FINAL REPORT

Project Title:	Real-time detection of codling moth using x-ray.
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Objectives: The principle objective is to demonstrate the potential of x-ray technology to identify apples that have been infested with coddling moth and the feasibility of installing x-ray equipment on the apple processing line for the identification and removal of infested fruit. A secondary objective will be to also identify apples with other defects such as watercore and core rot.

Specific objectives to complete the project were as follows:

1. Establish codling moth colonies at WRRC.
2. Obtained apples and infest them with coddling moth larvae.
3. Obtain digital x-ray images of the apples on a daily basis.
4. Input x-ray images into a scrolling program on a PC that simulates the apple processing line, and test the ability of human operators to identify the infested fruit.
5. Develop and test a computer algorithm to automatically identify the infested fruit.
6. Modify the algorithm to identify core rot and watercore.
7. Evaluate the feasibility and cost of installing the necessary x-ray equipment on an apple processing line for the removal of defective fruit.

Objectives completed in the last year:

1. Codling moth colonies have been established.
2. A sample of 24 apples were x-rayed on film on a daily basis, allowing an analysis of experimental parameters such as initial infestation rate, survival rate, and longevity of the apple.
3. Preliminary algorithm has been developed for automatic detection. However, the true accuracy can not be determined until a larger data set of digital images is acquired.
4. Scrolling program has been developed, also awaiting database of digital x-ray images.
5. A (casual) partnership has been developed with a local company that develops and builds linescan x-ray machines for industrial applications (Scantrac Corp). If the project demonstrates that x-ray is a feasible method for reliable detection of codling moth, they are interested in developing a commercial system.

Timeline for completion of project:

1. New x-ray machine is scheduled to arrive on or before July 2.
2. Summer help has been hired.
3. Infestation of apples to be completed by July 15.
4. X-rays to be completed by Aug. 15.
5. Human trials with scrolling program completed by Sept. 15.
6. Algorithm trials to be completed by Oct. 1.
7. Feasibility of commercial application determined by Oct. 30.

Reasons for deviation from original schedule:

The project was originally intended to be completed in a one year period. However, the linescan x-ray machine originally intended for this project is 15 years old, and has become unreliable. Furthermore, the image quality of newer machines is much better. It was therefore decided that the project should be delayed pending the purchase of a new machine. Delays in the budgeting and procurement

processes have been overcome, and the new machine is due to arrive on or before July 2. The project will then proceed as originally planned. We are therefore requesting to extend the project for another year, although no new funding is required.

Significant findings to date:

-The preliminary trial of x-rays of 23 apples revealed that the survival rate for the larvae placed on the apples was 11 out of 23. For the larger study we therefore anticipate infesting at least twice as many apples than the final number required.

The first signs of infestation in the x-ray images occur no earlier than the fourth day after infestation, and apples begin to deteriorate after the 18^{th} day.

-With training and testing on the limited set of images from the trial described above, the automatic recognition algorithm correctly identifies 27% of infestations between day 4 and day 7 (inclusive), 73% between day 8 and day 12, and 94% beyond day 12. False positives were approximately 10%. With such a small data set, these results indicate only that the algorithm appears to work reasonably well. Training and validation with a much larger set are critical, and results will change (hopefully for the better).

Methods for the remainder of the project:

1. Larvae from the existing codling moth colony will be used to infest apples of four cultivars: Red Delicious, Granny Smith, Golden Delicious, and Fuji. Organically grown apples will be used to ensure an absence of pesticides. The experimental design calls for a minimum of 50 apples of each cultivar for the infested images, as well as an additional 400 of each cultivar for the non-infested images. Thus, the experiment will require a total of 1600 apples, or about 40 boxes. For each cultivar, the initial 400 apples will be x-rayed to form the set of non-infested images. Then 125 of the apples will be infested as described below, as preliminary research indicates that the survival rate for the insects is approximately 50%. This will result in the required number of images (at least) for both infested and un-infested fruit.

   Details of the infestation process: Codling moth larvae are placed on apples immediately after hatching from the egg (first instar). Apples that show no sign of infestation in the x-ray images after 10 days will be removed. A fraction of the apples will be dissected on selected days to verify the life stage of the insect so that a correlation can be made between the extent of damage seen in the images and the actual stage of the insect.

2. The inoculated apples from each cultivar will be imaged every second day. Imaging will continue for approximately 18 days. Preliminary work has shown that the digital x-rays have resolution sufficient to identify codling moth infestations in apples as early as four days after inoculation (Fig. 1), and that by the 18^{th} day the apples become too rotten to continue. Past experience has shown that one technician should be able to image the 200 apples in four to six hours. After the last day of imaging, the apples will be sterilized in an autoclave and discarded. The resulting databases (one for each cultivar) will contain 400 images of apples with various levels of infestation as well as approximately 400 non-infested apples. On each day that x-ray images are taken, a fraction (depending on survival rate) of the apples will be dissected and the actual life stage of the insect determined, so that a correlation between the life stage and appearance in the image can be established.

3. On the days that the apples are not being imaged on the x-ray equipment here, they will be taken to Scantrac Corp (Hayward, CA) and imaged on a commercial linescan x-ray machine, yielding a second database of images on a machine that is suitable for installation in a processing plant. This will allow comparisons that may guide us in adapting the machine to be able to detect codling moth infestations.

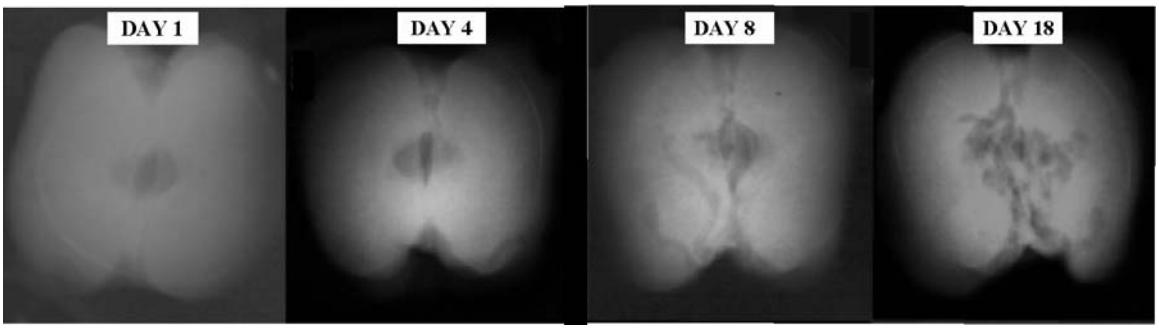

Fig. 1. X-ray images of an apple infested with codling moth larvae obtained with a real-time digital x-ray machine. The apple was infested on day 1 with a codling moth larvae (1st instar), then x-rayed on a daily basis. Signs of infestation start to appear in x-ray images by the fourth day, and are clearly visible by the eighth day.

4. A PC based scrolling program (already developed) that uses the x-ray images to simulate apples moving on a processing line will be used to test the ability of human operators to identify infested fruit. The program is designed so that images of infested and non-infested apples pass on the computer screen in a random fashion. By touching an apple on the screen, the operator being tested can indicate the perceived presence of an infestation. Recognition rates will be tested as a function of cultivar, degree of infestation, and scrolling speed.

   Details of the scrolling program: The scrolling program, developed using Tcl / Tk software, displays a single image panned across the display monitor. To implement a right to left scroll, the image is initially positioned (virtually) on the outer edge of the display (and out of view). The image is then panned at a fixed rate matching the speed of apples moving on a processing line, so that it crosses the screen and disappears on the left edge. Identification of defects is accomplished by the operator touching the image on the screen. Operator training is minimal, comprised of viewing images of infested and non-infested fruit beforehand. Identifying codling moth damage in x-ray images of apples is not a skill that requires a lot of training: if evidence of damage exists in the image then a relatively untrained person can identify it. At this point it is anticipated that the scrolling tests will be conducted with four different operators. The tests will be conducted using the images from the digital x-ray machine, as well as with the images from the commercial linescan unit. At this point, we have not been able to test the commercial unit, and do not know the quality of the images it will produce.

5. A computer algorithm has been developed to automatically identify the infested fruit. This program uses a discriminant analysis routine based on features extracted from the images obtained in the trial experiment described earlier. The necessity for rapid processing limits the number of features that can be extracted from the images for the discriminant analysis routine. This limitation is overcome by selecting a large number of potential features, then following a procedure that performs discriminant analysis on each possible combination of a smaller subset of the features. This procedure is outlined in the flowchart of fig. 2 in the case where three features are being selected from a larger group of potential features. The resulting discriminant function is then used as the basis of the final sorting algorithm. Because the selection of features has, so far, been limited to a small set of apple images, it is likely that the features will have to be modified when testing (and training) with a larger number of samples. The algorithm will be tested on the images from the two x-ray machines as described earlier, and results compared to those obtained by human operators using the scrolling program.

6. The results of the research will be evaluated to determine the best approach for the implementation of a sorting device in an apple processing plant. Clearly, the preferred approach will be to implement the automatic recognition algorithm, eliminating the need to have personnel observing each image. This would decrease the expense of operating the system and thus make it more likely that it would be adopted by the industry. The performance of the commercial linescan machine will be evaluated against the higher resolution unit in the lab. Necessary changes to the linescan unit to make it suitable for insect detection in apples will be explored.

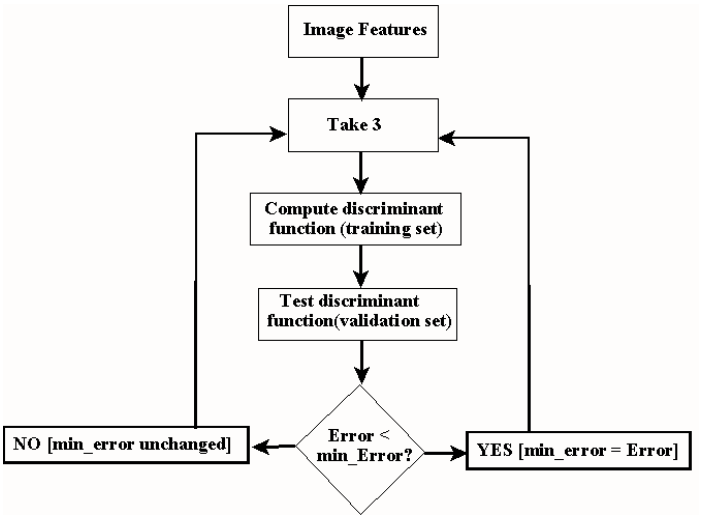

Fig. 2. Flowchart outlining the procedure for selecting the best possible combination of three features from a larger set of features. In this example, the three best features are being selected, but in reality any number of features could be used. The set of image features, previously extracted from the images, is divided into a training set and a validation set. The training set is used to compute the discriminant function, which is then tested on the validation set and the error compared with the previous minimum error.

Budget:

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The following table indicates the budget allocations for the past year as funded by WTFRC. The only additional cost was for the purchase of the new digital x-ray equipment ($40,000) which has been covered out of the base funds for our CRIS project. As the project was intended to be finished in a one year period, no further funding is requested for the upcoming year.

Item	Cost ($)
Labor (Albany)	16,000
Labor (Yakama)	5,000
Benefits 10% (USDA-ARS)	2,100
Transportation[1]	1000
Apples and supplies	900
Total	25,000

[1] Between Albany and Yakima