X-RAY BASED STEM DETECTION IN AN AUTOMATIC TOMATO WEEDING SYSTEM

R. P. Haff, D. C. Slaughter, E. S. Jackson

ABSTRACT. *A real-time, non-contact stem detection system was developed for crop plant location sensing in automatic weed control in transplanted tomato fields. A tractor-mounted, portable x-ray source projected an x-ray beam perpendicular to the crop row and parallel to the soil surface. In operation, the plant's main stem absorbs x-ray energy, decreasing the voltage output (signal) from the detector, allowing robust main stem detection even in the case where the main stem is occluded by weed or crop foliage. This signal was used to automatically control the operation of a pair of in-row mechanical weed knives. Minimizing the source to detector distance allowed for differences in signal strength between stems and background between 180 and 300 mV (60% to 100% drop in signal strength) at low x-ray energy and current levels (25 keV, 7 mA), which is a significant advantage for safety reasons. Background noise levels were ±30 mV, corresponding to a range of 10% to 16.7% of signal strength. The detector utilized a linear array of photodiodes aligned perpendicular to the soil surface. This configuration helped differentiate branches, which are angled and block only some of the photodiodes, from the main stem which has a similar vertical alignment as the array and hence blocks most or all photodiodes. A field trial was conducted at the standard time of first cultivation in a 17.5-m section of row in an organic transplanted tomato field, containing 43 tomato transplants. At a travel speed of 1.6 km/h, the detection system correctly identified 90.7% of main stems of the tomato plants. Four tomato plants (9.3%) were not detected because they had fallen over and passed below the detector. There were no false positive detections.*

Keywords. *X-ray, Detector, Weeds, Tomato.*

California is a major producer of processing tomatoes, with a yield of 10.7 million metric tons in 2008. This represents 94.4% of the total U.S. crop with a value of 897 million U.S. dollars (USDA, 2009). Despite a steady increase in crop value, from 57.4 $/ton in 2004 to 75.9 $/ton in 2008 (USDA, 2009), producers in the Sacramento Valley in California reported net returns of -4.3% on a per acre basis in 2008 (Miyao et al., 2008). Weed control is a major component of both the pre-planting operation and the cultural practices during the growing season and accounts for about 6.6% of production costs (Miyao et al., 2008). A substantial reduction in weeding costs thus has the potential to make the difference between operating at a loss and making a profit. Weeding costs are approximately divided evenly between chemical application, cultivating, and the labor of hand weeding. An automated weed control device would benefit the industry and consumers by alleviating these costs and reducing the potential for chemical residue on tomatoes. Reducing the use of herbicide also yields environmental benefits.

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For the case of organic farming, weeding is done exclusively by manual labor and costs are substantially higher. In the case of organically grown onions, for instance, weeding costs comprise about 15% of total costs, with hand weeding accounting for 89% of overall weeding costs. Therefore, 13% of the total organic onion production costs are due to hand weeding costs alone (Klonsky et al., 1994). Furthermore, Vargas et al. (1996) showed that hand-hoeing crews make mistakes and leave weeds in the row, eliminating only about 65% to 85% of the weeds on average. It is anticipated that an automatic system could approach 90% weed removal level on a consistent basis. If follow-up manual weed control were used, a higher level of weed removal could be attained since the machine has already removed most of the weeds.

A variety of herbicide (for non-organic production) and mechanical weed control techniques are applied in tomato fields at various times of the year. In general, weed control treatments are applied at four different times: fall (after harvest), preplant (before weeds emerge), postplant (after weeds emerge), and layby (after the crop is established) (California Tomato Commission, 2003). During these periods a combination of herbicide application (for non-organic fields), mechanical cultivation, and hand hoeing are generally employed to control weeds. Costs for manual weeding are continuously increasing and the availability of farm workers is becoming problematic in the United States and could become more so in the future. Conventional growers currently have a variety of approved herbicides, but future regulation could limit the choices (Stern, 2009). Consequently, weed control has been identified by the tomato industry as a key area of research need. In particular, the development of new technologies and techniques to control bindweed, nutsedge, and nightshade are needed (California Tomato Commission, 2003).

With the introduction of automated planters in the 1960s, plant spacing along tomato rows became precise enough to allow the introduction of automatic thinning equipment (Inman, 1968). This technology was quickly recognized to be a suitable basis for automatic weeding devices, and a great deal of research effort has been devoted towards this goal. The main components of an automated weeding system address differentiation between weeds and crops as well as destruction of weeds while leaving crop plants intact. For plant identification and differentiation, the majority of past research has focused on either machine vision or spectroscopy (Slaughter et al., 2008a). In a review of machine vision methods for weed sensing, Slaughter et al. (2008b) concluded that crop versus weed classification accuracies in the range of 65% to 95% are frequently reported in the literature under ideal conditions. These approaches tend to encounter complications due to the unpredictability of illumination in the natural environment (Lee et al., 1999). Attempts to develop automated weeding devices have included a variety of approaches. Rotating hoes have been used to remove weeds, with the hoes being physically raised when crop plants are encountered (Astrand and Baerveldt, 2002). Precision application of herbicides has been a particularly active area of research (Cox and McLean, 1969; Lee et al., 1999; Downey et al., 2004; Giles et al., 2004). Thermal methods for killing weeds have included flame (Mathews and Smith, 1969) and hot fluid spot application (Daar, 1994; Zhang et al., 2009). Finally, electricity in the form of both high voltage (15-60 kV) discharge and continuous current has been used to kill weeds (Diprose and Benson, 1984).

A mechanical device is currently under development for removing weeds in rows of transplanted tomatoes that does not depend on imaging or spectral analysis for plant differentiation, thus bypassing many complications inherent in machine vision or spectroscopy-based systems (Stern, 2009). This system employs articulated weed cutting knives and thus has the added benefit of not using chemicals for weed eradication, making it suitable for conventional and organic production. A schematic for this device is shown in figure 1.

In this system, a shielded safety tunnel is pulled behind a tractor along the crop row. This tunnel provides operator protection from radiation exposure and accidental exposure to the mechanical weeding knives, as well as soil flow control. Cultivation tunnels, which prevent tilled soil from burying tomato seedlings, are commonly used in conventional vegetable row crop cultivators during the first, close, inter-row cultivation when the tomato seedlings are small. Otherwise the freshly tilled soil often flows toward the center of the bed, burying the crop plants. At a later growth stage, this is desirable, since it buries weed seedlings without harming the crop, but at first cultivation, it can also bury the crop plants. A pneumatic cylinder powers a weed knife pair which travels below the soil surface and cuts down the weeds. The intra-row weed knife design was similar to that used in the Eversman sugarbeet thinner (Kepner et al., 1972). An x-ray source delivers collimated x-rays into the tunnel through a steel pipe, which are directed onto a detector mounted on the opposite side of the tunnel. The voltage

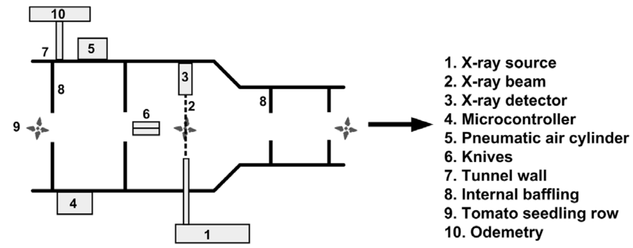


Figure 1. Schematic of automatic system for in row weed control in transplanted processing tomato fields.

output from the detector (hereafter referred to as the detector signal) is continuously analyzed by a microcontroller which controls the air flow to the pneumatic air cylinder. When the stem of a tomato plant blocks the x-ray beam, the reduced signal causes the microcontroller to generate an electronic pulse to activate the pneumatic cylinder, separating the knife blades so that they bypass the plant. The weed knives are mounted inside the tunnel and thus there is a fixed distance between the x-ray beam and the leading edge of the knives. Odometry, using an optical encoder connected to an unpowered ground wheel determines position and velocity of the system. The real-time controller monitors the distance traveled after stem detection and actuates the knives when they reach the appropriate location. This system is intended for use when the transplants are significantly taller than the weeds, in the early post-planting period (fig. 2). In the event that weeds have grown tall enough to block the x-ray beam and have vertically oriented main stems of comparable diameter to the crop plants, then they would be falsely identified as tomato plants and left intact. Figure 3 shows the prototype system in the field.

X-rays are used to detect the tomato plants because the plants are draped with their own leaves or are occluded by weed foliage, which can block an infrared laser or visible light beam and activate the knives at the wrong time. An x-ray image of a tomato transplant (fig. 4) illustrates the advantage of x-ray, as the leaves are much more transparent than the stems and do not interfere with accurate stem detection. Some difficulty arises because the density of the branches is similar to that of the stem, potentially causing the knives to open earlier and longer than desired. Note that this image merely illustrates different x-ray densities for different parts of the plant, as x-ray imaging is not part of the apparatus design.

This article focuses on the development and testing of the x-ray based stem detection component of the automated weeding device. X-ray technology has been used in a similar

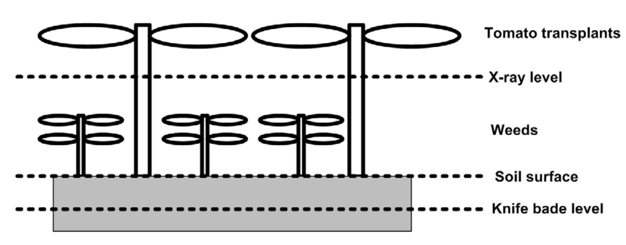


Figure 2. Schematic showing the knife blade level, soil level, and x-ray level as related to the heights of the tomato transplants and present weeds. The design of the apparatus depends on the assumption that the weeds are significantly shorter than the tomato plants.

Figure 3. A prototype automated device for in-row weeding of processing tomato transplants.

Figure 4. Scanned film x-ray of a tomato transplant. This image was generated on Kodak Industrex CX film using a Faxitron x-ray film cabinet (30 keV, 90seconds). The film was scanned at 150 dpi on a Microtek Scanmaker 9800XL film scanner.

fashion to measure the maturity of lettuce heads for mechanical harvesting (Lenker and Adrian, 1971 and 1980; Schatzki et al., 1981a and 1981b). Adrian et al. (1973) showed that x-ray density was more effective than either mechanical or gamma ray based sensing systems for accurately judging interior density. Each of these prior approaches employed a single photodiode as the x-ray detector, which was sufficient for their application as the size of the lettuce head is much greater than the size of a photodiode. The case of detecting tomato plant stems, especially young transplants, is more complicated due to the smaller size of the stem.

Objectives

The objective of this research was to design, construct, and test an x-ray system to detect the location of the main stems of crop plants in a commercial processing tomato field. The x-ray system was a component of an automated tomato row weeding system, controlling the operation of a pair of mechanical knives which cut weeds while leaving tomato plants intact.

Methods and Materials

Initial concept testing was performed in the laboratory using 10 tomato plants in 4-in. (10.2-cm) pots. The plants were placed on a conveyor belt at a speed of 50 cm/s, approximately equal to the tractor speed (1.6 km/h) in subsequent field trials. The plants were conveyed between the x-ray source and the detector array, with a source to detector distance of 14 cm. The detector signal was recorded using an oscilloscope. This experiment was repeated daily for six consecutive days, and the average stem diameter, plant height, and detector output were recorded in order to determine the range of plant sizes over which the device would reliably detect the main stems.

A schematic of the x-ray detector circuit used to detect the stems is shown in figure 5. The photodiode array used in the detector, which was salvaged from an obsolete linescan x-ray machine (E-scan model, Astrophysics Research Corp., Long Beach, Calif.) consisted of 32 photodiodes (0.5 mm diameter) overlaid with Gadolinium Oxysulfide, a rare earth x-ray phosphor (Gd_2O_2S:Tb). The output voltage of each photodiode was amplified using an operational amplifier circuit, the outputs of which were joined at a single point at the input of a summing amplifier. Hereafter, the term detector shall refer to the photodiode array plus the summing amplifier, so that the voltage output of the detector (detector signal) refers to the voltage output from the summing amplifier. Thus the output of the detector was the sum of the outputs of the individual photodiodes, rather that individual outputs as would be the case for in imaging. A linear array of photodiodes was selected over a single photodiode of larger area to increase the signal-to-noise ratio and to take advantage of the geometry of the tomato main stem. While the x-ray detection system can easily differentiate between leaves and stems, the branches can cause false positive detections if using a single photodiode. This problem is

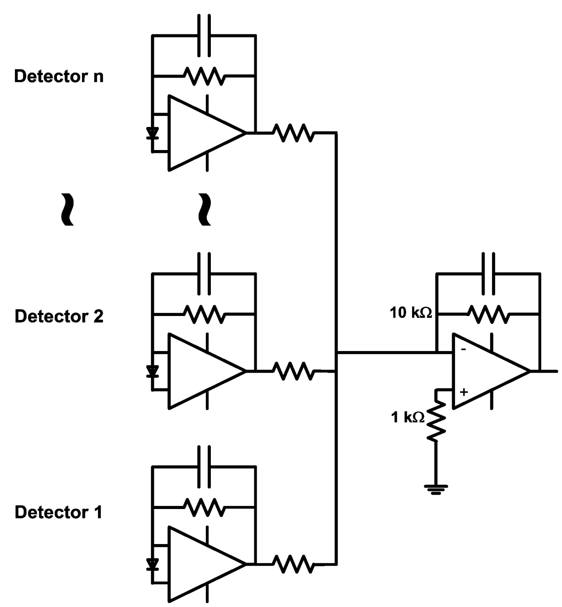


Figure 5. Schematic of a linear array of photodiodes with outputs tied to the input of a summing amplifier as used for the x-ray detector. The output of the detector is the sum of the outputs from each photodiode circuit.

reduced with a linear array of photodiodes mounted vertically as the branches cross the line of sight of the array at an angle while the main stem runs (roughly) parallel to the array (fig. 6). Thus, the branches tend to block only a small number of the photodiodes in the array, while the stem blocks most or all, and the difference in signal is sufficient to differentiate stems from branches.

The detector was mounted in metal housing which provided mechanical protection, electronic noise suppression, and extended the array away from the side of the tunnel so that source (end of the steel pipe, as described below) to detector distance was reduced to 14 cm (figs. 7 and 8). This minimized the dispersion of the x-ray beam as it traveled across the tunnel to the detector while leaving sufficient space for the tractor to navigate the row without destroying the tomato plants. The 14-cm spacing was similar to the spacing between the knives in a traditional cultivator, and thus it is not a problem for the driver to avoid hitting tomato plants with the detector or the pipe.

The x-ray source was a Lorad air-cooled portable x-ray system (model 1351006071, Test Equipment Distributors, Troy, Mich.). The x-ray tube and casing were mounted to the side of the tunnel as shown in figures 1 and 3. A galvanized steel flange was mounted over the output window of the x-ray tube so that a 19-mm inside diameter galvanized steel pipe could be threaded over the window. The pipe, which provided collimation of the x-ray beam, was positioned parallel to the soil surface at a height of 4 cm and terminated 7 cm from the crop row (fig. 8). The beam height was selected to minimize false classification of soil clods or weeds as tomato stems, while striking the tomato stem at a point where its diameter allowed sufficient x-ray absorbance to facilitate consistent detection. The pipe was also necessary because the size of the x-ray tube and casing was such that it had to be mounted over the furrow so that it would not be dragged in the soil (figs. 1 and 3).

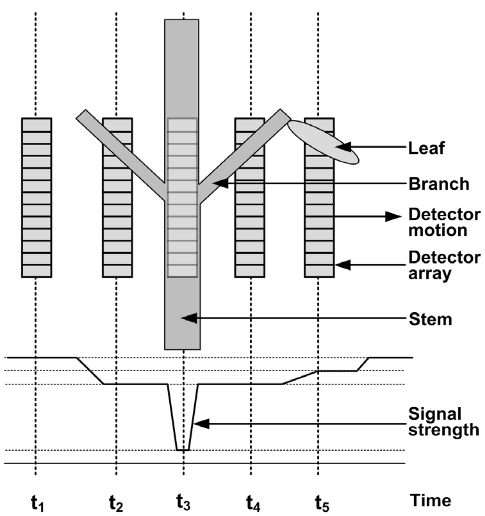
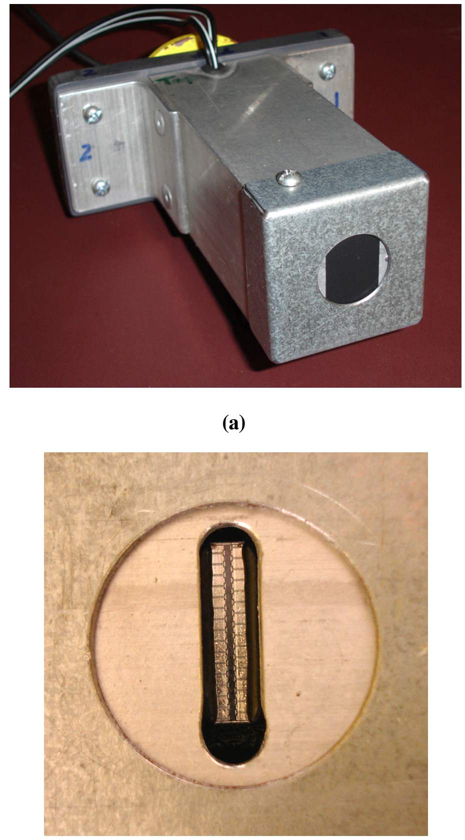


Figure 6. Due to the vertical alignment of the detector array, leaves and branches block the signal at the detector much less than the main stem. This figure illustrates the alignment of the array as compared to leaves and branches at various times as the array approaches and passes a tomato plant. In this configuration, the x-ray beam is directed into the plane of the figure.



(a)

(b)

Figure 7. X-ray stem detector. (a) View of the assembled detector. The metal housing provided mechanical protection and electronic noise shielding. The detector array was located in the center of the circular hole and covered by black electrical tape to block ambient light. (b) Close up view showing the vertical array of photodiodes used to detect x-rays.

Field tests were conducted to evaluate the performance of the x-ray system in a randomly selected 17.5-m section of a processing tomato field containing approximately 50 tomato transplants. The field site was located at the Western Center for Agriculture Equipment (WCAE), on the University of

Figure 8. Top view of the galvanized pipe (right side) delivering the collimated x-ray beam and the x-ray detector box (left side). Both are mounted to minimize the source to detector distance, improving the signal strength and increasing the signal to noise ratio.

California, Davis campus. The seedlings were transplanted using standard commercial practices with a traditional Holland-type transplanter on raised beds between 30 and 45 days after the seeds were planted in transplanting flats. Row spacing was 1.5 m and plant spacing along the row was 38 cm. At the time of the field tests, 7 of the 50 plants had died and 4 had fallen over due to wind such that a portion of the main stem was parallel to the ground and the top of new growth was several centimeters below that of the upright plants. The remaining 39 plants were generally upright, with a median angle between the main stem and vertical axis of about 15°. However, a few plants were bent as much as 45°. All plants were taller than 12.2 cm, so a 40% signal drop was applied as the threshold for stem detection, as determined from the results of the laboratory trials (see fig. 9 and discussion). No herbicides were used in the test plots, simulating organic production and thus allowing weeds to grow. The test of the detector was conducted at a travel speed of 1.6 km/h. The x-ray power source was set at 25 keV, 7 mA, the lowest energy that saturated the detector output when no stem was present. This was necessary as radiation exposure outside the tunnel, especially at the open ends, is a concern for safety reasons. Each plant was considered as a replicated detection event, and there were 43 main stems in the 17.5 m of row selected for study.

A ruggedized, embedded controller (model cRIO-9004, National Instruments, Austin, Tex.) with a low-power CPU (195 MHz Pentium, Intel, Santa Clara, Calif.) and 512 MB of nonvolatile flash memory storage was used to record the detector signal during the test. The raw detector signal was digitized at 16-bit resolution at a real-time rate of 10 kHz using an input module (NI 9205, National Instruments, Austin, Tex.) interfaced controller as the system was pulled along the row. System odometry was sensed using an optical shaft encoder (model 0622 Grayhill, Inc., Ill.) mechanically interfaced to an unpowered ground wheel with a pneumatic tire that traveled in the furrow, providing a resolution of 0.6 mm in the direction of travel. A high-speed digital input module (NI 9411) was used to maintain a cumulative count of the odometry value associated with each x-ray measurement. The ground truth location where each tomato main stem entered the soil surface was manually determined using a tape measure. The sensor data was analyzed using the SAS statistical software package to locate the main stems while ignoring any leaves or branches. The raw detector signal was filtered to remove high frequency noise with a 25-point convolution window (corresponding to 2.5 ms) using a Savitzky-Golay central moving average quadratic smoothing operation (Savitzky and Golay, 1964; Steinier et al., 1972). The filtered signal data collected during the field trial was then scanned to detect the dominant local minima within a 30-cm moving window using a custom program written in SAS Institute Inc. (2010). The window size of 30 cm was selected to cover a region along the seed line of approximately 75% of the plant spacing, and was required in order to avoid false identification of large branches of a tomato plant as the main stem location. A threshold of 180 mV was selected as the level below which the x-ray signal must drop to be considered a potential tomato stem in the field test. The dominant local minima (with a signal below 180 mV) within each 30-cm convolution window was defined as a tomato stem for the field test data. It is important to note that the statistical analysis described here was used only to correlate the detector signal with the actual location of tomato stems as measured with the tape rule for the field trial, in order to measure the accuracy of the system. In actual operation, the weed knives are a fixed distance from the x-ray beam, and the knives are actuated at a time after signal drop determined by odometry information. Hence, the statistical analysis is not part of the normal operation of the system.

The use of x-rays creates the potential for radiation exposure, both for researchers developing the prototype and for workers using the system in the field. For this design, the cultivation tunnel was constructed with 14 gauge steel plate (approximately 2 mm thick) to ensure radiation levels outside the tunnel are not discernable from background, except at the open ends. Internal metal baffling (two baffles at the front of the tunnel and two at the back, fig. 1) was incorporated into the tunnel design to minimize the opportunity for stray x-rays to exit the tunnel while allowing for the passage of plants. The length of the tunnel was sufficient to prevent a person from reaching past the last metal baffle and placing their hand into the x-ray beam and the tunnel side walls extended more than 3 cm into the soil to prevent x-rays from exiting the tunnel along the sides. The source / detector system was designed to minimize the overall length of the x-ray path, so that sufficient signals could be generated at the lowest x-ray energies possible. Radiation surveys were conducted using an ion chamber survey meter (Model 44-7, Ludlum Measurements, Sweetwater, Tex.). To minimize the chances and/or severity of accidental exposure, an emergency shutoff button was mounted on the top of the tunnel, as well as a red warning light that activated when x-rays were on. All maintenance openings to the tunnel that could be inadvertently opened were secured with keyed padlocks and supplied with interlock devices that prevented x-ray power if disengaged. Finally, the pneumatically controlled knives could be a hazard to a worker who reached inside the tunnel. For this reason, as well as to reduce the x-ray intensity at the tunnel openings, the tunnel length was designed so that the knives (and x-ray source) were unreachable from the tunnel openings. Actual measured x-ray levels and NRC limits will be discussed in the next section.

Results and Discussion

The average detector signal for the laboratory tests with potted transplants are shown in figure 9. The average plant height on the first day was 10.9 cm with an average stem diameter of 4.0 mm. On the sixth day the average height was 13.4 cm, with a stem diameter of 5.6 mm. The single dominant spike in the detector signals represent the main stem, while the surrounding smaller spikes represent branches. Differences in the absolute voltage values between the field and laboratory trials were a consequence of the amount of gain applied to the output of the summing amplifier. While identical conceptually, the actual circuit was significantly modified between the laboratory and field trials in terms of components used, as the field version operated in much harsher conditions and needed to be more rugged than the laboratory version. In addition, noise levels vary significantly between lab and field conditions and the gain in the field was adjusted to increase SNR as much as possible. The relevant factor is the percentage drop in the

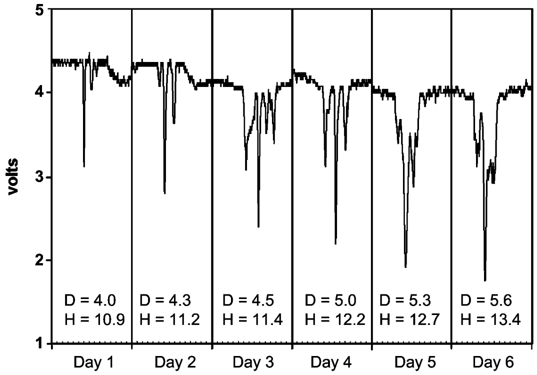


Figure 9. Daily plots of the detector array voltage output drops as potted tomato transplants pass between the detector array and x-ray source. D represents stem diameter in mm and H represents the height of the plant in cm. Each plot is the average of the voltage output for 10 plants, aligned so that the main spikes representing the stem coincide. D and H are also averages for 10 plants.

voltage output. Applying a 40% voltage drop threshold indicates that reliable stem detection requires a stem diameter over 5.0 mm. For these plants this represents a height of 12.2 cm. Of course, the ratio of stem diameter to plant height would vary for different cultivars and even different growing conditions. The 40% threshold was derived by trial and error and educated guessing, but was confirmed in the results of the field trials below.

The x-ray sensor signal collected during the field tests is shown in figure 10. The noise level of the detector signal was approximately ±30 mV. The detector signal measured near 300 mV when nothing blocked the x-ray beam, and dropped below at least 120 mV (equivalent to at least 60% drop in signal strength) when a tomato stem was present. The initial voltage level was determined by the amount of gain on the summing amplifier and was selected to maximize the signal to noise ratio. The level of signal drop was proportional to the size and density of the object blocking the beam, and thus as expected, plants with thicker main stems were easier to detect than those with thinner stems. Tomato main stems on 39 plants (90.7% of the total) were detected. The median voltage level for the standing tomato plants was 29 mV (90.3% reduction in signal strength) with a maximum voltage (smallest reduction) of 117 mV (60% reduction). The only stems that were not detected were on four plants (9.3% of the total) that had fallen over after transplanting due to wind and the new growth did not have sufficient height to be detected. There were no false positive detections. The lack of false positive detection, a potential consequence of soil buildup at the detector, indicated that the tunnel design was working well. The system is clearly expected to perform best in rows with uniform plants that have not fallen over. The accuracy in determining the point where the stem enters the soil is improved when the main stem is vertical. The data indicates that setting a detection threshold at 180 mV for this detector arrangement, or 60% of the original signal, is sufficient to detect all stems in this trial. This corresponds to the 40% drop in signal described earlier.

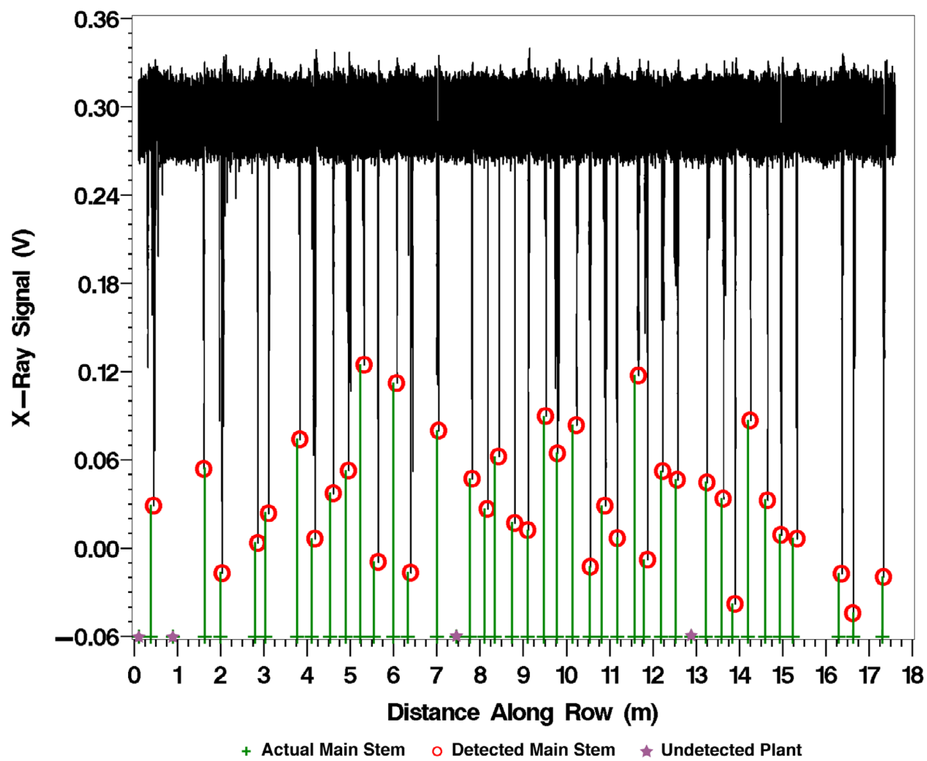


Figure 10. Plot of the x-ray signal output by the sensor as the system traveled along the row of tomato transplants. The black line shows the signal from the array of photodiodes. When nothing blocks the x-ray beam, the signal level is about 0.3 V. The signal level drops when an object blocks the x-ray beam. The level of signal drop is proportional to the size and density of the object blocking the beam. The circles show the location of the tomato main stems detected by the sensor. The horizontal axis represents the distance along the row. Green lines were drawn on the graph to show where along the row the actual tomato stems were located as determined by placing a flexible measuring rule on the soil.

A summary of the deviation between the location where the x-ray sensor detected the main stem and the location determined by manual measurement using a measuring tape is shown in table 1. The average deviation between the stem location detected by x-ray and the measured location of the stem at the height of the detector was -0.62 cm, while the average deviation at the soil level was 1.03 cm. As expected, there was considerable variation in the deviation with a standard deviation of about 3 cm at the sensor height increasing to almost 4 cm at the soil level. For plants at a 45° angle with the vertical axis, the maximum deviation at the soil level approached 8 cm, representing a worst case situation.

It would certainly be possible to incorporate the statistical analysis used above in a standard low-cost microcontroller for a future prototype device, so that it becomes part of the working mechanism. Many modern industrial embedded controllers use Field Programmable Gate Arrays (FPGA) which are economical and fast. The actual computations used here were not computationally intensive. The Savitsky-Golay method required only 25 multiplications and 25 additions per step in the moving average smoothing operation, which is trivial for modern processors (including low-cost embedded controllers). The final stem scanning required a few simple comparisons per step in the process. There is only a one-dimensional data stream coming from the x-ray sensor, not a 2D x-ray image, as the outputs from the 32 photodiodes were summed in the analog summing amplifier before being digitized by the data logger. Thus, the data load is not difficult to handle. Further, as long as the distance from the x-ray sensor to the knife is large enough, the exact analysis that was done here in SAS could be re-written in C++ or VHDL and run on a controller. In our design plan, we did foresee the need for a distance buffer between the detector and the knife in order to allow the system to fully evaluate the x-ray output. It is anticipated that analog signal filtering would be included in a final commercial product, which would eliminate the computation for smoothing. The algorithm would then be reduced to a simple comparison per data point. SAS was selected in this study out of personal preference and due to its ability to easily handle large data sets, but the program could have been written in Python, Java, or any other modern language, since no SAS procedures were used in the analysis other than PROC GPLOT to display the results.

The use of x-ray for stem detection has a number of inherent disadvantages compared with other technologies such as visible light or lasers. These include equipment cost, size and weight, and issues with radiation. The portable system reported here, which costs roughly US$25,000, was used for the prototype system because it was rugged and commercially available. This system was designed to operate at energies up to 140 kV, and consequently included a bulky power supply. The size of the tube casing dictated the need to mount the tube in the furrow so that it was not dragged in the soil (fig. 3). Since the x-ray energy and current levels required for stem detection were quite low (25 keV, 7 mA) a much smaller tube and power supply would suffice, lowering the cost and design complexity. A smaller tube could be mounted inside the tunnel, significantly reducing the source to detector distance and allowing the same results at even lower energies. This in turn would reduce the amount of shielding required and the potential for radiation exposure. Even so, other technologies would be more economical and convenient, if the problem with leaves blocking the signal could be overcome. Testing with other technologies has so far been unsuccessful, and consequently the use of x-ray is at this point advantageous.

Table 1. Summary of detection accuracy of tomato main stem locations using x-ray.

Deviation	No. of Plants	Mean (cm)	Std. Dev. (cm)
Of stem at sensor height	39	-0.62	3.08
Of stem at soil level	39	1.03	3.81

X-ray intensities at the openings of the tunnel were measured to be within safety limits and fell to background levels beyond about 3 ft from the opening. This ensures no exposure to the operator driving the tractor. Above background levels of radiation exposure, the NRC requires that its licensees limit maximum radiation exposure to individual members of the public to 100 mR per year, and limit occupational radiation exposure to adults working with radioactive material to 5,000 mR per year (NRC, 2010). In a worst case scenario, in which a worker was directly exposed to the source (25 keV, 7 mA) at a distance of 30 cm the dose is about 3600 mR/h (measured using an Accu-dose radiation measurement system, Radcal Corp, Monrovia, Calif.). Therefore, to reach the annual limit of 100 mR would take about 100 s. To reach the limit for adults working with radioactive material of 5,000 mR would take 5000 s (1.39 h). A worker could be exposed to significant radiation by handling the live x-ray tube, as the radiation directly at the window is intense enough to cause significant injury. Presumably this would never happen. In any kind of accident that could expose the source, interlock mechanisms would kill power to the tube. At the distance between the source and the driver's chair of the tractor, radiation levels would drop to around 0.3 mR/h without any shielding. With shielding in place, there is no risk of exposure. Of course, we do not recommend anyone ride on the tunnel or walk alongside it during operation, although they could safely do so. We could also consider the fact that to sterilize moths or pupae for use in Sterile Insect Technique requires doses on the order of 15000 Rad, so at a distance of 30 cm from the exposed source it would take over 4 h to sterilize an insect.

Conclusion

An x-ray based system was developed for automatic detection of tomato plant stems to guide weed knives for weed control in transplanted tomato fields. A portable x-ray source was aligned with a detector such that tomato plants would block the signal as the system moved along the tomato row. The use of x-ray allowed stem detection even in the presence of leaves. Differences in signal strength between stems and background were between 180 and 300 mV (40% to 100% signal drop) versus background noise levels around 30 mV at low x-ray energy and current levels (25 keV, 7 mA), which is a significant advantage for safety reasons. The detector utilized a linear array of photodiodes aligned perpendicular to the soil and parallel to the main stem of the crop plants. This configuration helped differentiate branches, which are angled and block only some of the photodiodes, from main stems which have the same approximate vertical alignment as the detector and hence block most or all photodiodes. The system was tested in a 17.5-m section of row containing 43 standing tomato transplants. At a speed of 1.6 km/h, the detection system identified all 39 stems of fully upright plants with no false positives. Four plants that had been blown over by wind and had not recovered to sufficient height to reach the x-ray beam were not detected.

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