PERFORMANCE EVALUATION OF OFF-SHELF RANGE SENSORS FOR IN-FIELD CROP HEIGHT MEASUREMENT

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ABSTRACT

In-season plant height is a good predictor of yield potential, which needs to be measured with techniques of high spatial resolution and accuracy. In this study, systematic performance evaluations were conducted on three types of commercial range sensors, an ultrasonic sensor, a laser range finder and a range camera on plant height measurement, under laboratory and field conditions. Results showed that the average errors between the measured heights and the ground truth heights were 16.2%, 12.4% and 18.9% for the ultrasonic sensor, the laser range finder and the range camera, respectively. Considering the measurement accuracy, robustness and cost, the ultrasonic sensor and the laser range finder have better perspective to be applied in in-field, real-time high-resolution plant height measurements.

Keywords: precision agriculture, ultrasonic sensor, laser range finder, range camera, crop height measurement

INTRODUCTION

Variable rate spraying (VRS) is an application of precision agriculture on chemical use. Development of VRS is motivated by the ever increasing prices of natural gas which is the energy source used for the production of nitrogen (N) fertilizers, as well as the low nitrogen use efficiency (NUE) of 33% in world cereal production (Raun and Johnson, 1999). Except for the natural loss of N, one reason for the low NUE is due to the traditional way of N application which gives a single rate of N to a large scale of field neglecting the in-field variability existed in soil properties, water availability and field topography, etc. (Zhang et al., 2002). VRS intends to solve this problem by two steps: sensing in-field variability and executing variable-rate chemical application based on decisions made in the previous step. The success of the first step is critical in the whole process. It relies on the development of sensing systems which can map desired variability accurately in proper resolution.

In-season plant height is a commonly recognized indicator of plant growing status. Combining corn by-plant height with NDVI could achieve better prediction for corn biomass and yield than using NDVI alone (Freeman et al., 2007). High spatial resolution plant height sensing can offer useful information for VRS system. However, difficulties exist in measuring plant height of those crops which have narrow and erratic shape of leave such as corn and sorghum. Most of research have been done in this area are limited in the lab environment in which sensing objects were plants grown in pots. Few researches have been done under field condition where there are overlaps between plants and other disturbance factors such as wind or vibration of the sensor.

The technology of non-contact range sensing has been greatly developed and widely used in various areas in the last few decades. Three range sensing technologies have been studied so far: stereo vision, ultrasonic sensor and laser range finder. The data processing of a stereo vision system is relatively computational expensive which may not be suitable for on-line VRS. This study focused on those range sensors which sensed distance directly.

An ultrasonic sensor measures the distance based on the speed of sound wave and the time interval between sending the wave out and receiving its echo back. Research has been reported for using ultrasonic sensors to measure plant height in cotton field and blueberry field (Sui et al., 2006; Sharma et al., 2008; Swain et al., 2009). Some applications can be found for corn plant height measurement in lab environment (Shrestha et al., 2002; Aziz et al., 2004; Jones et al., 2004). Good correlations were obtained between sensor measurements and manual measurements in those cases. Few reports can be found for application in corn or sorghum fields.

A laser range finders sends out laser light and measures the distance based on the speed of light and the time interval between sending the light out and receiving its reflection back. They have higher spatial resolution comparing with ultrasonic sensors because the laser light beam would not diverge much during travelling. A laser scanner achieves a line scan by rotating its laser source pointer. Airborne laser range finder has been widely used in photogrammetry and remote sensing for digital terrain modeling or large-scale crop surface mapping (Kraus and Pfeifer, 1998; Blair et al., 1999; Shrestha et al., 2005). For the ground-based sensing platform, one of the applications of laser range finder is autonomous navigation (Barawid et al., 2006; Lee et al., 2007). Another application is in crop shape profiling and density estimation (Wangler et al., 1994; Wei and Salyani, 2004, 2005; Saeys et al., 2008). Kataoka et al. (2002) compared the performance of an ultrasonic sensor with a single-beam laser sensor on measuring the height of soybean and corn. They concluded that the laser beam sensor was not suitable for crop height sensing because it was too sensitive comparing with the ultrasonic sensor.

As a new player in distance measurement arena, a range camera can provide users 3D distance information in an image form. Almost no applications of using the range camera in agricultural production have been reported so far. In other fields, it is applied for automatic guidance, object tracking and behavior analysis (Bostelman et al., 2006; Guðmundsson et al., 2008; Grassi et al. 2008).

The objective of this study was to evaluate the performance of three range sensing technologies (ultrasonic sensing, laser scanning, and range camera sensing) on crop height measurement, and to recommend an approach which has potential to realize in-field high spatial resolution crop height measurements in future. The specific objectives included: (1) to develop data acquisition and control systems for the three sensors, respectively, so that they could be used to collected data in field; (2) to develop corresponding data and image processing algorithms for height information extraction and by-plant recognition; and (3) to compare the performance of three sensors based on measurement accuracy, robustness and cost.

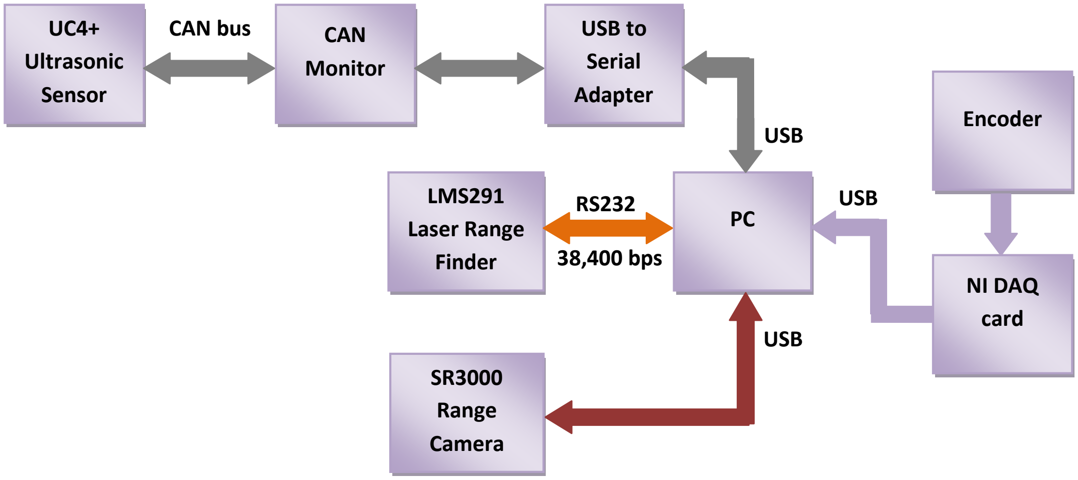


Fig. 1. Block diagram of the data acquisition systems.

MATERIALS AND METHODS

Sensors Description and Data Acquisition Systems

Three commercial range sensors were used in this study: NORAC UC4+ ultrasonic sensor (NORAC Systems International Inc., Saskatoon, Canada), SICK LMS291 laser range finder (SICK AG, Waldkirch, Germany) and SR4000 range camera (MESA Imaging AG Inc., Switzerland). Their feature specifications are listed in Table 1, 2, 3. Data acquisition systems were developed for each sensor respectively. The ultrasonic sensor output CAN messages and communicated with a PC through a USB to serial adaptor; the laser range finder communicated with PC through RS232 at 38,400bps; and the range camera communicated with PC through USB. An optical encoder and a DAQ card were used in each data acquisition system to make sure the sensors to record data at certain distance interval. An illustration of the hardware part of the data acquisition systems is shown in Fig. 1. Programs were developed in LabVIEW to control ultrasonic sensor and laser range finder to collect and store data every 10cm and every 5cm respectively. For the range camera, the MESA Imaging proprietary software SR_3D_View was used. The overlaps between images were eliminated during later image processing.

Table 1. Feature specification of NORAC UC4+ ultrasonic sensor.

Manufacturer Calibrated Range	0.30m ~ 1.3m (12’’ ~ 50’’)
Beam Angle	15°
Transducer	SensComp 600 Series, 50kHz
Resolution	±1% over entire range
Power Supply	12VDC
Communications	CAN bus to USB

Table 2. Feature specification of LMS291 laser range finder.

Laser source	905 nm (Near-infrared)
Effective sensing range	8 m (with 1mm resolution)
Angular resolution	0.25°
Time for a complete scan	53 ms
Max. scanning angle	100°
Max. number of measurements	401 (0.25°, 100°)
Measurement resolution	1 mm
Data interface	RS 232
Communication rate	38,400 baud rate
Supply voltage	24 VDC ± 15%
Laser protection class	1 (eye-safe)

Table 3. Feature specification of SR4000 range camera.

Illumination Wavelength	850 nm
Modulation Frequency	29/30/31 MHz
Emission Angle	34.6° (vertical) × 43.6° (horizontal)
Focal Length	10 mm
Pixel Array Size	144 (vertical) × 176 (horizontal)

Calibrated Range	0.8 ~ 5.0 m
Angular Resolution	0.23°
Power supply	12 VDC ± 5%

Sensors Calibration on the Lab Platform

A lab platform was constructed with a size of 3m × 1m × 2m (length × width × height) (Fig. 2). Sensors were mounted facing down. They can move along a rail simulating the vehicle moving condition in field. For each sensor, two calibrations were conducted: sensing accuracy calibration and sensing resolution calibration. In the sensing accuracy calibration, a 1cm × 1cm paper board was placed from 15cm to 150cm away from the ultrasonic sensor and from 50cm to 150cm away from the laser range finder and the range camera. The board was directly under the sensor, in parallel to its front surface. In the sensing resolution calibration, two tests were conducted: 1) for the ultrasonic sensor, the orientation of the 1cm × 1cm paper board and the displacement of it away from the sensor’s center axis were investigated; 2) for the laser range finder and the range camera, a set of metal bars in different widths (1cm, 1.5cm, 2cm, 2.5cm, and 3cm) were placed along the moving direction of the sensors to test sensors resolution in moving condition.

Field Tests on a Trolley

Field test was conducted in October, 2009 in a sorghum field in Stillwater, Oklahoma. The sorghums were in their early growth stages (20cm~50cm tall). Two rows were selected as test samples, one was 5.74m long with 52 plants, and the other was 13.52m long with 143 plants. A

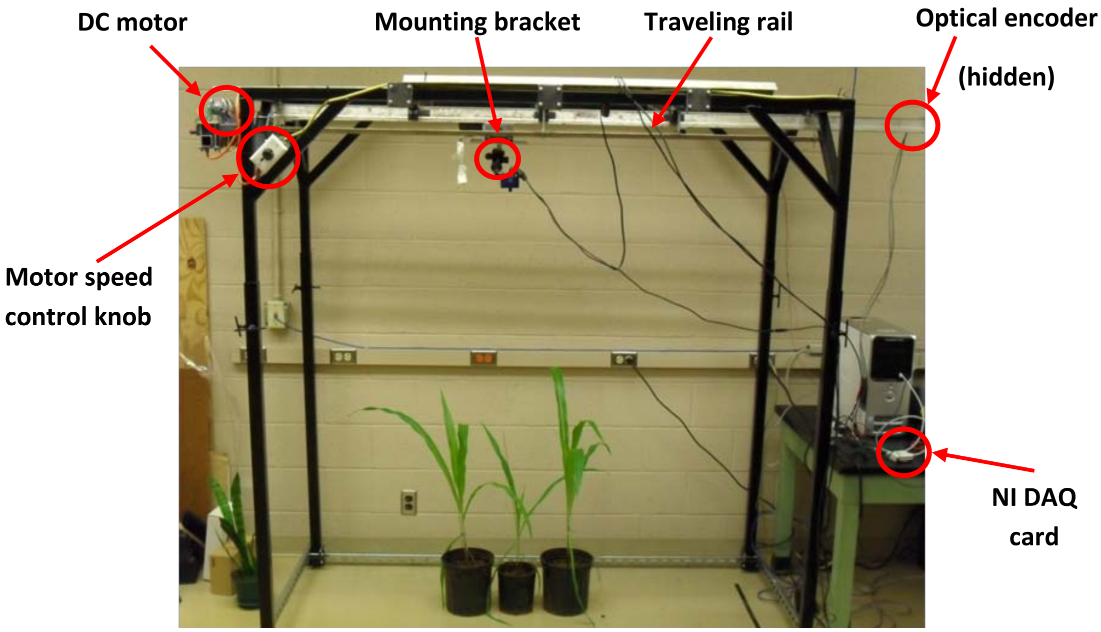


Fig. 2. Lab platform including travelling rail, sensor mounting bracket, DC motor, speed control, optical encoder, DAQ card and PC.

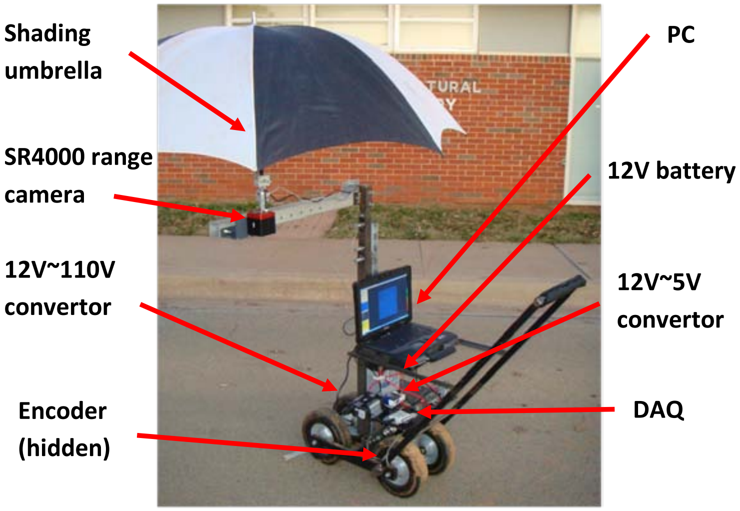


Fig. 3. Trolley for field test including 12V battery, voltage convertors, sensor mounting bracket, shading mechanism, shaft encoder, DAQ card and PC.

trolley was built with the same data acquisition systems as used for lab tests (Fig. 3). It was pushed along the alley between two rows with a speed lower than 0.447m/s (1mi/h). Sensors were mounted on the beam of the trolley, one at a time, facing down directly above the plant row. To reduce the effect of strong sunlight, a shading mechanism was used when testing with the range camera. The mounting heights for the ultrasonic senor, the laser range finder and the range camera were 1.05m, 1.06m and 1.20m respectively. The average spatial resolutions was Ø20cm (circle) for the ultrasonic sensor, 0.3cm on the scan axis ×

5cm on the sensor moving axis (rectangle) for the laser range finder, and Ø0.4cm (circle) for the range camera. These resolutions were determined based on sensors' sensing principle, configuration, mounting height, sampling rate and vehicle moving speed. 16 repetitions and 12 repetitions were conducted for the 5.74m row and 13.52m row respectively. Obstacles were set at the starts and ends of sensing routes to fix the sensing distance and position. The roll and pitch angle of the vehicle caused by the unflatness of the soil ground were ignored during the data collection. The height and position of each sorghum plant were manually measured and used as ground truth.

Data/Image Processing Algorithms

Data Processing Algorithm for the Ultrasonic Sensor

Data collected by the ultrasonic sensor was processed by a MATLAB program developed to extract the desired height information and calculate the measurement accuracy. Data messages had already been grouped during collection according to the encoder readings. In each interval group, distance reading was extracted for each data message. They were further converted from the sensor coordinate to the ground coordinate (Fig. 4). Then the maximum height reading within each interval group was extracted to represent the height reading in that interval.

Data Processing Algorithm for the Laser Range Finder

The data processing algorithm for the laser range finder was similar to the one for the ultrasonic sensor. After coordinate conversion, only those data points corresponding to the row

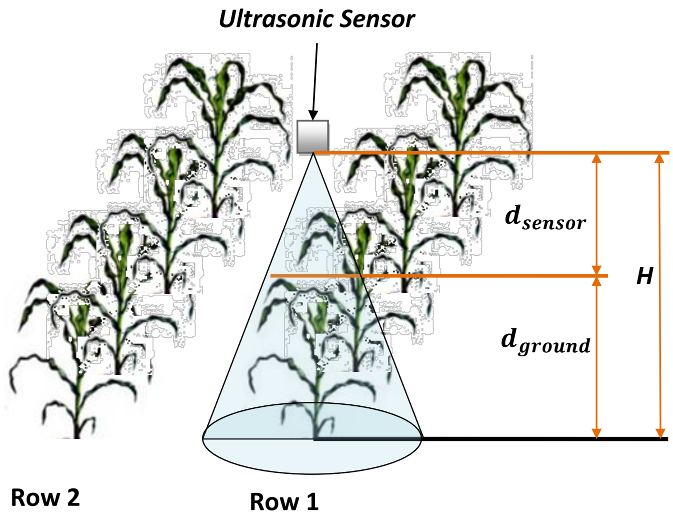


Fig. 4. Illustration of the coordinate conversion of ultrasonic sensor data. H is the sensor mounting height, d_{sensor} is the raw data measured by the sensor, $d_{ground} = H - d_{sensor}$.

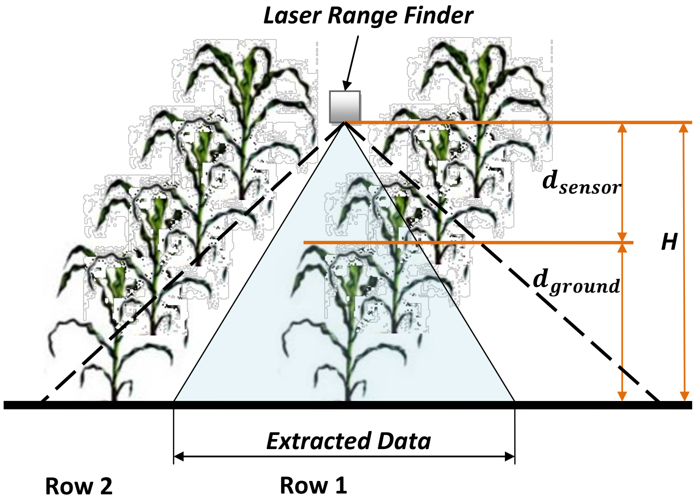


Fig. 5. Illustration of the coordinate conversion and data extraction of laser range finder data. H is the sensor mounting height, d_{sensor} is the raw data measured by the sensor, $d_{ground} = H - d_{sensor}$. Extracted data is those data points extracted from the raw data represents one row.

directly below the sensor were extracted in each scan (Fig. 5). Instead of extracting the maximum height reading in each interval group in the ultrasonic data, the maximum height reading of each scan was extracted here.

Image Processing Algorithm for the Range Camera

De-noising

Fig. 6 shows an example of the de-noising processing of two images collected by the SR4000 range camera. Fig. 6 (1a) and (2a) are two raw distance images with much noise though the shade was used during data collection. Two de-noising methods were used: threshold filtering and 'confidence map'. Because the actual height of those plants should be within a range of 20cm ~ 55cm in this study, any point outside the range was considered as a noise point and re-assigned to a closest threshold value. The confidence map was generated by the sensor's build-in software based on the distance and intensity measurements and their temporal variations. It represented how correct the distance measurement at each pixel was. It was also used here for de-noising. Noise was largely reduced after the de-noising process (Fig. 6, 1b, 2b).

Image Registration

Fig. 6(1c) and (2c) are two patches used for image registration. Fig. 6(1c) was the patch selected by the algorithm based on the assumption that this patch area should have maximum vegetation pixels. Fig. 6(2c) shows the matching patch selected based on the assumption that it should have a minimum sum of difference from Fig. 6(1c). Fig. 6(4) is the registration result of Fig. 6(1c) and 6(2c). Apply the same strategy to the distance images selected from repetition 7, a registration image for the whole 5.74m row was shown in Fig. 6(5). For each registration image, maximum height reading of each pixel row was extracted.

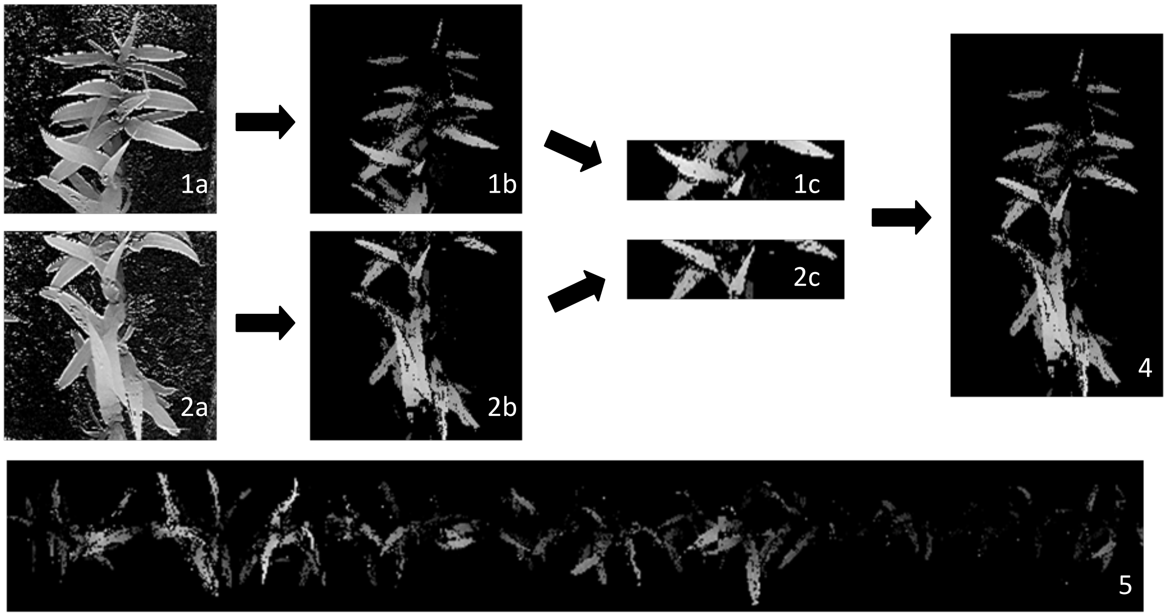


Fig. 6. Image processing results. 1a & 2a: raw images with noise; 1b & 2b: de-noised images; 1c & 2c: patches found in 1b & 2b; 4: registration image; 5: Image registration result of 5.74m row from images in 7th repetition.

Accuracy Calculation

The algorithm for calculating the measurement accuracy was common for three sensors. Although the ultrasonic sensor and the laser range finder were supposed to be triggered every certain distance interval so that all repetitions should have same number of scans, the actual numbers of scan varied among repetitions. This was caused by the unflatness of the field ground and the missing rotation of the wheel. So the sensing interval for each repetition was re-scaled using the total sensing distance divided by the number of scans in each repetition (Equation 1).

$$\text{Rescaled Interval} = \frac{\text{Total Distance}}{\text{Number of Scans in that Repetition}} \qquad (1)$$

Each data point was distributed to the position where the nearest ground truth plant was. Mean and standard deviation of all data points at each ground truth position were calculated. The performance of the sensor was evaluated with an average error defined in Equation 2.

$$Error = \frac{\sum \frac{\left|H_{ground\ truth} - H_{mean\ of\ sensor}\right|}{H_{ground\ truth}}}{\#\ \mathrm{of\ plants}} \tag{2}$$

where Error is the average error in a row sample, $H_{ground\ truth}$ is the manually measured height at a ground truth position, $H_{mean\ of\ sensor}$ is the mean calculated from all of the sensor measured heights at the same ground truth position, and $\#\ \mathrm{of\ plants}$ is the number of plants in that row sample from manual measurement. A total error of the ultrasonic sensor was calculated based on a weighted average of the average errors of the two row samples, shown in Equation 3:

$$\mathrm{Error}_{\mathrm{total}} = \frac{[\mathrm{Error}_{5.74\mathrm{m}} \times (\#\ \mathrm{of\ plants}_{5.74\mathrm{m}}) + \mathrm{Error}_{13.52\mathrm{m}} \times (\#\ \mathrm{of\ plants}_{13.52\mathrm{m}})]}{(\#\ \mathrm{of\ plants}_{5.74\mathrm{m}} + \#\ \mathrm{of\ plants}_{13.52\mathrm{m}})} \tag{3}$$

where $\mathrm{Error}_{\mathrm{total}}$ is the total measurement error of the ultrasonic sensor, $\mathrm{Error}_{5.74\mathrm{m}}$ and $\mathrm{Error}_{13.52\mathrm{m}}$ are the average errors of the two testing rows, and $\#\ \mathrm{of\ plants}_{5.74\mathrm{m}}$ and $\#\ \mathrm{of\ plants}_{13.52\mathrm{m}}$ are the number of plants in the two rows based on the ground truth measurement.

RESULTS AND DISCUSSION

Sensors Calibration

According to the calibration results, three sensors all returned accurate distance readings for the 1cm × 1cm horizontal surface within the calibrated sensing range: 15cm ~ 150cm for the ultrasonic sensor; 50cm ~ 150cm for the laser range finder; and 50cm ~ 150cm for range camera. However, for the ultrasonic sensor, the stable accurate readings were only limited in its 15° cone angle. For the bar resolution calibration of the laser range finder and range camera, the sensors could still see the 1cm width bar continuously at 150cm distance away. These calibration results mean that the three sensors would be able to measure the height of a surface as long as it has a not less than 1cm × 1cm area parallel to the sensor front surface which is very likely to be found in the plant top canopy.

Field Tests with the Ultrasonic Sensor

The average error of measurement using the ultrasonic sensor was 20.2% and 14.8% for the 5.74m row and 13.52m row respectively. Fig. 7(a) shows the averages and standard deviations of the re-distributed valid sensing data at each ground truth position of the 5.74m row. Those green bars in figure represent the heights and locations of actual plants. The blue diamond dots represent the means of all the measured data points at each ground truth position. The blue whiskers connected to those diamond dots represent the corresponding standard deviations.

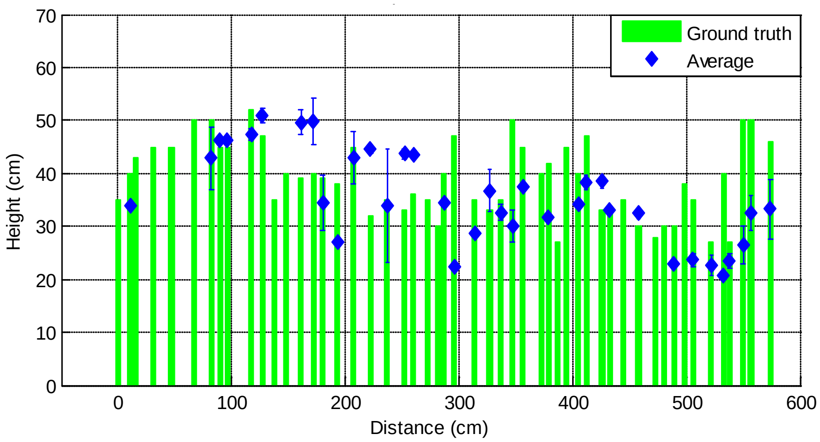
Fig. 7(b) shows the errors calculated between the averages of sensor measurements and the ground truths. Many zeros or very small readings which can be considered as invalid data in the ground coordinate were found during data processing. A major reason for these low valid data ratio was that the sensor was set in the ‘soil mode’ instead of the ‘crop mode’, in which the sensor just sensed the last echo back which corresponded to the soil surface if it could see it. Switching between the two modes needed an access of internal configurations by the manufacturer. Due to the time limit, no further work was conducted under the ‘crop mode’ in this study.

Field Tests with the Laser Range Finder

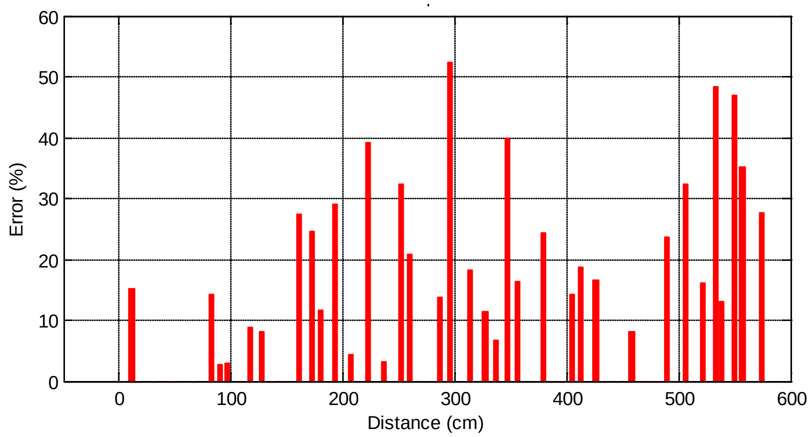
The average error of measurement using the laser range finder was 13.9% and 11.9% for the 5.74m row and 13.52m row respectively. Fig. 8 (a) shows the mean and standard deviation of the re-distributed sensing data from the laser range finder of the 5.74m row. Fig. 8 (b) shows the corresponding average errors of the 5.74m row. It was observed that large errors occurred at those overlap positions where the heights of neighbor plants changed largely.

Field Tests with the Range Camera

The average error of measurement using the range camera was 18.9% for the 5.74m row. Fig. 9 shows the means, standard deviations and errors of data collected by the range camera on the 5.74m row. Errors induced during the image registration process may contribute the relative high average error.

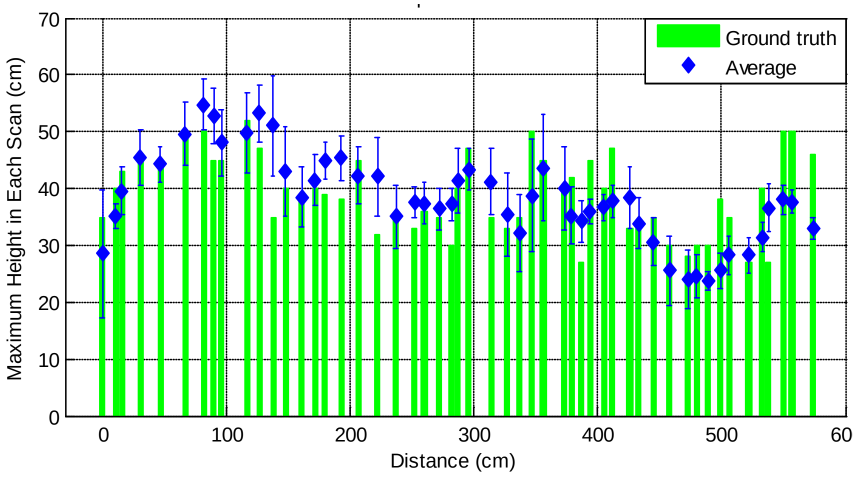


(a)

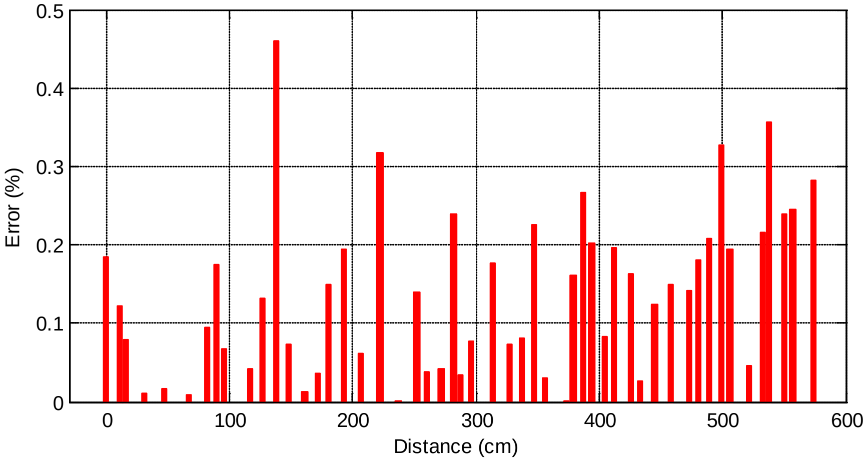


(b)

Fig. 7. Partial data collected by the ultrasonic sensor on 5.74m row. (a) mean and standard deviation of measured height vs ground truth height; (b) average error at each ground truth position.

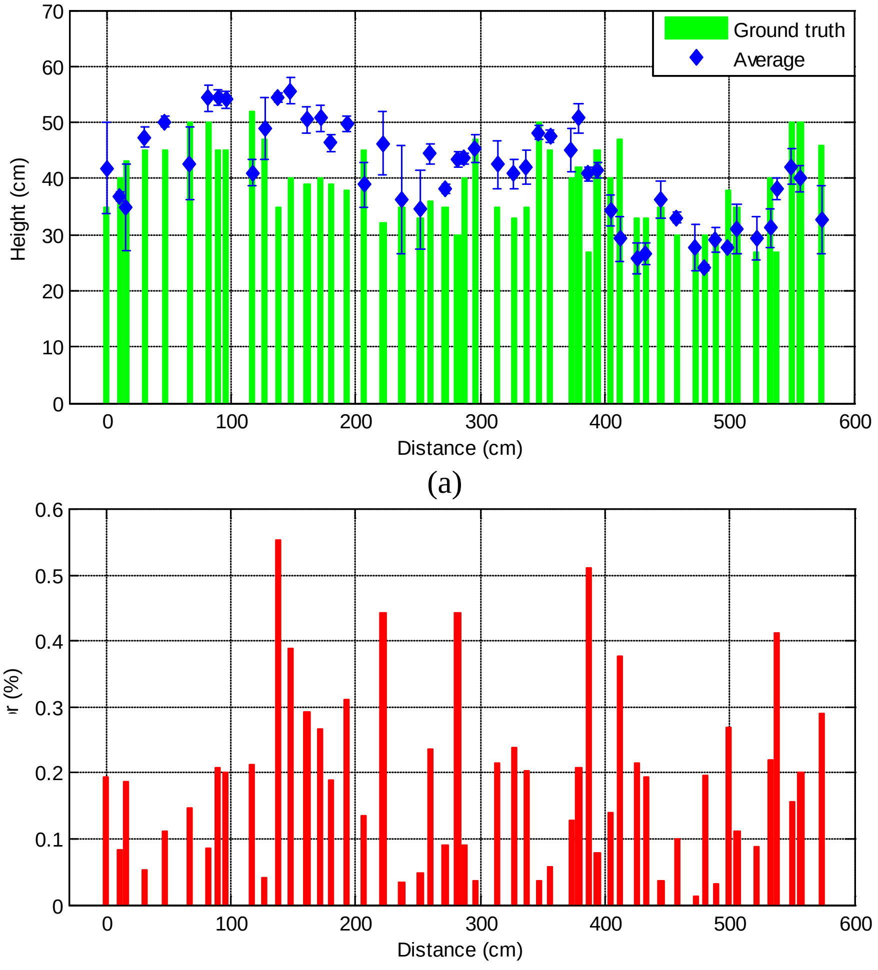


(a)



(b)

Fig. 8. Data collected by the laser range finder on 5.74m row. (a) mean and standard deviation of measured height vs ground truth height; (b) the average error at each ground truth position.



(a)

(b)

Fig. 9. Data collected by the range camera on 5.74m row. (a) mean and standard deviation of measured height vs ground truth height; (b) the average error at each ground truth position.

Overall Performance Comparison

Table 4 shows a performance comparison among three sensors. The total errors were 16.2%, 12.4% and 18.9% for the ultrasonic sensor, the laser range finder and the range camera respectively. They were calculated as weighted averages of average errors based on the number of plants in each row as discussed previously (Equation 3). The sensing resolutions were 10cm, 5cm and 0.5cm respectively. The approximate costs of three sensors were also given in the table. The laser range finder had highest accuracy in this study while its cost is relative high comparing with the ultrasonic sensor. The ultrasonic sensor had lowest cost while having a median performance. To apply the range camera may need more research due to the difficulties existing in developing image processing algorithm and lowering the cost.

Table 4. Performance comparison of three sensors.

	Average Error		**Total Error**	**Resolution**	**Approximate Cost**
	5.74m Row (52 plants)	**13.52m Row (143 plants)**			
Ultrasonic Sensor	20.2%	14.8%	16.2%	10cm	$900
Laser Range Finder	13.9%	11.9%	12.4%	5cm	$5,000
Range Camera	18.9%	NA	18.9%	0.5cm	$10,000

CONCLUSIONS

Three off-shelf sensors were tested for in-field plant height measurement in this study. Tests were conducted under lab and field conditions. Data and image processing algorithms were developed to extract height information and calculate the measurement accuracy. Measurement errors of the ultrasonic sensor, the laser range finder and the range camera were 16.2%, 12.4% and 18.9%, respectively.

The ultrasonic sensor featured with low cost, robust in-field performance, but relative low spatial resolution. The laser range finder had high measurement accuracy and robust in-field performance; however, its cost is relative high comparing with the ultrasonic sensor. The range camera offered most detailed information; however, errors could be induced easily during image processing. It is also susceptible to the outdoor sunlight and needs proper shading design. Hence, considering all the aspects, the ultrasonic sensor and the laser range finder have better perspective to be applied in in-field, real-time high-resolution plant height measurements. Further field tests will be conducted with a sprayer to evaluate the performance of the sensors when incorporated with variable rate applicators.

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