Development of uncut crop edge detection system based on laser rangefinder for combine harvesters

Zhao Teng[1,2], Noboru Noguchi[2], Yang Liangliang[2], Kazunobu Ishii[2], Chen Jun[1*]

(1. *College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100,China*;
2. *Vehicle Robotics Laboratory, Graduate School of Agriculture, Hokkaido University, Sapporo, Japan*)

Abstract: The objective of this research was to develop an uncut crop edge detection system for a combine harvester. A laser rangefinder (LF) was selected as a primary sensor, combined with a pan-tilt unit (PTU) and an inertial measurement unit (IMU). Three-dimensional field information can be obtained when the PTU rotates the laser rangefinder in the vertical plane. A field profile was modeled by analyzing range data. Otsu’s method was used to detect the crop edge position on each scanning profile, and the least squares method was applied to fit the uncut crop edge. Fundamental performance of the system was first evaluated under laboratory conditions. Then, validation experiments were conducted under both static and dynamic conditions in a wheat field during harvesting season. To verify the error of the detection system, the real position of the edge was measured by GPS for accuracy evaluation. The results showed an average lateral error of ±12 cm, with a Root-Mean-Square Error (RMSE) of 3.01 cm for the static test, and an average lateral error of ±25 cm, with an RMSE of 10.15 cm for the dynamic test. The proposed laser rangefinder-based uncut crop edge detection system exhibited a satisfactory performance for edge detection under different conditions in the field, and can provide reliable information for further study.

Keywords: laser rangefinder technology, crop edge detection, combine harvester, navigation, field profile modeling
DOI: 10.3965/j.ijabe.20160902.1959

Citation: Zhao T, Noguchi N, Yang L L, Ishii K, Chen J. Development of uncut crop edge detection system based on laser rangefinder for combine harvesters. Int J Agric & Biol Eng, 2016; 9(2): 21－28.

1 Introduction

Despite the population growth around the world, agricultural population shows a decreasing and aging tendency[1]. Autonomous navigation systems can help promoting the development of agriculture to a larger extent[2-4]. Therefore, there is a necessity to develop robot vehicles to stimulate the development of agriculture. So far, various technologies have been used to develop several navigation systems for agricultural machinery[5-7]. However, sometimes there are some limits for their applications, such as the weather condition for transmitting and receiving signal, and advanced path planning for navigation based on GPS[8,9], or the processing speed, illuminance and shadows for navigation based on vision[10]. Thus, considering these factors, a laser rangefinder based uncut crop edge detection system was proposed, for the automated harvester using in the near future.

Laser rangefinder (LF) technology will not be affected by ambient lighting conditions[11] and thus can be more reliable in an agricultural environment[12]. Considering the cost, path management, and influencing factors affecting navigation systems, this work proposes the development of a LF based navigation system for a combine harvester, which can adapt optimally to the

Received date: 2015-05-17 **Accepted date:** 2016-01-16
Biographies: Zhao Teng, PhD candidate, research interest: agricultural robots, Email: zhao@bpe.agr.hokudai.ac.jp; **Noboru Noguchi**, PhD, Professor, research interest: agricultural robots, Email: noguchi@bpe.agr.hokudai.ac.jp; **Yang Liangliang**, PhD, research interest: Agricultural robots, Email: yang@bpe.agr.hokudai.ac.jp; **Kazunobu Ishii**, PhD, Associate Professor, research interest: agricultural robots, Email: ici@bpe.agr.hokudai.ac.jp.
***Corresponding author: Chen Jun**, PhD, Professor, research interest: agricultural robots. Northwest A&F University, Yangling, Shaanxi 712100, China. Tel: +86-29-87091867, Email: chenjun_jdxy@nwsuaf.edu.cn.

variations of several path conditions in real-time. The aim of this research was to develop a cut/uncut crop edge detection system in order to support the guidance system of a combine harvester that enables it to navigate in a field.

This system will also help to reduce both the number of sensors and the influence of external factors, and also improve the driving flexibility among various paths.

The feasibility of adopting the LF as the primary sensor for recognition and controlled automation in the agricultural environment has been verified by many researchers[13-15]. Literatures[16,17] reported the development of vision based and multi-sensor based methods used to detect the uncut crop edge during the operation of a head-feeding combine harvester, with remarkable results in the performance of the navigation system.

In this study, a pan-tilt unit was adopted to enlarge the area ahead of the combine harvester, so that much more information can be acquired, which was benefit to rebuild the situation of the ahead wheat field in real time. Additionally, an edge detection method was selected to classify the cut and uncut wheat at a fast speed.

2 System components

A combine harvester (Yanmar Co. Ltd. AG1100) was selected as the platform for this study. A LF (Hokuyo Co. Ltd. UTM-30LX) was used as the key component of the detection system, which has a maximum sweep angle of 270° with a resolution of 0.25° and a maximum range of 30 m. A pan-tilt unit (PTU) (FLIR D46-17) (Table 1), controlled by binary command mode, provided the tilt rotation within a certain area (Figure 1) by moving up and down continuously in the vertical plane, at a speed of 51.4 (°)/s. Simultaneously, an IMU (VN-100R) recorded the position of the LF on a three degree of freedom system (roll, pitch and yaw). The detection system is shown in Figure 1.

Figure 2 shows the LF reference system $R=(x_L, y_L)$. Its origin O is in the center of the half-circle scanning range of the sensor. The laser beam performs a counterclockwise sweeping from –45° to 225°, and thus the sensor provides the position of each detected point in polar coordinates (ρ, θ), where ρ is the distance between reference origin and object's detected point; θ is the angle between x_L axis and the beam direction.

Table 1 Pan tilt unit specifications

Parameter	Description
Minimum tilt speed	0.0123 (°)/s
Maximum tilt speed	300 (°)/s
Tilt range	+31(°)/–80(°)
Angle resolution	0.05143°

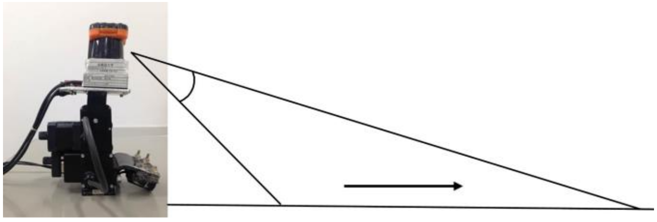


Figure 1 Set of detection system

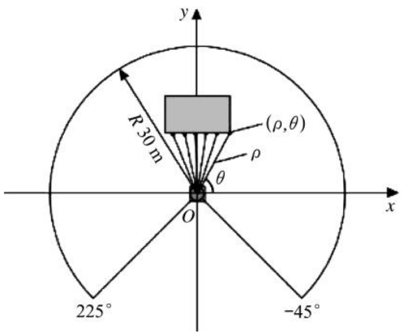


Figure 2 Schematic diagram of laser rangefinder

Therefore, the surface of the detected object is characterized by a set of points (ρ_i, θ_i) from the beginning to the end of the object (i=0, 1, ..., N).

The data logged by the LF is given in a two-dimensional coordinate system; i.e. the data measured by the LF are in the x (x_L, y_L) plane, thus the range component along the Oz axis is zero as shown in Equation (1).

$$\begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} = \begin{bmatrix} \rho\cos(\theta) \\ \rho\sin(\theta) \\ 0 \end{bmatrix} \quad (1)$$

Considering Equation (1), it is possible to describe the crop edge using a mathematical model; i.e. to express the crop in three-dimensional coordinates.

As is shown in Figure 3, the origin of the vehicle's Cartesian coordinates system (x, y, z) is defined by the projection of the rotation center of the PTU into the ground plane. Therefore, y_L is in the direction of the front of the vehicle, x_L is perpendicular to y_L and parallel to the ground plane, and z_L is perpendicular to the ground plane[18].

Figure 3 Sensor position and coordinate system

Considering the rotation on the pitch direction and the inclination on the roll direction, the coordinate transformation from the LF's coordinates system (x_L, y_L) into the vehicle's Cartesian coordinates system (x, y, z) is described by Equation (2).

$$\begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} = \begin{bmatrix} \cos(\theta_r) & 0 & \sin(\theta_r) \\ -\sin(\theta_r)\sin(\theta_p) & \cos(\theta_p) & \cos(\theta_r)\sin(\theta_p) \\ -\sin(\theta_r)\cos(\theta_p) & -\sin(\theta_p) & \cos(\theta_r)\cos(\theta_p) \end{bmatrix} \begin{bmatrix} x_L \\ y_L \\ -z_L \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ H \end{bmatrix} \quad (2)$$

where, θ_r is angle on roll direction; θ_p is angle in pitch direction; H is height of the LF.

3 Calibration method

Although it is assumed that x_L is parallel to the ground plane, there are all kinds of factors influencing the accuracy of the sensors and thus it is necessary to calibrate the sensor system. In this study, the whole set of the sensors is mounted on the combine cab. The experiment was conducted on a flat and wide court yard; this ground surface was measured as an ideal flat plane. The initial angles of the scanning plane of the sensor in the pitch (p_0) and roll (r_0) directions, and the height of the LF (H) were calculated. The plane fitting was calculated using the least squares method.

Due to the mechanical installation of the sensor system, the relative position between the LF and the cutter of the harvester does not change. Therefore, it is necessary to detect the position of the cutter in the LF's coordinate system, in order to model the relative position between the crop and the harvester appropriately.

4 Edge detection method

The most important task for the detection of the uncut crop edge is to extract the edge point on each scanning line. There are already many researches about the processing of edge detection implementing different kinds of sensing methods[16,17]. Choi et al.[19] presented a correlation method to extract rows in a soybean crop based on LF. Also, Debain et al.[20] used a correlation approach to detect different kinds of crop edge.

We propose a unique approach using Otsu's method to process the data logged by the LF. The algorithm assumes that the data sets contain two classes of measurements; a cut crop measurement and an uncut crop measurement. Then the algorithm calculates an optimum threshold separating the two data classes on each scanning line. By using Otsu's method we search for a threshold that minimizes the intra-class variance (the variance within the class) given in Equation (3), and maximizes the between-class variance given in Equation (4); then, we can define this threshold as the demarcation of the two classes[21].

$$\sigma_w^2 = \sum_{i=0}^{u*}(u_i-\mu_1)^2 * \frac{u*}{u_{\max}} + \sum_{i=u*+1}^{u_{\max}}(u_i-\mu_2)^2 * \frac{u_{\max}-u*}{u_{\max}} \quad (3)$$

$$\sigma_B^2 = \frac{u*(\mu_1-\mu)^2 + (u_{\max}-u*)(\mu_2-\mu)^2}{u_{\max}} \quad (4)$$

$$\max imize\left(\frac{\sigma_B^2}{\sigma_w^2}\right) \rightarrow u_{opt} \quad (5)$$

where, u_i is the value in the i_{th} point on one scanning line (i=0,1,…N); u* is separates the two classes; $u_{\max}$ is the max series on one scanning line ($u_{\max}$=N); μ is mean of the two classes; μ_1 is mean of class 1; μ_2 is mean of class 2; σ_B^2 is between-class variance; σ_w^2 is intra-class variance; u_{opt} is optimum demarcation of the two classes.

The flow diagram depicted in Figure 4 schematizes the algorithm for the cut/uncut crop edge detection process, which consists of four steps:

1) For one scanning line of the LF, pick out the area of interest and then convert the obtained polar coordinates (ρ_i, θ_i) to the vehicle's Cartesian coordinate system (x, y, z) by using Equation (2). In this stage, a threshold was set up to classify the data set, the points which are out of the threshold range such as dust are considered as invalid and discarded from the data set as far as possible.

2) Use Otsu's method to process the scanning line, by searching a threshold u_{opt} that can maximize σ_B^2 and minimize σ_w^2 by using Equation (3) and Equation (4); i.e. the maximum value of σ_B^2/σ_w^2. The u_{opt} corresponds to the position of the crop edge. Save the relative information of u_{opt} in the vector V_{edge}.

3) If the tilt movement of the PTU within the predetermined rotation range finished one cycle, i.e. tilt goes up and down for once, use the least squares method to fit the crop edge line, and then clear out the vector V_{edge}. If the tilt movement of the PTU has not finished the cycle, go back to step 1.

4) Calculate the lateral error. We define a reference line that looks ahead the combine harvester. This reference line is an extension of a known point (x, y) in the right-side cutter of the combine harvester (As shown in Figure 5).

During step 3, three types PTU's vertical sweep movement were designed to calculate the cut/uncut edge line. The first kind was adopting the data from upwards sweep of the PTU's movement, the second kind was using the data from the downward sweep of the PTU's movement, and the third kind was taking both upwards and downwards sweep data set of the PTU's movements.

Thanks to the PTU's vertical sweep motion, high amounts of data from the front of the vehicle can be acquired. Taking advantage of the continuous characteristic during each vertical sweep movement, it is possible to log a series of adjacent scanning lines. There is one edge point on each scanning line. For each one of the vertical sweep movements, the adjacent edge points can be connected to fit the uncut crop edge. Then, it is possible to calculate the lateral error to build up the relative position between the crop edge and the combine harvester.

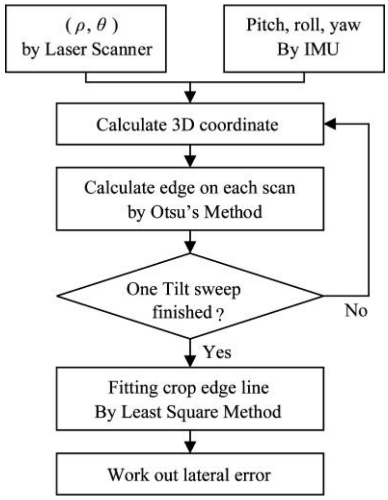


Figure 4 Flow diagram of the method

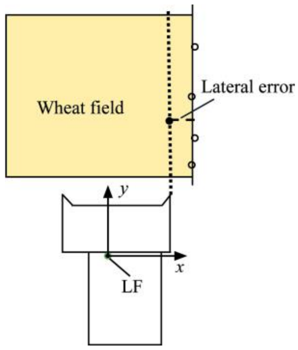


Figure 5 Schematic diagram of field test

5 Field tests

5.1 Simulation test

The simulation test was first carried out in the laboratory to verify the reliability of the edge detection system. A desk was placed in front of the combine harvester to provide an ideal straight uncut edge. We are interested in detecting the desk's left edge (As shown in Figure 6).

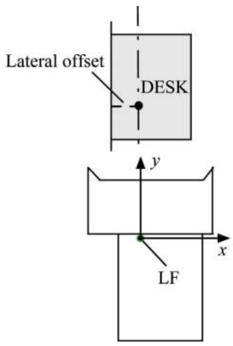


Figure 6 Schematic diagram of simulation test

Figure 7 shows the results of the desk's edge detection. Three sets of data are depicted, corresponding to each one of the PTU's vertical sweep movements. Figure 7a only considers upwards sweep data set, while Figure 7b only considers the downwards sweep data set and Figure 7c considers both upwards and downwards sweep data set. In Figure 7 the axes are in the same reference system to the vehicle's Cartesian coordinates depicted in Figure 3.

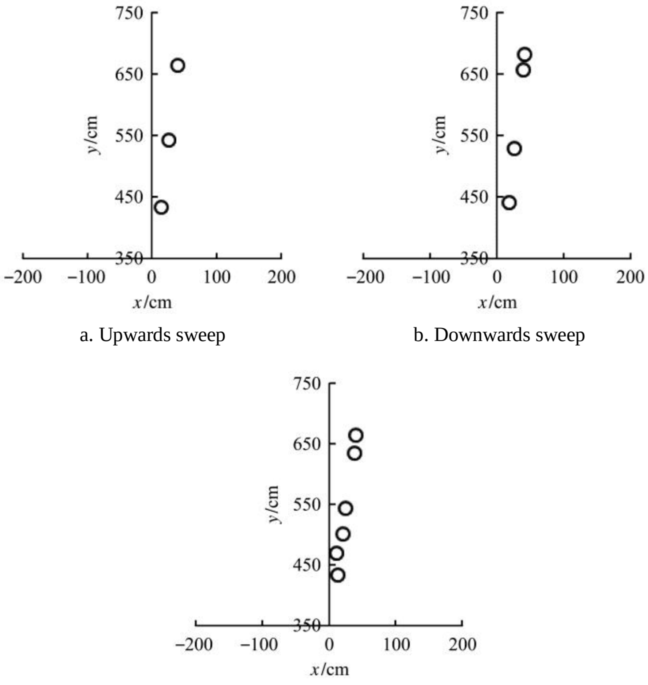


Figure 7 Desk's edge detection

Table 2 Results of the desk test (cm)

	Average lateral offset	RMSE
Upwards sweep	21.2	0.4
Downwards sweep	22.7	1.0
Upwards–downwards sweep	21.7	0.6

We calculate the lateral offset to verify the accuracy of the detection method.

Considering the relative position of the desk and the vehicle, we defined a point (0, y) on the vehicle's Cartesian coordinates system y axis. We measured the difference from this point to the left side of the desk as the lateral offset (As shown in Figure 6). This can help the detection system to always look ahead.

Figure 8 shows the lateral offset to the left side of the desk for to each one of the PTU's vertical sweep movements. The rotation movement of the PTU sweeping upwards and downwards one time is considered as one cycle. In Figure 8, the horizontal axis represents the successive cycles of the PTU's rotation. From Table 2, it can be observed that for the upwards sweep, the downwards sweep and both upwards and downwards sweep data sets, the difference in the average lateral offset is only a few millimeters. The Root-Mean-Square Error (RMSE) is calculated by Equation (6), where, d_i is the deviation between estimator with actual value, n is the measurement times. And the RMSE values of these 3 types are 0.4 cm, 1.0 cm and 0.6 cm respectively, which is also on millimeters level.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n-1}} \quad (i = 1, 2, ..., n) \tag{6}$$

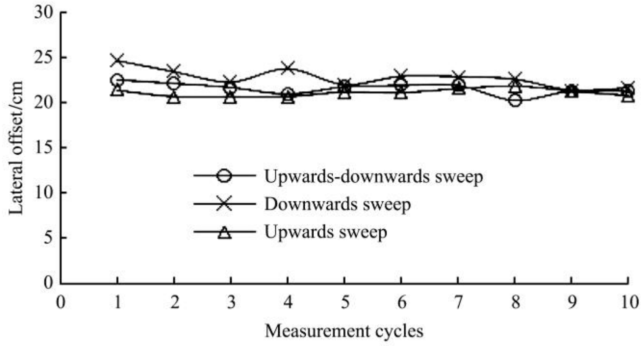


Figure 8 Lateral offset of the desk

Considering the quantity of data, the results of the three types of sweeping do not show a big differece on the average lateral offset. Therefore, for the test in an actual agricultural environment we consider the upwards and downwards sweep data set, just as the one shown in Figure 7c. This can provide sufficient data to improve the accuracy and robustness of the modeling of the crop edge.

5.2 Static test

As the proposed method has shown outstanding detection performance under simulation conditions, static tests and dynamic tests are designed to evaluate the performance of the proposed method in an actual wheat field.

In the static experiment, the combine harvester was set facing forwards the wheat field, with the uncut crop edge on the right of the harvester (As shown in Figure 5). A person carried a GPS receiver (Topcon Legacy-E) walking along the uncut crop edge to record its real position as reference data. The position of the LF and the header of the harvester were also recorded by the GPS receiver, so the relative position of the harvester and the crop edge was clearly identified. Then, the wheat field information was logged by the edge recognition system. The format of the data obtained from the static test is almost the same as the format of the data obtained from the simulation test.

Figure 9 shows the crop profile for a singular tilt position of the PTU under the vehicle's Cartesian coordinates system. The vertical axis represents the height of the wheat, while the horizontal axis is perpendicular to the driving direction as described in Figure 3. It is possible to pick up the edge on each scanning line by using Otsu's method. Since both the ground coordinates (logged by hand using the GPS receiver) and the heading direction (logged by the IMU) of the LF have already been recorded, the crop edge information can be transferred from the LF's coordinate system to the ground coordinate system using Equation (2). The relation between the real position of the cut/uncut crop edge and the detected edge is shown in Figure 10. Since the absolute coordinates for global positioning system are difficult to read, the coordinate of one point on the cut/uncut edge line was made as (0, 0), so the unit of Figure 10 was displayed with relative coordinates. The red line represents the real position, and the scatter points correspond to the edge points on each scanning line. Figure 11b shows the offset between the detected edge position and the real edge position, with the definition of it illustrated in Figure 11a. The offset is defined as the distance from each detected edge point to the adjacent real edge position.

The combine's lateral error is defined as the distance from the detected edge point to the extension line from the right-side cutter of the combine harvester. As shown in Figure 12, the lateral error fluctuated between −13 cm and 13 cm with an RMSE of 4.27 cm. The detection system shows an acceptable accuracy under static conditions.

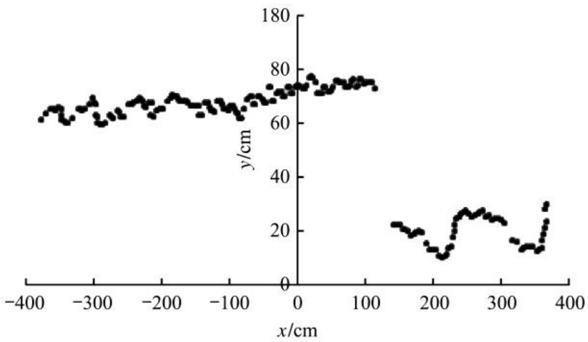


Figure 9 The profile for one scanning

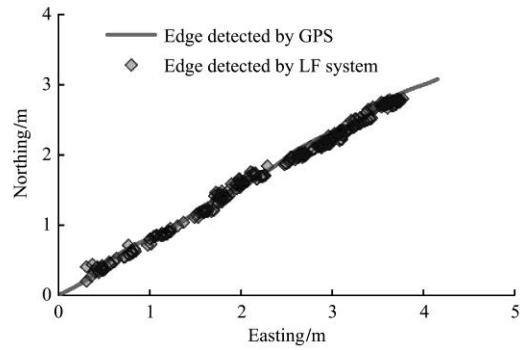
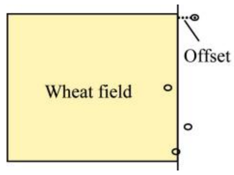
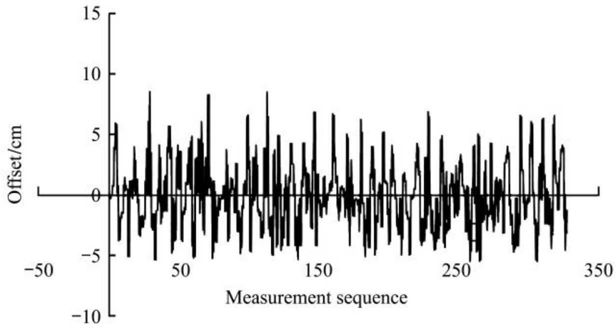


Figure 10 Detected and actual cut/uncut crop edge



a. Schematic diagram of static test



b. Result of the static test between detected and actual edge

Figure 11 The offset between detected edge and actual position

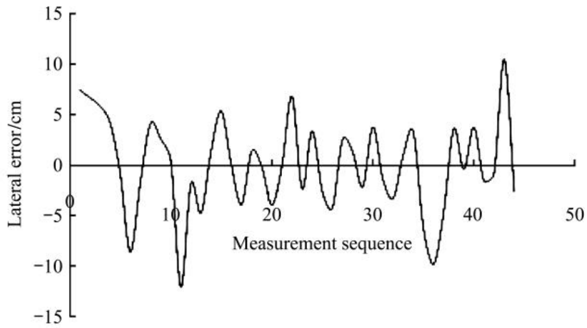


Figure 12 Lateral error under static conditions

5.3 Dynamic test

In the dynamic test, the uncut crop edge was also in the right side of the harvester. Usually the working speed for combine harvester is set between 1.0 m/s to 1.5 m/s, to guarantee the safety and well detect the information ahead of the harvester, the speed was set to 1 m/s in the dynamic experiment.

The test was designed as follows: the combine harvester was human-driven at a speed of 1 m/s in the field. Since the harvester was driven by a human, the steering could be corrected in time to satisfy that the harvester is always walking with the right-side cutter divider on the uncut crop edge. As a result, the lateral error displays a fluctuation between −25 cm and 25 cm, with a RMSE of 10.15 cm, as depicted in Figure 13.

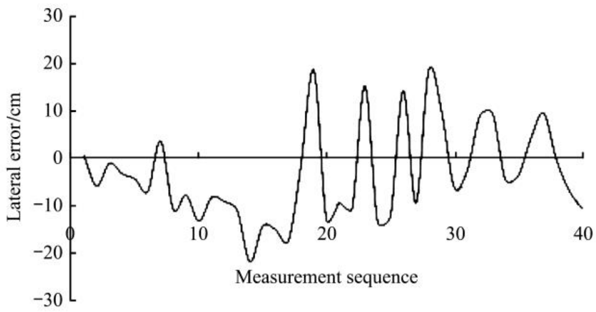


Figure 13 Lateral error under dynamic conditions

During the dynamic test, there are some kinds of factors influencing the accuracy, such as vibration of the vehicle and steering control. Also, even if the wheat on the edge is in the same row, there is also some difference in different scans. Thus, a Moving Average Filter was used to smooth data values and eliminate most of the noise.

The offset from the detected uncut crop edge to the actual position of the edge is less than 30 cm, as is observed in Figure 14. The results of dynamic tests shows that the performance of the LF based uncut edge detection system can fulfill the need for agriculture use, and this system is acceptable.

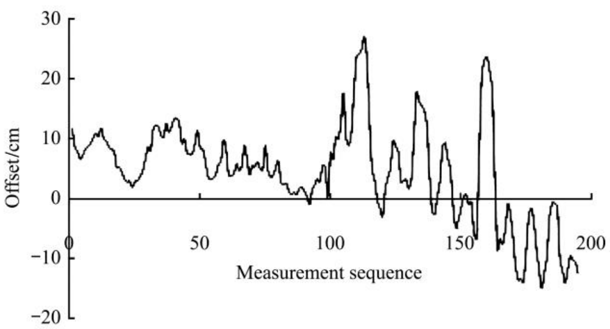


Figure 14 Offset between detected edge and actual position

However, since the resolution of the LF used in this system is 0.25°, for some remote scans the real position of the edge maybe lost within the gap of two adjacent LF beam sweeps. Taking this into account, we plan to introduce a camera in future work, and take advantage of the fusion technology of image processing and LF to improve the accuracy of the cut/uncut crop edge detection system.

6 Conclusions

In this study, an uncut crop edge recognition system based on laser rangefinder (LF) for a Yanmar AG1100 combine harvest was developed. The Otsu's method was used to detect the uncut crop edge position on each scanning profile, and the least squares method was used to fit the crop edge line. Indoor tests were performed, detecting a desk's straight edge in ideal conditions in order to verify the accuracy of the method. Static and dynamic tests were conducted in an actual wheat field. A Topcon Legacy-E GPS receiver was used to measure the actual location of the combine harvester and the crop edge. The lateral error was ±12 cm under static conditions and ±25 cm under dynamic conditions, with an RMSE of 3.01 cm and 10.15 cm, respectively. The proposed LF-based uncut crop edge detection system has shown a satisfactory performance on edge detection under different conditions in the field, and can provide reliable information for further study in the area of automatic guidance systems.

Acknowledgements

The research was supported by the fund of China Scholarship Council, Chinese Universities Scientific Fund (ZD2013015), and the research Fund for the Doctoral Program of Higher Education of China (20130204110020).

[References]

[1] Zhang Z. Development of a Robot Combine Harvester Based on GNSS. PhD thesis. Graduation School of Agriculture, Hokkaido University, Sapporo, Japan. 2014.

[2] Zhang C, Yang L L, Noguchi N. Development of a robot tractor controlled by a human-driven tractor system. Engineering in Agriculture, Environment and Food, 2015; 8(1): 7–12.

[3] Yang Liangliang. 2013. Development of a Robot Tractor Implemented an Omni-directional Safety System. PhD Thesis. Graduation School of Agriculture, Hokkaido University, Sapporo, Japan.

[4] Yin X. Development of in field transportation robot vehicle using multiple sensors. PhD thesis. Graduation School of Agriculture, Hokkaido University, Sapporo, Japan. 2013.

[5] Subramanian V, Burks T F, Arroyo A A. Development of

machine vision and laser radar based autonomous vehicle guidance systems for citrus grove navigation. Computers and Electronics in Agriculture, 2006; 53: 130–143.

[6] Takai R, Yang L L, Noguchi N. Development of a crawler-type robot tractor using RTK-GPS and IMU. Engineering in Agriculture, Environment and Food, 2014; 7(4): 143–147.

[7] Hiremath S, Frits K. van Evert, Braak C T, Stein A, Heijden G V D. Image-based particle filtering for navigation in a semi-structured agricultural environment. Biosystems Engineering, 2014; 121: 85–95.

[8] Li M, Imou K, Wakabayashi K, Yokoyama S. Review of research on agricultural vehicle autonomous guidance. Int J Agric & Biol Eng, 2009; 2(2): 1–16.

[9] Iida M, Yamada Y. Rice harvesting operation using an autonomous combine with a GPS and a FOG. Proceedings of the Conference of Automation Technology for Off-road Equipment, ASAE, 2006. pp.125–131.

[10] Ding Youchun, Wang Shumao, Chen Du. Navigation Line Detection Arithmetic Based on Image Rotation and Projection. Transactions of the CSAM, 2009; 40(8): 155–160. (in Chinese with English abstract)

[11] Chateau T, Debain C, Collange F, Trassoudaine L, Alizon J. Automatic guidance of agricultural vehicles using a laser sensor. Computers and Electronics in Agriculture, 2000; 28: 243–257.

[12] Choi J M, Yin X, Yang L L, Noguchi N. Development of a laser scanner-based navigation system for a combine harvester. Engineering in Agriculture, Environment and Food, 2014; 7(1): 7–13.

[13] Barawid O C, Mizushima A, Ishii K, Noguchi N. Development of an autonomous navigation system using a two-dimensional laser scanner in an orchard application. Biosystems Engineering, 2007; 96(2): 139–149.

[14] Liu P, Chen J, Zhang M Y. Automatic control system of orchard tractor based on laser navigation. Transactions of the CSAE, 2006; 27(3): 196–199. (in Chinese with English abstract)

[15] Chen J, Jiang H R, Liu P, Zhang Q. Navigation Control for Orchard Mobile Robot in Curve Path. Transactions of the CSAM, 2012; 43(4): 179–182. (in Chinese with English abstract)

[16] Cho W J, Iida M, Suguri M, Masuda R, Kurita H. Vision-based uncut crop edge detection for automated guidance of head-feeding combine. Engineering in Agriculture, Environment and Food, 2014; 7(2): 97–102.

[17] Cho W J, Iida M, Suguri M, Masuda R, Kurita H. Using multiple sensors to detect uncut crop edges for autonomous guidance systems of head-feeding combine harvesters. Engineering in Agriculture, Environment and Food, 2014; 7(3): 115–121.

[18] Ehlert D, Heisig M. Sources of angle-dependent errors in terrestrial laser scanner-based crop stand measurement. Computers and Electronics in Agriculture, 2013; 93: 10–16.

[19] Choi J M. Development of guidance system using local sensors for an agricultural machinery. PhD thesis. Graduation School of Agriculture, Hokkaido University, Sapporo, Japan, 2014.

[20] Debain C, Chateau T, Berducat M, Martinet P, Bonton P. A guidance-assistance system for agricultural vehicles. Computers and Electronics in Agriculture, 2000; 25(1-2): 29–51.

[21] Kondo N, Monta M, Noguchi N. Agricultural Robots (I): Fundamentals and Theory. Beijing: China Agricultural University Press, 2009; 140p.