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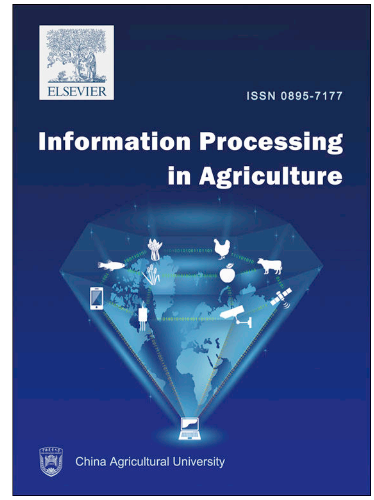

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Feasibility and reliability of agricultural crop height measurement using the laser sensor array

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Highlights:

- The crop height detection system using laser technology is practical for cropping and spraying stages.
- The system is supported for quick, real-time and easy measurement.
- The coefficient of determination of the designed-system was between 0.85 and 0.96.
- A protocol of decision making based on the developed sensing system.

Abstract Crop height measurement is widely used to analyze and estimate the overall crop condition and the amount of biomass production. Not only is manual measurement on a large scale time-consuming but also it is not practical. Besides, advanced equipment is available but they require technical skills and are not reasonable for smallholders. This article investigates the feasibility of a simple and low-cost measurement system that can monitor crops height of paddy rice and wheat using laser technology. After designing and fabricating, this system was tested and evaluated in both laboratory and farm sections. In the laboratory, paddy rice height was measured, and in the field section, the height detection system measured wheat height. The results showed that the coefficient of determination (R^2) between manual measurement and height detection system measurement for paddy rice was 0.96 and for wheat was 0.85. Besides, there was no significant difference between the two datasets at the level of 5%. Hence, this system can be a useful and accurate tool to monitor crops height in different growing steps.

Keywords: Plant height; Laser; Rice; Wheat; Crop monitoring.

1. Introduction

Population growth will lead to the demand for food increasing for most of the current century. By 2050 the world's population is expected to rise to 9.7 billion [1]. The detrimental effects of climate change on crops and population explosion require significant improvements in agricultural production [2]. Generally, production optimization through precision-agriculture management strategies and crop improvement through genetics and plant breeding are two main research fields to increase agricultural production [3, 4]. One of the most important sections in these fields is plant trait measurement such as leaf-area cover, crop density, plant crown size, and plant height that are crucial to reduce product losses and increase yield potential [5].

Plant height is a critical trait that influences the production and processing of agricultural products [6]. This trait helps to analyze and predict plant growth, the amount of biomass production and final grain yield [7-10]. Plant height is also recognized as an important index in the plant's evaporation and transpiration [11] and crop health [12].

Theoretically, plant height is defined as the shortest distance between the highest point of a plant and the ground level [6]. Manual measurement is a conventional and simple method to detect crop height. Collecting data via manual measurement is laborious, expensive, destructive, subjective and time-consuming prone to error during reading and recording [13-15]. Therefore, this method is not possible for large scale experiments or repetitive measurements in the long term [16, 17]. Hence, new methods are needed to be able to evaluate plant phenotypes with saving time, less energy, and high accuracy.

In recent years, ultrasonic sensors have been utilized to measure plant height in several studies [18-23]. For instance, Zaman et al. detected weed and blueberry's height using ultrasonic sensors [24]. They designed and fabricated an automated variable-rate sprayer for real-time spot-application of agrochemicals with the obtained information [24]. Ultrasonic sensors sense plants within its operating range and provide an average distance that results in an inherent noise filtering of the variable plants within a plot [20]. However, the ultrasonic sensor field of view (FoV) selection is complex, because narrow FoV may not cover a suitable area of the plant canopy, while wide FoV may include non-plant objects outside this area [9].

Another technology that is used to detect plant heights is Light Detection and Ranging (LIDAR) [10, 25-27]. Weiss and Biber detected plant height via this technology in the laboratory and on the farm [10]. In this study, the average accuracy of the LIDAR was more than 99% in the simulation medium, more than 90% in the laboratory, between 80% and 90% in the farm [10]. LIDAR provides better resolution of the 3D canopy structure in comparison with Ultrasonic sensors when mounted on a mobile field vehicle [25, 26]. It should be considered that LIDAR output is very sensitive to the sampling frequency, their geo-locations during movement, and LIDAR resolution [9].

Jiang, Li and Paterson used Time of Flight (ToF) camera and Microsoft Kinect, in two separated research to measure plant height [28]. ToF camera and Kinect-v2 camera were used as a 3D sensing instrument to acquire valid depth images for plants. By 3D plant reconstructions, they could measure different part of crops, such as plant height, leaf length and leaf angle. However, direct sunlight has negative influences on Kinects and they need proper shading to provide appropriate measurements [29].

Bendig et al. estimated summer barley biomass using the plant height (PH) from Crop Surface Models (CSMs) [7]. CSMs were derived from color images captured from a small unmanned aerial vehicle (UAV). In another article that has been published in 2017, Chang et al. monitored Sorghum height with digital imagery from the Unmanned Aerial System (UAS) [30]. Other similar studies were performed using UAV and digital imagery [5, 31, 32]. One of the main drawbacks of UAV is the quality of the UAV-based image. Because it can be degraded due to image motion blur whether rotary-wing or fixed-wing UAVs are used. Camera movement during image acquisition under strong winds and turbulence can cause Image motion blur [33].

Among the available technologies, Light Amplification by Stimulated Emission of Radiation (LASER) can measure the height of objects according to its unique characteristics. Nowadays, the use of laser technology has increased in many areas [34]. Laser triangulation-based object height measurement [35], monitoring of laser metal deposition height [36], measurement of trees height by a laser scanner [37] and creating crop surface models by terrestrial laser scanning [38, 39]. The advantage of lasers is that they produce controlled and powerful radiation from a light source. Besides, the ability to respond quickly and the high accuracy of this method can help to detect plant height.

Common methods of using laser technology require technical skills. Hence, the main goal of this research is to develop a new method of measuring the agricultural crop height using laser which is simple, non-destructive, in-situ, cost-effective, with low complexity and high accuracy. The measurement and control algorithm were implemented on a microcontroller to provide real-time analysis of collected data from laser sensors and allow on-demand adjustment of the crop height.

2. Materials and methods

2.1 Selection of samples

The plant height detection system was assessed in laboratory and farm. In the laboratory section, 10 rice plants were transferred from a farm to the laboratory and planted in two separate pots (Fig. 1). The average maximum and minimum height in the highest and lowest parts of paddy rice plants were measured manually, respectively. It is necessary to mention that 60 plots of rice plants have been measured using the height detection system. In the farm section, the selected wheat field was located at Behshahr city, Mazandaran province, Iran (latitude: 36˚41′51″N, longitude: 53˚30′27″E, altitude: 12 m above sea level) (Fig. 2).

Fig. 1 Rice plants in pots

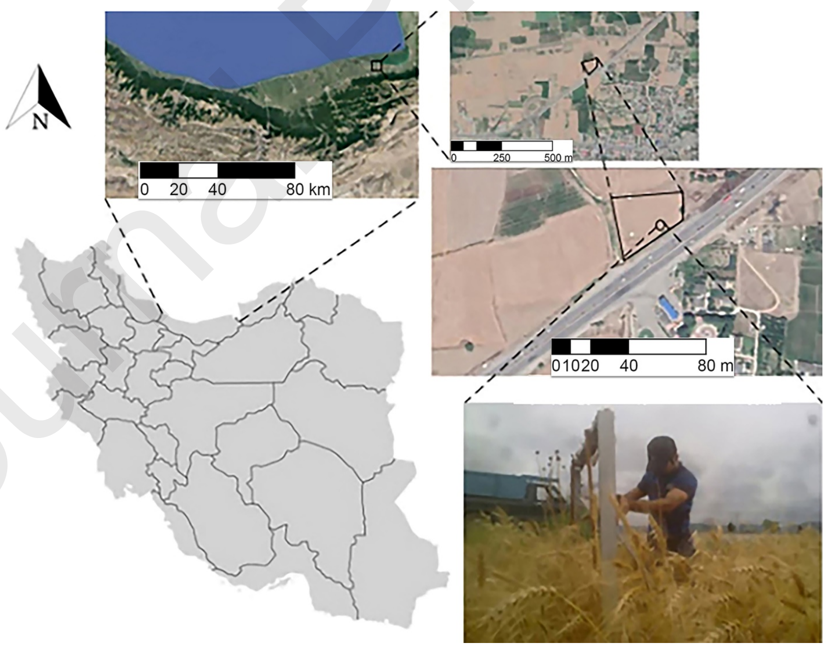


Fig. 2 A map of survey farm in the study area in Behshahr, Mazandaran Province, Iran

For this measurement, 20 different parts of the farm were randomly selected, and each area was repeated 5 times. In each iteration, the plant height detection system was moved 5 meters, and all the output numbers were collected. All measurements have been taken in two sections in June 2018. Samples' height recognized using a ruler and the height detection system, separately. For analyzing, collected data entered in Excel 2018.

2.2 Platform design

The plant height detection system is based on laser light receiving. Laser light is constantly sent by laser transmitters, and receivers are constantly receiving this light. If the receiver does not receive light, this means that there is an obstacle between the transmitter and the receiver. Fig. 3 illustrates the initial system's algorithm. The initial design of the system was that the highest point of the plant should always be between the two middle sensors. Therefore, receivers that are in the upper half receive the light that is sent by transmitters, while the lower half receivers do not receive light due to obstacles (plants). Transmitters and receivers must be moved for reaching initial balance, once this balance is upset by plants. So, this closed-loop feedback algorithm helps to remain the highest point of the plant between the two middle sensors. The accuracy of this method is highly dependent on the distance between the two middle sensors. In other words, the closer the two middle sensors are to each other, the more accurate they are. It is necessary to mention that the minimum distance should be that each receiver receives only the light from a laser that is located in front of itself, and laser lights should not interfere with each other. Hence, in this study, the minimum distance between two lasers was considered 1 cm.

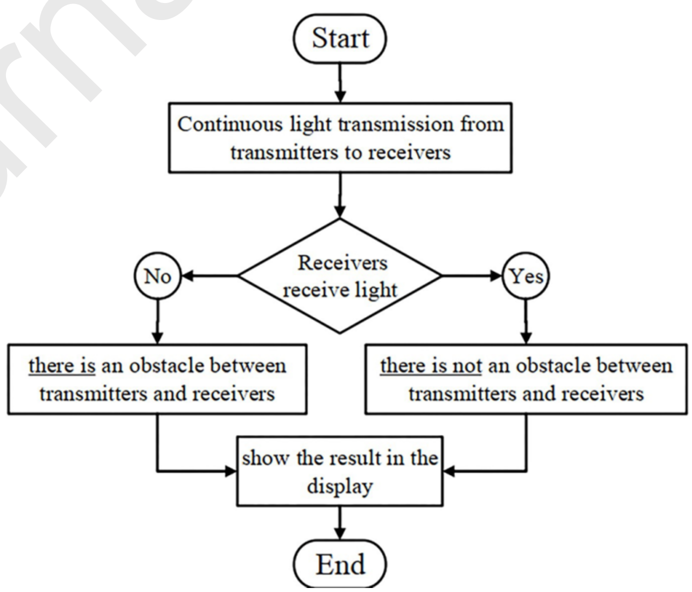


Fig. 3 Workflow for using the laser to detect obstacles

2.3 System design

According to the required mechanisms, the dimensions of the height detection system were determined, and prepared for the designing and fabricating stage. The location of each mechanical and electronic component on the device is specified. After designing, all parts were drawn by SolidWorks 2016 software, assembled in the software, and then fabricated (Fig. 4). These parts have been designed and fabricated in two separate units, mechanical and electronic.

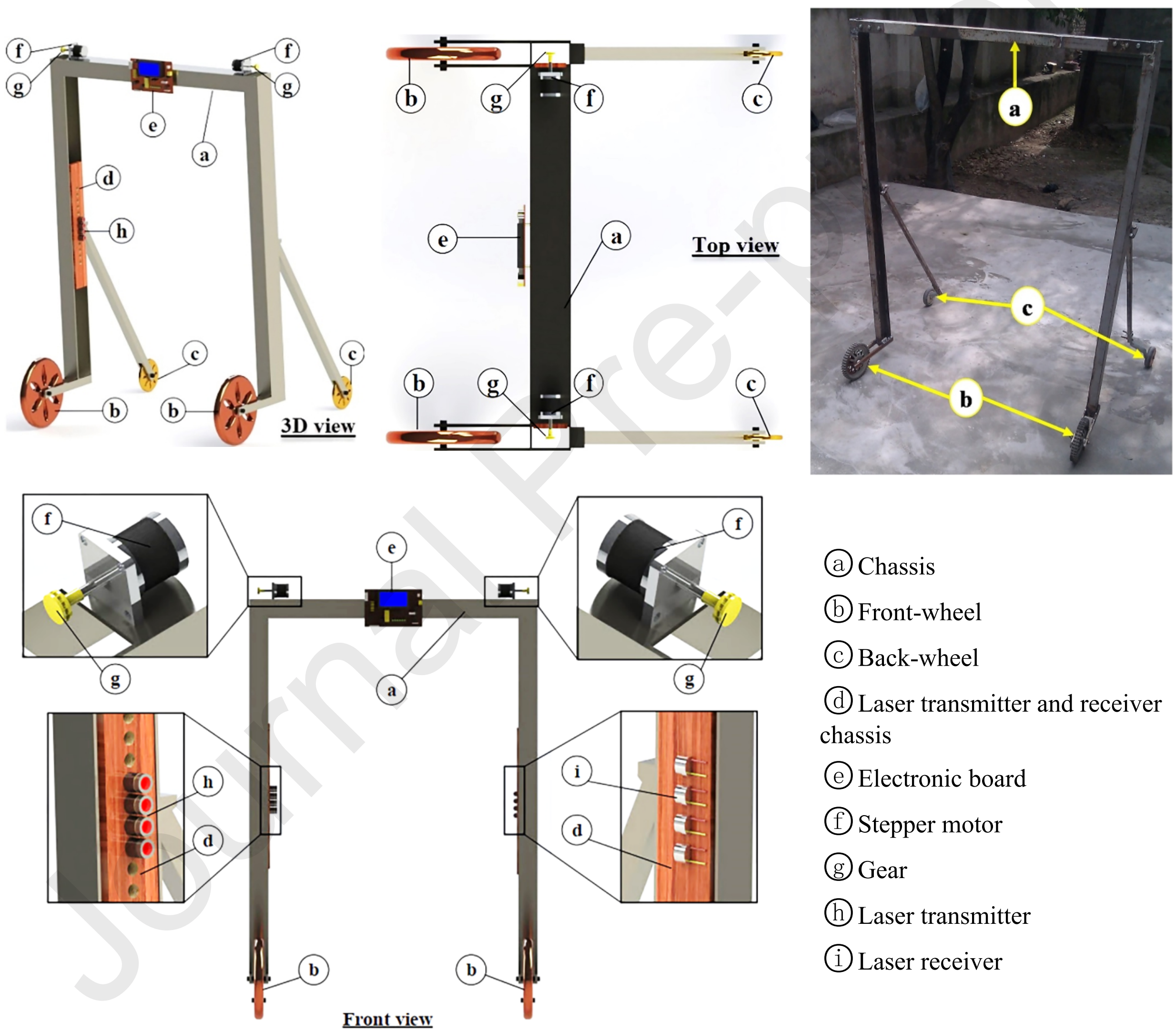


Fig. 4 The position of equipment for measuring agricultural crop height using the laser on the main chassis(ⓐ). Crops are located between laser transmitters (ⓗ) and receivers (ⓘ). The laser transmitter and receiver chassis (ⓓ) move-up/ move-down by stepper motors (ⓕ) and gears (ⓖ) according to the height of crops. The Electronic board (ⓔ) controls stepper motors, calculates and shows crops height.

2.4 Mechanical section

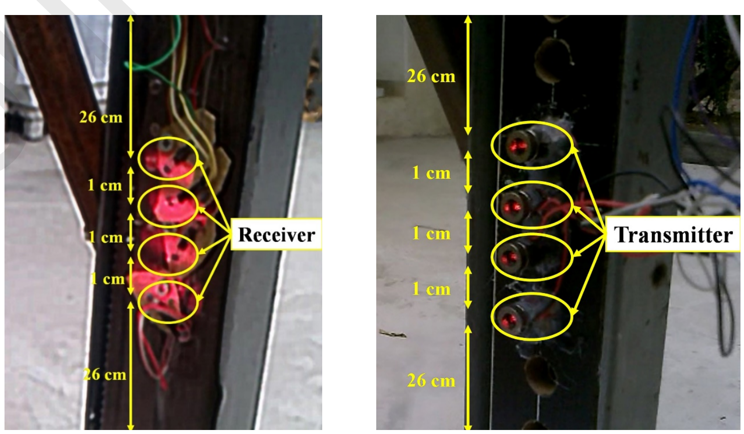
The mechanical unit includes the design and fabrication of the main chassis (Fig. 4a) and wooden frames for laser transmitters and receivers (Fig. 4d). Important factors in the mechanical design include: minimum weight, portable and lightweight, ability to move horizontally on the ground, high strength against the uneven ground during movement, and easy movement of lasers chassis on the main chassis.

2.5 Main chassis

The main chassis is one of the most crucial parts of the device (Fig. 4a), and all components are installed on this part. The important part of chassis design was that the plants always must pass between transmitters and receivers. Additionally, the main chassis must be able to move on the ground without damaging plants. Another main function of this chassis is to protect transmitters and receivers' chassis. To describe precisely, wooden chassis should move easily inside the main chassis, and during movement, the main chassis must eliminate extra forces that destroy the balance. it was made by a sheet metal plate with a thickness of 3 mm.

2.6 Transmitters and receivers' chassis

After fabricating the main chassis, the next step was to construct two chassis to carry the laser transmitters and receivers (Fig. 4d). These parts fabricated by two pieces of Medium-Density Fiberboard (MDF) with 5 cm width, 60 cm length and 1 cm thickness. Fig. 5(a) and Fig. 5(b) demonstrate laser receivers' and chassis laser transmitters' chassis, respectively.



(a) (b)

Fig. 5 The distance of laser receivers (a) and laser transmitters (b) from each other

2.7 Motors

According to the lasers' chassis movement that should be vertical, two linear motors were required. These motors are more expensive than rotary motors. Hence, rotary motors were selected, and with a special gear (Fig. 4g) the rotational motion of these motors was changed to the linear motion. Various factors were considered for choosing a suitable motor such as motor power, motor electric current, motor motion (rotary or linear), speed of Motors under different loads, and price. Finally, stepper motor (TECO 4H5609S) was selected (Fig. 6). The main reasons to choose this motor was high power (the maximum weight that motor could move was 4 kg in the laboratory) and ability to hold weights at different heights without error. Besides, its price has been lower than other motors, and these motors required little space on the main chassis.

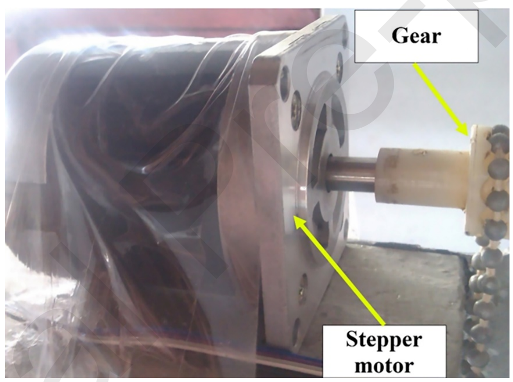


Fig. 6 The gear and Stepper motor (TECO 4H5609S)

2.8 Electronic section

The electronic part was designed according to the needs, available facilities, appropriate layout and using the logical connection of its parts. The main components used in the circuit board (Fig. 4e) was: (i) ATmega128 AVR Microcontroller (ATMEL Corporation, USA), (ii) 128 × 64 Graphic LCD Display (Arduino company, USA), (iii) 12v switching power supply (PWR+, USA), (iv) Crystal clock oscillator (NDK company, Japan), (v) Laser transmitter (SYD1230 650 nm 5mW) (Zhongshan He Tong Optics Electronic Technology Company, China) , and (vi) Laser receiver (PD438) (Everlight Electronics Company, Netherlands).

2.9 Height measurement by the system

In this system, the presence or absence of plants at a certain point identify by lasers, and the measurement of plant height is done by measuring the displacement of the laser chassis. This vertical displacement is done by two stepper motors. It should be mentioned that the main advantage of this type of motor is Accurate measurement of displacement. According to the technical specification of the motor, a full round is equivalent to 200 steps. In other words, the displacement of each step is 1.8 degrees. To calculate the circumference of the specific gear that is shown in Fig. 4ϑ, the radius of gear was measured. According to the number of steps of the stepper motor for a complete round, the amount of linear displacement of gears was calculated using Eq. (1) that is 0.031 4 m.

$$\text{Circumference of Circle} = 2\times\pi\times r \tag{1}$$

Where r represents radius. After accurately measuring the amount of movement on each step, this data was added to the microcontroller. Therefore, by measuring the number of steps, the number of height changes was calculated.

2.10 Evaluation of the system's performance

There are some important criteria to evaluate the performance of a system. These criteria include: Mean Absolute Percentage Error (MAPE), Root Mean Squared Error (RMSE), the coefficient of determination (R^2) of the linear regression line between the height detection system's output and the manual output. These criteria are defined as follows:

$$MAPE = \frac{1}{n}\sum_{j=1}^{n}\left|\frac{d_j - p_j}{d_j}\right|\times 100 \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{j=1}^{n}(d_j - p_j)^2}{n}} \tag{3}$$

$$R^2 = \frac{\left[\sum_{j=1}^{n}(d_j - \overline{d})(p_j - \overline{p}\right]^2}{\sum_{j=1}^{n}(d_j - \overline{d})^2 \times \sum_{j=1}^{n}(p_j - \overline{p})^2} \quad (4)$$

Where d_j the jth component of the manual measurement output; p_j is the component of the system's output; n is the number of data; $\overline{d}$ and $\overline{p}$ are the average of the whole manual and system's output, respectively.

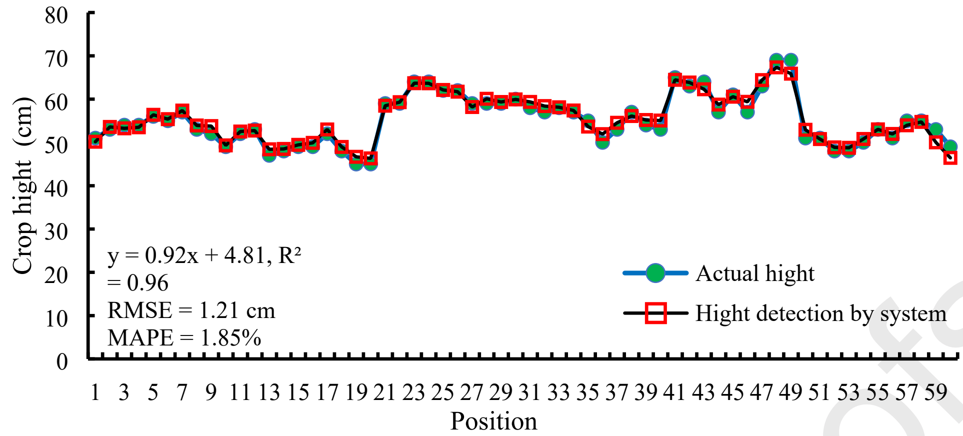
The average, variance, kurtosis and skewness of the manual output and system's output were statistically compared to evaluate the height detection system. *t*-test, fisher and Kolmogorov–Smirnov test that are statistical tests, were used to compare the average, variance and statistical distribution of the two datasets.

3. Results and Discussion

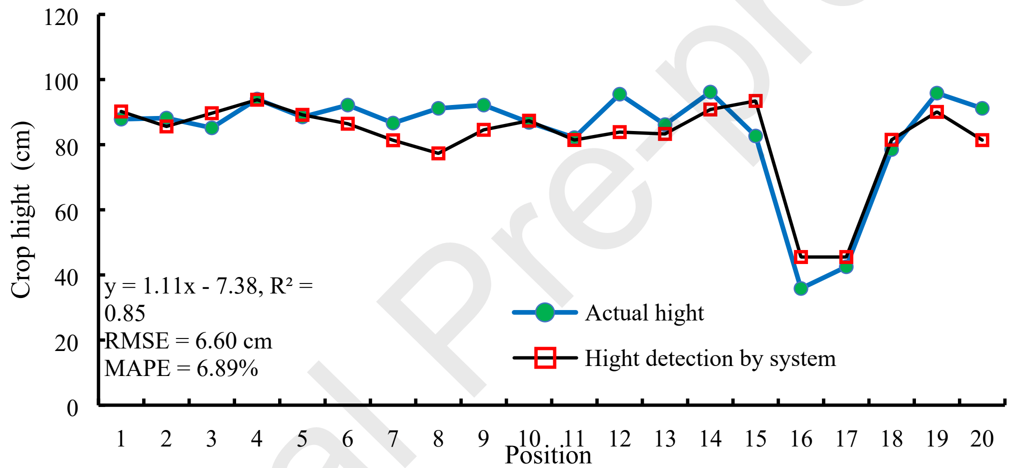
3.1 Statistical analysis

In Fig. 7, the manual measurement data sets of paddy rice and wheat have been compared to the height detection system's output. As can be seen, Mean Absolute Percentage Error of designed-system for paddy rice and wheat were 1.85% and 6.89%, respectively. Besides, wheat's RMSE was 6.60 cm and RMSE for paddy rice was 1.21 cm. On the other hand, the coefficient of determination of the regression line between the manual measurement and system's output for paddy rice was 0.96 and for wheat was 0.85. As the results show, the designed system estimated the height of paddy rice more accurately than the height of wheat. This is due to the two main reasons. The first reason is the uniformity of paddy rice height in the laboratory compared to wheat on the farm. the second reason is the more the farm surface is uneven, the less the height detection system's output is accurate. Because the uneven of the ground causes sensors vibration during data acquisition.

Therefore, if the variety of the product or the cultivation conditions of the product are provided favourably, the accuracy of measuring the height of the product can be more assured. Besides, mounting laser sensors on vehicles instead of the frame can decrease sensors vibration that will lead to the improvement of the crop height detection system accuracy.



(a)



(b)

Fig. 7 Comparison between manual measurement and measurement with the height detection system for (a) rice and (b) wheat

The average, variance and statistical distribution of paddy rice and wheat height datasets at the 5% level were compared with each other to further evaluate the efficiency of the designed system. The values of the mean, variance, kurtosis and skewness of the manual output and system's output have been shown to evaluate the designed system performance in Table 1. Additionally, the *p*-value (> 0.05) of the paired Student's *t*-test, Fisher and Kolmogorov-Smirnov test has calculated to evaluate the difference of mean, variance and statistical distribution of the two manual and system's output. The results show that there is no significant difference between the mean, variance and statistical distribution of the two datasets at the level of 5%. Therefore, the measurement performance of the designed system can be statistically reliable.

Table 1 Some statistical properties of manual measurement and height detection system measurement of paddy rice and wheat

Crop	Values	Average	Variance	Kurtosis	Skewness
Rice	Actual	55.47*	28.57	2.20	0.26
	Measurement	55.22*	32.51	2.61	0.42
	p-value	0.80	0.62	0.91	
Wheat	Actual	82.11*	176.31	6.51	-2.13
	Measurement	83.95*	258.26	6.98	-2.27
	p-value	0.70	0.41	0.28	

*: Unit is Centimeter (cm)

3.2 Comparing with similar works

To evaluate the designed-height detection system against similar works, it has been compared with some previous methods worked on plant's height detection. All research that mentioned in Table 2, required computer and software to analyze collected data. Lidar technology is more expensive than other methods [9]. According to the table, the accuracy of Ultrasonic sensors is low. Image processing-based methods are time-consuming because collecting image, preprocessing and processing are basics steps of this method. While in the designed system, data analysis is done by a microcontroller. This advantage makes it possible that results can be used online. On the other hand, the designed system is not sensitive to the density of crops, which can be considered as a defect.

Table 2 Similar research results

Used technology (Model)	Data processing method	Mounted on	Objectives	Accuracy (%)	Reference
3D Lidar (FX6)	Computer	Agricultural robot	Artificial plants (Lab) Maize (Field)	> 90 80–90	[10]
2D Lidar (LMS 291)	Computer	Tractor	Miscanthus giganteus (Lab)	93–98	[27]
Ultrasonic	Computer	All-terrain vehicle	Blueberry (Field)	60–83	[24]

(LV-MaxSonar-EZ1)					
Image processing (ILCE-6000 Sony)	Computer	Fixed-Wing UAV*	Sorghum (Field)	62–88	[35]
Terrestrial Laser Scanning (Riegl VZ-1000)	Computer	Tripod	Rice (Field)	91	[39]
3D Reconstruction (Microsoft Kinect v2)	Computer	UAV*	Grass ley (Field)	> 80	[32]
Digital Surface Model (GoPro Hero3+)	Computer	UAV* Walkera QR350	Wheat (Field)	—	[31]
proposed system (Laser)	**microcontroller**	**Frame**	**Rice (Lab)** **Wheat (Field)**	**97** **91**	**Our method**

*: Unmanned Aerial Vehicle

4. Conclusions

The use of new measuring instruments with high accuracy help to manage agricultural production. The main purpose of this research was the feasibility study of a simple, rapid and low-cost height detection system. In this study, paddy rice and wheat's height have been measured in the laboratory and farm, respectively. Results showed that this system can detect the height of crops with high accuracy, and it has some clear advantages such as lower cost, simplicity and high accuracy. The designed-system can be used in different sections such as the amount of straw entering combine harvesters can be reduced if the designed system mounts on combine headers. Because this system can measure crops height continuously, and then according to the height of the crops, header height can be controlled automatically. Besides, by adding a GPS unit on the electronic part of this system, farms' biomass will be estimated. Besides, the system can be used in spraying row crops. It locates crops on rows, and by specialized spraying, the use of pesticides will be reduced.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: