there was a small concentration of insects in the center of the bin which indicated that the fumigation was not entirely successful. The fumigation did corrode the extension cable connectors left in the bin which resulted in the system failing during a replicate field test the following summer (1997). This has led to the current use of non-corrosive, sealed, Mini-Con-X connectors (Conxall Corp., Villa Park, Illinois, and USA) for the cables and silicon potting of exposed traducer leads in the sensor probes. Initial tests have demonstrated the feasibility of allowing the EGPIC System to remain in operation during phosphine fumigation.

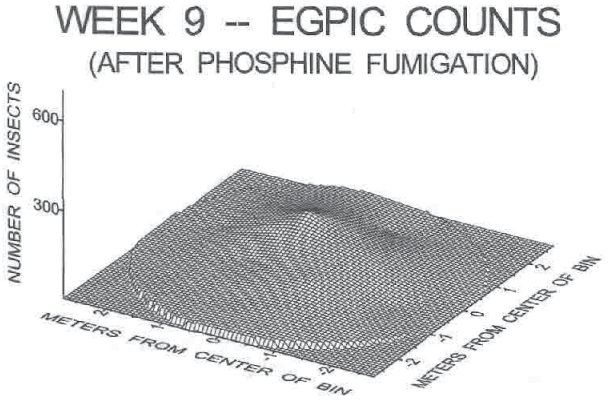

Fig. 6. A three-dimensional surface plot of the EGPIC system counts for the September 24 – October 1, 1996. Trapping period shows a dramatic decrease in the insect population as a result of a phosphine Fumigation. However, a significant number of insects survived the fumigation in the center of the bin, where the fine material was concentrated (Volume = 1020.4 insects $\cdot m^2$).

Although the discussed EGPIC System can indicate the location of a growing insect population, manual inspection would still be needed to identify the species. Automated discrimination of species based on body size is currently being investigated. As previously mentioned, the phototransistor produces an output signal that is proportional to the fraction of the beam masked or the size of the insect silhouette. This can be seen by plotting the signal peak voltage measured for different species dropped through the sensor head (Figure 7)

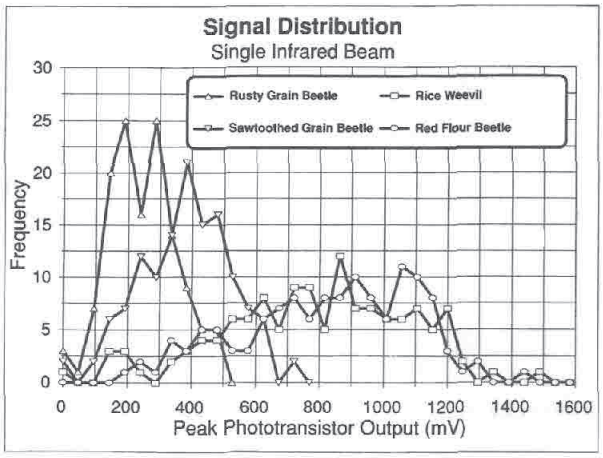

Fig. 7. The distributions of signal peaks at the phototransistor output for four insect species. This data was acquired by dropping 135 dead insects of each species through a probe of the present sensor head design and viewing the output peaks on an oscilloscope. The 0 mV data points correspond to insects that were not sensed by the probe.

Since the irregularly shaped insects' falling orientation is random and the infrared-beam intensity is not uniform throughout its cross-section, each species produces a peak voltage distribution that overlaps with other species' distributions. The species discrimination uncertainty resulting from this variance has been reduced by averaging the signal peak voltages from three intersecting orthogonal beams through which the insect falls as seen in Figure 8.

Other current aims are to aid in technology transfer of the EGPIC System by expanding its use in research, validating its potential as a stored-product pest management tool, and increasing its exposure to the agricultural industry. A cooperative research workshop held at the Center for Medical, Agricultural, and Veterinary Entomology (CMAVE) in Gainesville, FL during May 1998, was attended by scientists who will be using EGPIC Systems. They include Dr. Richard T. Arbogast (USDA/ARS, CMAVE), Dr. James E. Throne, Dr. Franklin H. Arthur (USDA/ARS, GMPRC, Manhattan, KS), Dr. Charles Burks (USDA/ARS, HCRL, Fresno, CA), Dr. David K. Weaver (Montana State Univ., Bozeman, MT) and Dr. Thomas W. Phillips (Oklahoma State Univ., Stillwater, OK). The primary research effort will be a field validation study to be conducted in corn and wheat in Kansas, wheat in Oklahoma and wheat in Montana, although it may be expanded to include almonds in California and corn in Florida. Other research areas include 1) trap interpretation and utilization of the EGPIC time-stamped insect count data, 2) optimization of trap body design, 3) environmental

factors that might affect trap capture, 4) biological/ behavioral factors that might affect trap capture, and 5) continued engineering refinement for large-scale commercial applications. One immediate outgrowth of this effort has been the knowledge gained from the larger-scale manufacturing of the sensor probes for the scientists For example, in switching from the prototype sensor head material of PVC plastic to Delrin plastic (DuPont, Wilmington, DE, USA) because of its superior machinability, the detrimental effect of internal infrared-light reflections became recognized and was reduced by treatment of the sensor heads' internal surfaces in the vicinity of the beam.

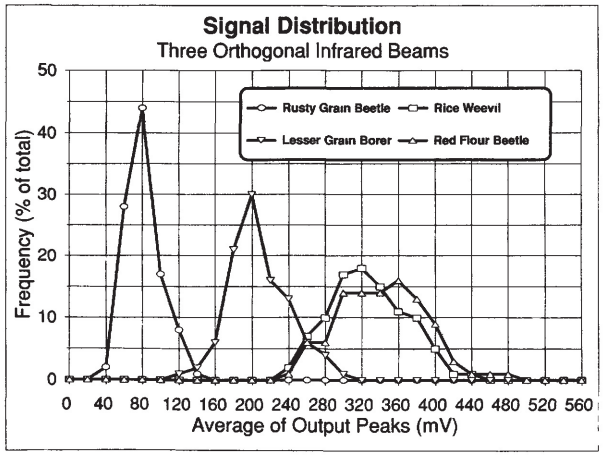

Fig. 8. Dead insects were dropped through the intersection of three orthogonal infrared-beams in a laboratory experiment and the peak outputs of the three phototransistors were averaged to create these distributions (Shown as percentage of total number of insects of each species) The reduced overlap of the distributions Indicates that species discrimination should be possible with a suitably designed multi-beam sensor head

Conclusion

As interest in the reduction of pesticide use and in pesticide alternatives grows, and as concern about worker safety increases, so does the need for computerized monitoring of stored-product insect populations. Different sensing methods for such automated systems are being researched in various feasibility studies. Development of the infrared-beam EGPIC System has progressed and performance tests have demonstrated its strengths. A cooperative research effort is currently aiming to validate and further explore EGPIC's potential, while simultaneously enhancing its capabilities and adapting it for large-scale commercial implementations.

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