DEVELOPMENT OF UAV-BASED LIDAR CROP HEIGHT MAPPING SYSTEM

BY

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THESIS

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Adviser:

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ABSTRACT

Crop height monitoring is important to appropriate field management. Previous studies have indicated that a Light Detection and Ranging (LiDAR) sensor was capable of accurate and fast data collection. As technology of Unmanned Aerial Vehicles (UAV) advanced, the airborne LiDAR system became a promising remote sensing based method for non-destructive crop height measurement. The objective of this study was to develop a UAV-based LiDAR system for crop height measurement. The system consisted of a 360-degree 2D laser scanner and an onboard computer mounted on an open source UAV platform. A data processing and visualization algorithm was developed to process dense spatial point cloud data and generate a crop height map of the target field. Outdoor experiments were conducted in a real corn field to evaluate the height measurement performance of the UAV-based LiDAR system. The results show that the average $R^2$ value of 0.87, average mean error (absolute error) of 4.47% and average RMSE of 0.143 m, were achieved in comparison with manual measurements. The UAV-based LiDAR system could cover a 2 acre corn field within eight and half minutes, saving about 90% operation time compared with a tractor-based LiDAR system. The UAV-based LiDAR system developed in this study demonstrated its accurate and efficient crop height measurement in a real crop field, and is expected to be applied in practical agricultural production.

Keywords: Unmanned Aerial Vehicle, LiDAR, Remote sensing, Point cloud, Crop height
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAV</td>
<td>Unmanned Aerial System</td>
</tr>
<tr>
<td>LiDAR</td>
<td>Light Detection and Ranging</td>
</tr>
<tr>
<td>SDK</td>
<td>Software Development Kit</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinematic</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>ROS</td>
<td>Robot Operating System</td>
</tr>
<tr>
<td>FC</td>
<td>Flight Controller</td>
</tr>
<tr>
<td>RC</td>
<td>Remote Controller</td>
</tr>
<tr>
<td>R²</td>
<td>Coefficient of Determination</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Avg. Dev</td>
<td>Average Deviation</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION

The consumption of food, raw materials and biofuels is increasing with the rapid growth of the population and development of the economy, which causes the increase in demand for agricultural production. Many studies indicate that crop production needs to be increased by 60% to 110% worldwide by 2050 to meet these rising demands [1]. Expanding cropland areas and increasing the use of fertilizer are two key traditional methods to increase the yield. However, the exploitable cultivable land is very limited and over fertilization leads to soil pollution, which means the traditional methods are neither sustainable nor environmentally-friendly. A sustainable and environmentally-friendly method is urgently needed.

Precision Agriculture, which aims at minimizing the input and maximizing the output, is regarded as a promising solution to meet the needs of increasing global crop production [2]. Precision Agriculture is an information-based field management method, which means the agricultural production data collection is basis of the appropriate field management. Among various agricultural production data, crop growth data is one of the most important agricultural data since it helps field managers to make crop management strategies so as to ultimately increase crop yield [3]. However, it is not easy to measure the crop growth status directly. The previous studies have proved that the morphological characteristics of crops could reflect the crop growth status and developed crop growth monitoring method through morphological characteristics measurement [4-6].

Among possible measures of plant growth, crop height is the most direct measurement and is the most direct indicator of productivity and growth rate [7]. Manual measurement is still often adopted in crop height data collection. However, manual measurement is time-consuming,
costly and will introduce human error [3]. Additionally, it will destroy the measured crops to some extent. Many non-destructive crop height measurements method based on remote sensing platform have been developed, like the tractor-based or airborne imaging system and ground robot-based ultrasonic sensing system [8-11]. However, these methods have significant drawbacks and limitations. Take the tractor-based imaging system as an example. The image processing has requirement for light condition. And the areal coverage of tractor is limited.

Besides imaging system and ultrasonic sensing system, the Light Detection and Ranging (LiDAR) sensor are increasingly important in crop height measurement because of the efficient and accurate data collection [12]. The previous studies have developed several terrestrial LiDAR systems and these systems could perform accurate crop height measurement. However, as mentioned above, the covered area of tractor platform is limited. Also, the tractor has requirement for the moving path in the field, otherwise it may destroy the neighbor crops. The airborne LiDAR system could overcome drawback and limitation of terrestrial LiDAR system. With the development of technology in mini-size aircraft and automatic control system, the Unmanned Aerial Vehicles (UAV) begin to play an important role in practical production. The UAV platform enhance the measurement performance of the airborne LiDAR system. The UAV-based LiDAR system is capable of reconstructing the target object’s 3D structure through the dense point cloud and accurate position reference. The crop height characteristic can be extracted from the crop’s 3D structure [13]. As Anthony [14] stated, “UAV borne LiDAR systems will become a promising method for crop height measurement.”

Considering the important role that crop height data play in crop growth monitor and the significant drawbacks and limitations of the existing system, the UAV-based LiDAR crop height mapping system is crucial and necessary.
CHAPTER 2: OBJECTIVES

The purpose of this study is to develop a UAV-based LiDAR system for corn plant height measurement in a real field condition, which could increase the data collection efficiency in both agricultural research and development (e.g. for high-throughput phenotyping or seed crop monitoring, etc.). Specific sub-targets are:

1) Design and implementation of a commercial UAV-based LiDAR system, includes mounting the LiDAR sensor to the UAV platform and developing a data acquisition program which can read, record and integrate LiDAR data and Positioning data (GPS and attitude) in real time during flight.

2) Introduce an autopilot system which enables field managers customize flight parameters through a smart phone allowing the system to execute measurement missions automatically.

3) Develop a dense point cloud processing algorithm for fusing navigation data and LiDAR data, extracting height information and generating a plant height map of the target field.

4) Assess the performance of the developed system in an outdoor testbed and real field condition.
CHAPTER 3: LITERATURE REVIEW

3.1 The Application of UAV in Agriculture

With the development of technology in aircraft and automatic control system, the UAV begins to play an important role in Precision Agriculture. The UAV could provide higher spatial and temporal information but at lower cost compared with manual experiments, aerial or satellites and other traditional field information collecting methods [14]. Because of these advantages, it is believed that the UAV could offer a new solution for field management and monitoring [15].

Current research of the application of the UAV in agriculture typically focuses on taking aerial images and obtaining the desired information through image processing in a more efficient manner than traditional methods. Xiang and Tian [16] developed an autonomous UAV-based system for field image data collection. Yu et al. [17] improved soybean yield estimation and predicted plant maturity with the UAV platform. Honkavaara et al. [18] used the UAV imaging system to take FPI spectral imagery and estimates of the biomass. Torres-Sánchez et al. [19] developed a method to generate a vegetation fraction map in early-season wheat fields using the images from the UAV.

Another active topic is the UAV-based spray system which can meet the requirement of chemical application in very specific production system [20]. Huang et al. [21] developed a spray system for a fully autonomous UAV system that can precisely apply sprays. Faiçal et al. [22] investigated a methodology based on Particle Swarm Optimization for fine-tuning the control rule for spraying pesticides on crop fields. Lan et al. [23] studied the effect of adjuvants on the downwind deposition and transport of a UAV-based sprayer.
3.2 Airborne LiDAR System

The airborne LiDAR system or airborne laser scanning system is capable of depicting target objects or areas through the related collection of dense point clouds with accurate coordinate triples [13]. In the past decades, due to the cost and the UAV size, most airborne LiDAR systems were designed for government or military purposes or to validate the concept that the UAV borne LiDAR system could achieve accurate and efficient data collection [24]. Development in small-scale technology and manufacturing technology brings the UAV borne LiDAR system an ideal remote sensing platform to provide high spatial and temporal data at a generally affordable cost [24].

Currently, the UAV borne LiDAR has been widely explored and applied in various remote sensing areas. Filin and Norbert [25] developed an algorithm for the building segmentation of airborne laser scanning data. Zhou and Neumann [26] proposed a robust approach to creating 2.5D building models from aerial LiDAR point clouds. Boyko and Funkhouser [27] extracted roads from unstructured dense point clouds of a large scale urban environment. Hopkinson et al. [28] mapped the spatial distribution of snowpack depth beneath a variable forest canopy. Choi et al. [29] developed a UAV-based multi-sensor platform which could execute rapid mapping for emergency responses.

Besides geological surveys and industry applications, the UAV borne LiDAR is also employed in agricultural production. Jaakkola et al. [30] first built a low-cost UAV borne LiDAR system and demonstrated its capability of performing forest inventory at the individual tree level. Wallace et al. [24] developed a UAV borne LiDAR system for forest inventory and fused multi sensor with HD video so as to conduct accurate measurements. Asner et al. [31] proposed a universal method for tropical forest carbon mapping through airborne LiDAR data.
Luo et al. [32] built a LiDAR data based model to estimate the leaf area index of wetland vegetation. Li et al. [33] validated the LiDAR model to estimate the biomass components of maize.

### 3.3 The Morphological Characteristics of Crops

The morphological characteristics of crops provide agronomists valuable information about crop’s growth status, which helps to make crop management strategies such as fertilization, irrigation and pesticide spraying, so as to ultimately increase crop yield [3]. Many previous studies have proven the correlation between the crop’s morphological characteristic and biological characteristic. Omasa et al. [4] revealed that a plant’s eco-physiological responses are strongly related to the 3D structure of the plant. Also, canopy size and structure will affect a plant’s water use and photosynthesis [5]. The leaf area has obvious interaction with the yield and biomass since the leaf area is important to the efficiency of the photosynthesis [6]. Clifton-Brown et al. [34] showed that crop height can be an indicator to distinguish different genotypes. Therefore, the crops’ morphological characteristics can be used to monitor the plant growth status.

Among the various morphological characteristics, crop height is one of the most important morphological characteristic, since the crop height is the most direct indicator of the health status. For example, the health plant will grow to certain height in certain growth stage [7]. But the lack of the mineral elements or the disease will cause the slow growth and dwarf. Additionally, the crop height can be used to estimate the productivity before the harvest. Zub et al. [35] proved crop height is positively related to the yield. Tilly et al. [12] verified that plant height and biomass is highly correlated.
3.4 Crop Height Measurement System

Previous research has developed different kinds of remote sensing based methods to measure the crop height. Digital imaging processing is one of the most generally adapted methods for canopy measurement. Bendig et al. [8] used the UAV-based RGB imaging to create a crop surface model to estimate plant height information. Sritarapipat et al. [7] set the marker bar in the field as height reference and extracted the plant height information from the images by comparing the marker bar to the initial point. Zhang and Huang [9] used an ordinary camera to get tree photos and calculate the tree height by comparing marker points and the top point. Han [10] used three marker points along the tree trunk to correct tree images so as to calculate tree height. Carlone et al. [11] combined the multi sensor fusion and the use of computer vision to obtain a 4D model of the crop. The digital image processing is capable of crop height measurement. However, it has specific requirements for image resolution and the light condition.

The Ultrasonic sensor is another commonly used non-destructive method for canopy characterization measurement. Aziz et al. [36] investigated an ultrasonic sensing based approach to estimate corn plant height. Llorens et al. [37] employed an ultrasonic sensor to extract plant height information in different varieties and growth stages in a vineyard. Gamarra-Diezma et al. [38] tested the feasibility of applying a commercial ultrasonic sensor to measure an olive tree canopy in a real field condition. Planas et al. [39] verified the appropriateness, stability and accuracy of a commercial ultrasonic sensor for fruit tree canopy characteristic. However, Barker et al. [40] revealed that the ultrasonic sensor is sensitive to temperature, which affects the measurement accuracy in a real field condition.

Besides digital image processing and ultrasonic sensors, LiDAR sensors are increasingly important in crop height measurement because of the efficient and accurate data collection [12].
Zhang and Grift [41] developed a tractor based LiDAR system for measuring stem height of Miscanthus giganteus. Garrido et al. [42] established a robot based multi-LiDAR sensor platform for maize plant height measurement and 3D reconstruction. Sun et al. [3] built a LiDAR based high-throughput phenotyping system to measure cotton plant height. The terrestrial LiDAR system could perform accurate measurements, but the areal coverage and field condition is relatively limited [43].
CHAPTER 4: MATERIAL AND METHODOLOGY

4.1 Data Acquisition System

4.1.1 Data Acquisition System Components

![Figure 4.1: The UAV-based LiDAR system](image)

A DJI Matrice 100, as shown in Figure 4.1, was selected as the remote sensing platform in this study. The Matrice 100 is designed and manufactured by DJI (Shenzhen, China), the world's leader in the civilian-drone and aerial imaging technology industry. With the help of the DJI-Onboard-SDK and the Universal Power and Communication ports, the developer can customize and tailor this flight platform, tell it how and where to fly, and gather information from the entire system in real time. The Matrice 100 is a quadcopter equipped with four brushless motors which operate at different rotor speeds to achieve directional flight. These four motors offer increased stability and decreased vibration in comparison to other UAV platforms.
The stability and the robustness are essential to execute exact measurement and get accurate and precise result. Figure 4.2 lists the technical specs of Matrice 100.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Propulsion System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagonal Wheelbase</td>
<td>DJI 3810</td>
</tr>
<tr>
<td>Weight (with TB47D battery)</td>
<td>2355 g</td>
</tr>
<tr>
<td>Weight (with TB48D battery)</td>
<td>2431 g</td>
</tr>
<tr>
<td>Max Takeoff Weight</td>
<td>DJI 1345s</td>
</tr>
<tr>
<td>Optional Accessories</td>
<td>DJI E SERIES 420D</td>
</tr>
<tr>
<td>Expansion Bay Weight</td>
<td>45 g</td>
</tr>
<tr>
<td>Battery Compartment Weight</td>
<td>160 g</td>
</tr>
<tr>
<td>Zenmuse X3 Gimbal and Camera Weight</td>
<td>247 g</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hovering Accuracy (P-Mode, with GPS)</td>
<td>Vertical: 0.5 m, Horizontal: 2.5 m</td>
</tr>
<tr>
<td>Max Angular Velocity</td>
<td>Pitch: 300°/s, Yaw: 150°/s</td>
</tr>
<tr>
<td>Max Pitch Angle</td>
<td>35°</td>
</tr>
<tr>
<td>Max Speed of Ascent</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Max Speed of Descent</td>
<td>4 m/s</td>
</tr>
<tr>
<td>Max Wind Resistance</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Max Speed</td>
<td>22 m/s (ATTI mode, no payload, no wind)</td>
</tr>
<tr>
<td>Hovering Time (with TB47D battery)</td>
<td>No payload: 22 min; 500g payload: 17 min; 1kg payload: 13 min</td>
</tr>
<tr>
<td>Hovering Time (with TB48D battery)</td>
<td>No payload: 28 min; 500g payload: 20 min; 1kg payload: 16 min</td>
</tr>
<tr>
<td>Hovering Time (with TB47D battery and Zenmuse X3)</td>
<td>No payload: 19 min</td>
</tr>
<tr>
<td>Hovering Time (with TB48D battery and Zenmuse X3)</td>
<td>No payload: 23 min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>-10 to 40 °C</td>
</tr>
<tr>
<td>Remote Controller</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>C1</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>5.725–5.825 GHz</td>
</tr>
<tr>
<td>Max Transmission Distance (unobstructed, free of interference)</td>
<td>FCC Compliant: 3.1 miles (5 km)</td>
</tr>
<tr>
<td>EIRP</td>
<td>10dBi or 9dBi</td>
</tr>
<tr>
<td>Video Output</td>
<td>USB, Mini-HDMI</td>
</tr>
<tr>
<td>Power Supply</td>
<td>Built-in battery</td>
</tr>
<tr>
<td>Charger</td>
<td>DJI approved charger</td>
</tr>
<tr>
<td>Dual Users Capability</td>
<td>Master-and-Slave control</td>
</tr>
<tr>
<td>Mobile Device Holder</td>
<td>Supports smartphones and tablets</td>
</tr>
<tr>
<td>Output Power</td>
<td>9 W</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-10 to 40 °C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>&lt; 3 months: -20 to 45 °C &gt; 3 months: 22 to 28 °C</td>
</tr>
</tbody>
</table>

**Figure 4.2:** Technical Specs of Matrice 100

DJI packages a Positioning and Orientation system for the Matrice 100. This system is called DJI Ace One, as shown in Figure 4.3, which consists of three parts: Main Controller, GPS and IMU. The GPS unit is integrated with a compass in a GPS & Compass Module, which is used to identify position and direction. The IMU (Inertial Measurement Unit) includes a 3-axis accelerometer, a 3-axis angular velocity and a barometric altimeter, which is used to recognize attitude. The Positioning and Orientation system provides detailed real-time state information up to 200 Hz.
The LiDAR sensor mounted on the UAV was a RPLIDAR A2, regarded as the next generation low cost 360-degree 2D laser scanner (LIDAR) solution developed by SLAMTEC (Shanghai, China). The sensor can perform 2D 360-degree scans within a maximum range of eight meters, which was originally designed for mapping indoor environments, localization and object/environment modeling. The typical scanning frequency is 10 Hz (600 rpm). Under this condition, the angular resolution will be 0.9°, allowing it to take 4000 samples per second. Figure 4.4 lists the technical specs of RPLIDAR A2.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance Range</td>
<td>Meter(m)</td>
<td>0.15</td>
<td>-</td>
<td>8</td>
<td>Based on white objects with 70% reflectivity</td>
</tr>
<tr>
<td>Angular Range</td>
<td>Degree</td>
<td>-</td>
<td>0-360</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Distance Resolution</td>
<td>mm</td>
<td>-</td>
<td>&lt;0.5</td>
<td>&lt;1% of the distance</td>
<td>+1.5 meters</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>Degree</td>
<td>0.45</td>
<td>0.9</td>
<td>1.35</td>
<td>10Hz scan rate</td>
</tr>
<tr>
<td>Sample Duration</td>
<td>Milisecond(ms)</td>
<td>-</td>
<td>0.25</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sample Frequency</td>
<td>Hz</td>
<td>2000</td>
<td>4000</td>
<td>4100</td>
<td>The rate is for a round of scan. The typical value is measured when RPLIDAR takes 400 samples per scan</td>
</tr>
</tbody>
</table>
Also, a special gimbal, as shown in Figure 4.5, was designed to mount the LiDAR sensor on the UAV platform. The gimbal is not only used for fixing the LiDAR sensor but for aligning the LiDAR sensor with the body of the UAV as well. The gimbal ensured the LiDAR sensor’s attitude same with the UAV platform during flight, which is important for the follow-up position determination of scanned point.

![Image of LiDAR sensor gimbal](image)

**Figure 4.5**: LiDAR sensor gimbal (a) Front view (b) Back view

The LiDAR sensor was driven by the onboard computer, Manifold. Also, the LiDAR data was recorded and pre-processed in the Manifold. Manifold is NVIDIA Tegra K1’s 4-Plus-1 Quad-core ARM Cortex-A15 Processor based high-performance embedded mini Linux computer (NVIDIA, Santa Clara, CA), which is customized for DJI-Onboard-SDK software and application. Thus, the Manifold could get the GPS data from the GPS module and the attitude data from the built-in IMU directly by calling the DJI-Onboard-SDK. Both DJI and SLAMTEC provide the SDK on ROS (Robot Operating System). The control program, which integrated the DJI-Onboard-SDK and RPLIDAR-SDK, ran on the ROS and would drive the LiDAR sensor work after the UAV took off and record the LiDAR data, GPS data and attitude data of the UAV.
during the flight automatically. After the UAV completed the mission, the Manifold would save the data in the local repository or send to a cell phone through Data Transparent Transmission. Figure 4.6 lists the technical specs of Manifold.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>197 g</td>
</tr>
<tr>
<td>Dimension</td>
<td>110 mm×110 mm×28 mm</td>
</tr>
<tr>
<td>Processors</td>
<td>Quad-core, 4-Plus-1 ARM Cortex-A15 MP-core Processor with NECN technology, Low-power NVIDIA Kepler-based GeForce graphics processor, Image-signal processor, Ultra low-power audio processor</td>
</tr>
<tr>
<td>Memory</td>
<td>2GB DDR3L system RAM, 16 GB eMMC 4.51 storage</td>
</tr>
<tr>
<td>Network</td>
<td>10/100/1000BASE-T Ethernet</td>
</tr>
<tr>
<td>Audio</td>
<td>Combo audio jack(mic/headphone)</td>
</tr>
<tr>
<td>USB</td>
<td>USB 3.0 Type-A Host connector×2, USB 2.0 Type-A Host connector×2, Micro-B USB connector (host/slave mode), Extended USB connector with DJI M-series Multicopter×2, Mini-HDMI connector, Half mini-PCIe expansion slot</td>
</tr>
<tr>
<td>I/O</td>
<td>UART port(3.3V)×2, Micro SD card connector, I/O expansion headers (26pins)</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>14 V – 26 V</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-10 °C – 45 °C</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>5 w – 15 w</td>
</tr>
</tbody>
</table>

**Figure 4.6: Technical Specs of Manifold**
Repeatability is an important key index in evaluating the performance of the measurement system. Repeatable measurement is important to the stability and accuracy during the test period and to monitoring the plant in future applications as well. Therefore, AgVision, an autopilot App (Ag-Sensus, Urbana, IL) was used, which allows the user to customize the flight path and tell the UAV how and where to fly. The App is operated on the iOS platform, integrated Google Map and DJI-Mobile-SDK. The user interface of the autopilot App is shown in Figure 4.7.

![Figure 4.7: Mission planning in autopilot App](image)

The user can set boundaries for the target area. Then the App will plan the flight path automatically. Also, the user could customize flight height, flight velocity, flight direction, etc. The mission can be saved for the next or future flights.
4.1.2 Data Acquisition System Workflow

Once the user sets the boundary and flight parameters, the App will plan the flight path and send the mission to the N1 (Flight Controller) through the RC (Remote Controller). After the N1 receives the command from the user, the UAV will take off and start to execute the mission. Then, the Manifold will start to work by reading and recording the LiDAR data from the LiDAR sensor and current location (GPS) and attitude of the UAV from the N1. Once the UAV completes the mission and is ready to land, the Manifold stops working and exports the data on the local file or sends to a mobile phone. The data acquisition system followed a similar workflow as shown in Figure 4.8.

![Data Acquisition System Workflow Diagram](image-url)

**Figure 4.8:** Data Acquisition System Workflow

4.2 Outdoor Calibration Test Setup

The test in the outdoor testbed aims at evaluating the UAV platform’s stability and the performance of LiDAR sensor, which could also provide reference for the follow-up data processing. Testbed tests were taken in the E-14 Parking Lot, Champaign, IL, USA (40°05'49.1"N, 88°14'20.4"W). There were six boxes fixed at the certain locations, serving as the reference.
The UAV would fly along the preset flight path. The GPS data and LiDAR data would be recorded during the flight. The geometry information and relative position of the fixed boxes extracted from the dense point cloud would be compared with manual measurement data, to validate the performance of LiDAR sensor mounted on a flying UAV. The extracted flight path and flight height information would be used to assess the flight performance of the Matrice 100 platform installed with LiDAR sensor and onboard computer.

The system parameters (flight height, flight speed, flight direction, angular resolution, and sampling frequency of the LiDAR sensor) were the same as the field test. The system parameter configuration will be discussed in the field test setup. Figure 4.9 displays the test setup in the outdoor testbed.

![Figure 4.9: Outdoor testbed test setup (a) Overview of testbed (b) Top view of rendering](image-url)
4.3 Field Test Setup

Field tests were taken in Urbana, IL, USA (40°05'04.7"N, 88°13'33.3"W, 40°05'04.7"N, 88°13'29.9"W, 40°05'07.7"N, 88°13'29.9"W, 40°05'07.7"N, 88°13'33.3"W) from July to September of 2017. The target field was about two acres. The field was divided into 28 parts, each part has 49 rows and each row has 20 to 40 plants, depending on the parts. The corn planted in different parts had different genotypes. For the corn growing in the same part, they had the same genotype. Different genotypes may lead to height variation, which can be used to verify the accuracy of the measurement system. Figure 4.10 is the overview of the experiment field.

Figure 4.10: Aerial map of experiment field
4.3.1 Configuration of Flight Parameters

The maximum hover time of the Matrice 100 is about 28 minutes without any payload. Once adding the 1 kg payload, the hover times decreased to 16 minutes. In terms of battery capacity, the high flying speed is preferred, which also saves operating time. However, high speeds will affect the flight stability, especially when the UAV is accelerating or making a turn. Thus, it has to balance the time efficiency and stability. 5m/s was selected in this study as it would allow the UAV to cover the experiment field (90 m * 80 m) with one battery. And according to pre-tests, the stability of the platform at 5m/s is acceptable.

The maximum detection range of the LiDAR sensor is within eight meters, which limits the flight height of 8m * Cos (30°) = 6.93m. In this study, the flight height was set as 6 meters, to ensure that the laser could hit the ground and the reflected signal could be received, so as to generate a ground profile as reference for height calculation.

The flight direction was set as East-West (from East to West or West to East).

4.3.2 Configuration of LiDAR Parameters

The typical scanning frequency (10 Hz/ 600 rpm) was selected for this study. Under this condition, the angular resolution would be 0.9°. It means the sensor takes 4000 samples per second, very close to the maximum sampling rate.

Although dense cloud points provide tremendous amounts of information, too many points will affect the efficiency of data processing. For each rotation, lasers emitted from a certain range of rotation degrees could hit the object, either corn or ground, due to the maximum detection range of the LiDAR sensor and crop distribution. The relationship between scan degree and measured distance to the ground can be explained in Figure 4.11 and Equation 4.1.
In Equation 4.1, $H$ is the height of the LiDAR sensor, $\theta$ is the scanning degree, $2d$ is the length of one row in any field part. Since $2d$ equals to 5.4864 meters (18 feet) in the experiment field and $H$ equals to 6 meters, $\theta$ should be at least 24.57° so that the entire row will be covered during scanning. In this study, the $\theta$ was set as 30, to guarantee the coverage.

4.4 Data Processing and Visualization

The data processing and visualization were implemented in two parts. The main purpose of the first part was to generate the point cloud, through calculating the height value of the scanned points and fused with the location (GPS) information. A point cloud generation algorithm in MATLAB R2015b (The MathWorks, Inc., Natick, MA) was developed to achieve this purpose. The second part was aimed at extracting height characteristics of each plot and visualizing the result. The operation was implemented using ArcGIS 10.5 (Esri, Redlands, CA).
4.4.1 Import Raw Data

During the flight, Manifold would keep reading and recording LiDAR data. Every time a completed circle was scanned, Manifold would read and record GPS and attitude information once. In the data file, GPS and attitude data are just located at the following line to the last LiDAR data of each rotation. LiDAR data includes measured distance from scanned point to the sensor and related rotation angle. GPS data includes Longitude and Latitude. Attitude data includes flight height and attitude quaternion which will be converted to Euler angles in the following processes.

4.4.2 Calibrate and Fuse the GPS Data

As mentioned above, the GPS data would be recorded once a complete circle is scanned. In this case, all the scanned points in same rotation will be assigned the same GPS data. However, the UAV keeps flying during the LiDAR sensor scanning which means the GPS of the points scanned from the same rotation is different in the moving direction (West-East in this study which means Longitude needs adjustment), which is illustrated in Figure 4.12.

![Figure 4.12: Schematic of scan pattern](image)
Adjusted GPS data (Longitude) can be derived from Equation 4.2:

\[ Lng_i = Lng_0 \pm \frac{\theta_i - \theta_0}{\theta} \times \frac{t}{N} \times \frac{V}{d} \]  

(4.2)

where \( Lng_i \) is the updated Longitude, \( Lng_0 \) is the Longitude read from GPS data, \( \theta_i \) is the rotation angle of one of any scanned points in one circle, \( \theta_0 \) is the rotation angle of last scanned point in one circle, \( \theta^\circ \) is angular resolution, \( t \) is one rotation period, \( N \) is the number of samples per rotation, \( V \) is the velocity in moving direction, \( d \) is distance (in meter) to per Longitude degree. “±” depends on flying direction: if the UAV flies from West to East, “-” will be applied; if the UAV flies from East to West, “+” will be applied.

The calibrated GPS represents the location of the LiDAR sensor during scanning, but not the scanned points. Although the adjusted GPS is not for the scanned points, it will be matched to the related scanned point and will be used to calculate the real GPS of the scanned points in the next step.

### 4.4.3 Calculate and Calibrate the Position of Scanned Points

The position of the scanned points can be derived from the position of the LiDAR sensor and the relative position relationship between the scanned points and the LiDAR sensor. The relative position relationship is defined not only by the distance between the two objects but the orientation as well. However, the tilt of the UAV during flight will affect the orientation. It is because the quadcopter needs to tilt to a certain extent so as to produce horizontal components for forward moving, as shown in Figure 4.13 (a). For example, when moving straight forward, motor three will increase spin speed as motor one decreases spin speed, the other two motors keep the spin speed [24], as displayed in Figure 4.13 (b). Thus, the attitude of the LiDAR sensor should be taken into consideration to compensate for the tilt.
During the measurement, the Matrice 100 moved from East to West, just like the forward and backward movement, the body of the UAV would tilt to a certain extent. The tilt led both the LiDAR sensor to not be perpendicular to the ground. Thus, the measured position of the scanned points needs calibration. And as mentioned above, the gimbal aligns the LiDAR sensor with the body of the UAV so that the attitude of the UAV read from the built-in IMU can be used as the attitude of the LiDAR sensor.

The relative position relationship between the scanned points and the LiDAR sensor can be explained in Figure 4.14.

Figure 4.13: The structure and operation principle of Quadcopter

Figure 4.14: The principle of scanned point’s position determination
The calibrated position of the scanned points can be derived in Equation 4.3 [44-45].

\[
\begin{bmatrix}
X \\
Y \\
H_d \end{bmatrix}_o = \begin{bmatrix}
X \\
Y \\
0 \end{bmatrix}_S + M(\Phi, \theta, \psi) \cdot r^s(\alpha \ d) \\
\end{equation}
\]

(4.3)

\[
\begin{bmatrix}
X \\
Y \\
H_d \end{bmatrix}_o = \begin{bmatrix}
X \\
Y \\
0 \end{bmatrix}_S + M(\Phi, \theta, \psi) \cdot \begin{bmatrix}
0 \\
0 \\
0 \\
\end{bmatrix} + d \cdot \sin(\alpha) \\
\end{bmatrix}_S + d \cdot \cos(\alpha) \\
\end{equation}

(4.4)

\[
M(\Phi, \theta, \psi) = \begin{bmatrix}
a_1 & a_2 & a_3 \\
b_1 & b_2 & b_3 \\
c_1 & c_2 & c_3 \\
\end{bmatrix} \\
\end{equation}

(4.5)

\[
a_1 = \cos(\theta) \cdot \cos(\psi) - \sin(\theta) \cdot \sin(\Phi) \cdot \sin(\psi) \\
a_2 = -\cos(\theta) \cdot \sin(\psi) - \sin(\theta) \cdot \sin(\Phi) \cdot \cos(\psi) \\
a_3 = -\sin(\theta) \cdot \cos(\Phi) \\
b_1 = \cos(\Phi) \cdot \sin(\psi) \\
b_2 = \cos(\Phi) \cdot \cos(\psi) \\
b_3 = -\sin(\Phi) \\
c_1 = \sin(\theta) \cdot \cos(\psi) + \cos(\theta) \cdot \sin(\Phi) \cdot \sin(\psi) \\
c_2 = -\sin(\theta) \cdot \sin(\psi) + \cos(\theta) \cdot \sin(\Phi) \cdot \cos(\psi) \\
c_3 = \cos(\theta) \cdot \cos(\Phi) \\
\]

where \([X, Y, H_d]_o\) is the position of the scanned points in local level frame (\(H_d\) is the vertical distance between the LiDAR sensor and the scanned point), \([X, Y, 0]_S\) is the position of the LiDAR sensor in local level frame (in this study, only read Longitude and Latitude from the GPS receiver), \(M\) is the rotation matrix from LiDAR sensor frame or navigation frame to local level frame defined by yaw(\(\psi\)), roll(\(\Phi\)), pitch(\(\theta\)), \(r^s\) is the coordinates of target point given in LiDAR sensor frame defined by the scan angle (\(\alpha\)) and distance (\(d\)).
The three rotation angles can be derived from Equation 4.6:

\[
\begin{bmatrix}
\phi \\
\theta \\
\psi
\end{bmatrix} = \begin{bmatrix}
\text{atan}2(2(q_0 q_1 + q_2 q_3), 1 - 2(q_1^2 + q_3^2)) \\
\text{asin}(2(q_0 q_2 - q_3 q_1)) \\
\text{atan}2(2(q_0 q_3 + q_1 q_2), 1 - 2(q_2^2 + q_3^2))
\end{bmatrix}
\]

(4.6)

where \(q_0, q_1, q_2, q_3\) are the quaternion read from attitude data.

### 4.4.4 Calculate Ground Height and Generate Point Clouds

The ground height value of the scanned point on the plant can be derived from Equation 4.7:

\[
H_p = H_0 - H_d
\]

(4.7)

where \(H_p\) is the ground height (vertical distance between scanned point and the ground) of the scanned point on the plant. \(H_0\) is the height (vertical distance between the LiDAR sensor and the ground) of the LiDAR sensor. \(H_d\) is the vertical distance between the LiDAR sensor and the scanned point.

In this study, the maximum \(H_d\) (relative height) for each rotation would be taken as the \(H_0\). The reason why we do not take the preset flight height or the flight height read from the UAV built-in sensor as the \(H_0\) is due to: 1) the UAV failed to stay at the fixed altitude [the detail information about height variation will be provided in the Chapter 5, results of outdoor calibration test], 2) the accuracy of the flight height read from the UAV built-in sensor is at 0.1 m level which is far more inaccurate when compared with the LiDAR sensor.
Once both GPS and ground height of each scanned point has been calculated and calibrated, the point cloud of the target field will be generated as shown in Figure 4.15:

**Figure 4.15:** Point cloud visualization
4.4.5 Extract Height Characteristic

The point cloud included the scanned point not only at the top of the corn but at other parts of the corn as well. In order to obtain the height of the corn, scanned points at the top of the corn should be extracted from the dense point cloud. The point extracting process was achieved in ArcGIS 10.5.

Step 1: Load the cloud points in the ArcMap.

Since every point already contains position information (Longitude, Latitude and Height), the geo reference is not required. However, the point data has to be converted to shapefile for the following process. Figure 4.16 displays the result of plotting cloud points on the base map.

![Figure 4.16: Point cloud plot on the base map in ArcGIS](image-url)
Step 2: Create the grid.

The Grid, as shown in Figure 4.17, was clipped from the experiment map, shown in Figure 4.18, and was used to remove unwanted scanned points and remaining scanned points at the top. Each grid cell represents a growth area for a single corn plant.

**Figure 4.17**: Grid clipped from the experiment map
Figure 4.18: 2017 NitroGenes NURSERY - Field M18W Experiment Map
Step 3: Spatial join and extract height characteristic.

Project all points on the grid. And for each grid cell, keep the point who has maximum height value and remove other points. This height value would be regarded as the height of the corn in this site. The height map of the target field will be available after this step, as shown in Figure 4.19:

![Height Map of the Corn Field](image)

**Figure 4.19:** Final crop height map of experiment field

To test the accuracy of the measurement system, the height data obtained from the measurement system will be compared with height data from a manual measurement. Details will be discussed in the Chapter 5.
4.5 Explore New Application

Although the system was originally designed for helping agronomist to increase the crop data collection efficiency, it is expected to be applied in practical agricultural production. A local farmer, Dr. Wesley M. Jarrell, proposed an idea that estimates the milk production from the biomass of the grass eaten by goats. The biomass of the grass can be derived from the grass’ height change. And the UAV-based LiDAR system developed in this study can be employed to monitor the grass’ height change.

In order to explore the new application of the system, the experiment in a local dairy farm (Prairie Fruits Farm & Creamery, Champaign, IL) was conducted. The farm mainly provides goat dairy and farmstead creamery and has its own pasture and hay field. The tests were conducted in the pasture every week. The height change of the grass from week to week was used to calculate the biomass, which helped the farmer to figure out the relationship between the biomass of the grass and the milk production.

The pasture where the test conducted is the red frame area in Figure 4.20.

![Figure 4.20: Overview of the Prairie Fruits Farm](image)
CHAPTER 5: RESULTS

5.1 Results of Outdoor Calibration Test

5.1.1 Platform (UAV) positioning accuracy measurement

The stability of flight height and deviation in vertical direction would be used to assess the performance of the UAV platform. The three views of the test result are shown in Figure 5.1.

![Top view](image1)

![Left side view](image2)

![Front view](image3)

**Figure 5.1:** Three views of the UAV positioning accuracy measurement

Table 5.1 and Table 5.2 list the result of platform positioning accuracy test.

**Table 5.1:** Test result of UAV platform flight height performance

<table>
<thead>
<tr>
<th>Mean (m)</th>
<th>Std. Dev (m)</th>
<th>Bias (m)</th>
<th>Max Diff (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.574648</td>
<td>0.436312</td>
<td>0.609954</td>
<td>1.411982</td>
</tr>
</tbody>
</table>

(Note: The flight height was set at 6 meters.)
The test results revealed that the current multi-rotor UAV platform cannot stay at certain altitudes during flight. It would rise and fall around the preset height (max 1.4 meter or 23.5% of the preset flying height). For plant height measurement, the platform position cannot be used in the calculation. This is why a relative height measurement method, which the maximum $H_d$ (relative height) for each rotation would be taken as the $H_0$ (the height of the LiDAR sensor), has been used in this research. On the other hand, the UAV platform was quite stable in the horizontal direction compared with the vertical direction. It is possible there was inertia in moving direction (horizontal). This higher accuracy in horizontal positioning helped us in the field to maintain the spatial resolution of the mapping system.

5.1.2 Relative Position Measurement Accuracy Tests

The measurement accuracy of the mapping system in the relative vertical height and horizontal width were used to evaluate the performance of the LiDAR sensor mounted on the flying UAV. For the horizontal direction, the mean difference between the LiDAR measurement and the manual measurement was about 0.1 meter, and the RMSE was about 0.1 meter as well. For the vertical direction, mainly measuring the height, the difference between the LiDAR measurement and the manual measurement was about 0.044 meter and the RMSE was about 0.044 meter as well. The LiDAR sensor’s measurement for then vertical direction was more accurate than for the horizontal direction. The test result is shown in Figure 5.2.

| Table 5.2: Test result of UAV platform performance in Horizontal Direction |
|-----------------------------------------------|-----------------|-----------------|
| Direction                        | Avg. Dev (m)   | Std. Dev (m)   |
| Perpendicular to Flight Direction | 5.16182E-15    | 0.107446205    |
| Flight Direction                 | 4.84841E-14    | 0.14471516     |
Table 5.3 and Table 5.4 list the result of measurement system accuracy test.

**Table 5.3**: Accuracy test result of LiDAR sensor in the Horizontal Direction

<table>
<thead>
<tr>
<th>Line</th>
<th>LiDAR (m)</th>
<th>Real (m)</th>
<th>Difference (m)</th>
<th>Mean (m)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>2.5256</td>
<td>2.6289</td>
<td>0.1033</td>
<td>0.09957</td>
<td>0.099891</td>
</tr>
<tr>
<td>L2</td>
<td>2.5219</td>
<td>2.6289</td>
<td>0.107</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3</td>
<td>2.5405</td>
<td>2.6289</td>
<td>0.0884</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.4**: Accuracy test result of LiDAR sensor in the Vertical Direction

<table>
<thead>
<tr>
<th>Height</th>
<th>LiDAR (m)</th>
<th>Real (m)</th>
<th>Difference (m)</th>
<th>Mean (m)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box 1</td>
<td>0.1977</td>
<td>0.1524</td>
<td>0.0453</td>
<td>0.0441</td>
<td>0.044269</td>
</tr>
<tr>
<td>Box 2</td>
<td>0.2736</td>
<td>0.2286</td>
<td>0.045</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Box 3</td>
<td>0.2909</td>
<td>0.254</td>
<td>0.0369</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Box 5</td>
<td>0.2987</td>
<td>0.254</td>
<td>0.0447</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Box 6</td>
<td>0.328</td>
<td>0.2794</td>
<td>0.0486</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Note: The geometry information of Box 4 is missing because only a few reflected signals were received.)
5.2 Results of Field Test

5.2.1 The Accuracy of the Measurement System

In order to test the measurement accuracy of the field test, a manual measurement height data was imported to compare with the LiDAR measurement data. Manual measurement data was collected by the Corn Functional Genomics Lab, under the leadership of Dr. Moose (Ph.D., Professor, Department of Crop Sciences, University of Illinois at Urbana Champaign). The researchers in Dr. Moose’s group measured all the way to the tip of the tassel. And for each plot, they would measure three individual plant’s height. The GPS of the manual data was not recorded at the same time as when the height measurement was implemented. It was read from the GPS-guided seed planter and every four plots would collect GPS data once. After two data sets were available, they were integrated.

The manual measurement data is shown in Figure 5.3:

![Figure 5.3: Manual measurement data plot on the base map in ArcGIS](image)
Before comparing the manual measurement and the LiDAR measurement, the two sets of data needed to be matched first. In this study, the location would be used as the factor to match the two sets of data. Since every four plots would collect GPS once, only a quarter of the total plots would be imported for comparison. For each plot, three individual plants would be manually measured. The selected three plants were neither highest nor shortest among their plot. The plot would be assigned a GPS location only, the location of individual plant was not recorded. Due to these factors, this study picked the median height of each plot to compare the manual measurement and the LiDAR measurement.

There were three LiDAR measurement field tests conducted from August to September 2017. The first test was taken on August 2, the second one on August 11 and the last one on September 17. The first two tests were conducted as the same time as when the manual measurement was taken. And the last test was conducted just before harvest.

The height value of compared points from the LiDAR measurement and the manual measurement is displayed in Figure 5.4.

Figure 5.4 shows the accuracy of the LiDAR measurement and the correlation of two datasets to some extent. However, to get more details of the accuracy and correlation, more mathematical statistical processing is required.
Figure 5.4: Measurement results comparison
(a) First test, August 2 (b) Second test, August 11 (c) Third test, September 17
Figure 5.5 shows the result of correlation analysis between the two datasets.

![Graph of Height Measurement](image)

**Figure 5.5**: Correlation analysis result
(a) First test, August 2 (b) Second test, August 11 (c) Third test, September 17

The $R^2$ for the first test was 0.8742, for second test was 0.8588 and for last test was 0.8775. The $R^2$ value of all three tests were larger 0.85 and very close to 0.9, which means the two datasets in these three tests were highly correlated.
Figure 5.6 shows the error distribution of the field tests. (This study took absolute error.)

**Figure 5.6**: Error distribution
(a) First test, August 2  (b) Second test, August 11  (c) Third test, September 17
The mean error of the first test was 4.36\% and 91.06\% of error was less than 10\%; the mean error of the second test was 4.54\% and 86.9\% of error was less than 10\%; the mean error of the last test was 4.52\% and 87.22\% of error was less than 10\%. The mean error and error distribution indicated that the error was small in these three tests.

| Table 5.5: Measurement performance of UAV-based LiDAR system |
|-----------------|-----------------|-----------------|-----------------|
| Mean Error (%)  | August 2 4.36   | August 11 4.54  | September 17 4.52 |
| RMSE (m)        | 0.13          | 0.16           | 0.13           |

To sum up, the $R^2$ were 0.8742, 0.8588 and 0.8775 for these three tests, which means the LiDAR measurement data was strongly correlated with the manual measurement data. The RMSE to these three tests were 0.13 m, 0.16 m and 0.13 m, as listed in Table 5.5, and the mean error of each test was 4.36\%, 4.54\% and 4.52\%, which indicates the LiDAR system had accurate measurements.

Although the three tests had about the same result, the RMSE and error distribution of the second test was not as ideal as other two tests. And the regression equation indicates the LiDAR measurement underestimated the result. The possible reason for causing these two issues and a potential improved method will be discussed in the Chapter 6.
5.2.2 The Efficiency of the Measurement System

During each field test, the total time for the UAV to cover the entire target field were recorded and is shown in Table 5.6.

<table>
<thead>
<tr>
<th>Flying time(s)</th>
<th>August 2</th>
<th>August 11</th>
<th>September 17</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight path 1</td>
<td>171</td>
<td>175</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>Flight path 2</td>
<td>173</td>
<td>168</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td>Flight path 3</td>
<td>168</td>
<td>178</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td>Total time</td>
<td>512</td>
<td>521</td>
<td>515</td>
<td>516</td>
</tr>
</tbody>
</table>

(Note: The experiment field was about 2 acres, 304 ft. L X 267.5 ft. W.)

Due to the size of the experiment field and the DJI-Mobile-SDK limitation, the UAV had to fly along the above-listed three paths so that it could cover the entire field.

For the first test, the UAV took 8 minutes and 32 seconds to cover the whole field; the second test took 8 minutes and 41 seconds and the last test took 8 minutes and 35 seconds. The average flying time to cover the whole field was 8 minutes and 36 seconds. This means the UAV covered a 2 acre field in about eight and a half minutes and only with one battery. Equipped with more backup batteries, the UAV can cover a larger field during one test.

For the manual measurement, it took almost one week to finish collecting height data of the plants. Compared with the manual measurement, the UAV-based LiDAR System is an efficient platform, which can save lots of researcher or field manager’s time to collect crop height data for the entire field.
5.3 Results of New Application Exploration

The grass height data collected from single week is shown in Figure 5.7. Although the farmer did not provide the manual measurement data of the grass height, the measurement result was quite different from how it really was, according to the images of the pasture and the observation.

![Figure 5.7: Point cloud data of single application extension test](image)

The reason why the measurement performance in pasture is not inaccurate is because the grass is too dense which leads to that the laser could not hit the ground for some scanning circle. Equation 4.7 illustrates how to calculate the ground height for each point. In Equation 4.7, the maximum $H_d$ for each rotation would be taken as the altitude of the LiDAR sensor. Since for some rotation the laser could not hit the ground, the $H_d$ was far from the real altitude, which cause the measurement result not as ideal as expected.

As the outdoor calibration test proved, the flight altitude varied during the mission. And as mentioned above, the flight height data read from the built-in IMU is not accurate when
compared with LiDAR data. These two factors cause the preset flight height or the flight height read from the UAV cannot serve as the height reference. Therefore, it is very hard for the system to get the ground profile, which is vital to generate final crop height map, in the field where the crop is very dense. Currently, the system is recommended to be applied for measuring row crops.
CHAPTER 6: DISCUSSION

During the field test, the UAV-based LiDAR System demonstrated its accurate and efficient performance in data collection under an uncontrolled field environment. From the result, the LiDAR System measured data and manually measured data were highly correlated, with the $R^2$ of 0.8742, 0.8588 and 0.8775. Also, the LiDAR System measured data was very close to the manually measured data, with the RMSE of 0.13 m for first and last test and 0.16 m for second test.

Although the result of second test on August 11 is acceptable, the statistical analyses indicates that the performance of the system during the second test was not as good as the other two tests. One possible reason contributing to the difference is the intensity of the GPS signal. The manufacture of the LiDAR sensor developed the modulated laser for safe and accurate measurement. However, the modulated laser is recommended for working in indoor environments and outdoor environments without sunlight. According to this, the field test in this study was conducted at night, which means the intensity of the GPS signal was not as good as daytime. The log file of the flight revealed that the intensity of the GPS signal in the first and third test were 13 and 15. However, the intensity of the GPS signal during the second test was 9. (Maximum is 16 and larger numbers indicate better signal intensity) Normally, if the indicated number is greater than 7, the UAV is allowed to fly at the GPS model. Otherwise, only the manual control mode is allowed. The weak GPS signal will cause the UAV to be off the preset course to some extent, which leads to some parts not being covered during the flight. Also, the weak GPS signal may cause the flight height to vary during the flight. The flight height was set to 6 meters, which was restricted by the maximum detection range of the LiDAR sensor. If the
UAV flies above 6 meters, the reflected laser signal may not be received by the LiDAR sensor. This will cause the system to miss some plots and even some areas.

**Figure 6.1**: Final crop height map of second test

From Figure 6.1, the points in the area marked with a red circle are very sparse, which means the LiDAR system did not receive a reflected signal in this area. However, some compared points are located in the sparse area. In order to complete the comparison, a neighborhood operation, like interpolation, will be applied to assign height value for the plot in these locations. A neighborhood operation can generate an estimation value, but it is not the actual measured value and will introduce an error. This is one of the reason why the final result of the August 11 test was not as accurate as the other two tests.
Some researchers developed a tractor-based LiDAR system to measure the height of plants in a field. And the test result shows that the LiDAR sensor mounted on the tractor platform could perform accurate measurements. In Zhang and Griff’s [41] dynamic test, the height measurement system could achieve an average error of 3.8%. The LiDAR-based HTP system developed by Sun et al. [22] could perform the height measurement with the R^2 value reaching to 0.99, the overall Mean Error was -0.02%, and the RMSE could be less than 80 mm. The following factors explain the reason why the measurement of the UAV-based LiDAR system is not as accurate as the tractor-based LiDAR system.

The first factor affecting the accuracy is the GPS. For some GPS, readings are from two measurements and may not be for the same individual plant. There are two factors that may cause this. For the manual measurement, the GPS of the plot was read from a GPS-guided seed planter. This is the GPS where the seed was planted. As the plant grows, it may not follow the vertical growth model, which leads to the top of the plant shifting from the seed’s location. This is the first point that causes a difference. For the second, the seed planter quipped with a RTK-GPS, the accuracy is at the centimeter level. By contrast, the GPS receiver on the UAV only has decimeter-level accuracy. According to the user manual, the accuracy is about 0.1 meter without any obstacles around. Although the DJI fuses various sensors to improve the accuracy of the positioning, which enables the built-in flight controller to correct the GPS position in real time, the GPS data read from the UAV still cannot reach the centimeter-level accuracy.

The second factor is the angular resolution. The distance between two neighborhood points projected on the ground is displayed in Figure 6.2. The distance value can be derived from Equation 6.1:
\[ \Delta D = D_2 - D_1 = H \times \tan(\theta) - H \times \tan(\theta - \hat{\theta}) \]

\[ = H \times [\tan(\theta) - \tan(\theta - \hat{\theta})] \]  \hspace{1cm} (6.1)

where \( H \) is the height of the LiDAR sensor, \( D_2 \) is the scanned point on the ground, \( D_1 \) is the neighborhood point to \( D_2 \), \( \theta \) is the related rotation angle to \( D_2 \), \( \hat{\theta} \) is the angular resolution. In this study, \( H \) was set to 6 meters, \( \hat{\theta} \) was set to 0.9°, and \( \theta \) was from 0 to 30°. Put them into Equation 6.1, the range of \( \Delta D \) came out, from 0.094 to 0.125 meter. The vertical distance between two plots was about 0.1524 meter, which was larger than \( \Delta D \). Thus, not all the scanned points were located at the top of the corn (Figure 6.2 helps to explain this). Some scanned points may locate at the ear of the plant, some may locate at the shoulder of the plants, and others may locate at other parts of the corn. In this case, the measured height of the crop would be less than the actual height. And error in sparse areas would be even larger since the laser more than likely hit the lower part of plant without a neighbor plant’s block.

**Figure 6.2:** Relationship between scan angle and distance projected on the horizontal plane
The third factor is the flying speed. To balance the stability and the time-efficiency, the flying speed was set at 5 m/s. The scanning frequency was 10 Hz. So, the period was 0.1 second which means the UAV moved 0.5 meter when the LiDAR sensor rotated once. The top view of scanning during flight is available in Figure 6.3.

![Figure 6.3: Relationship between flying speed and covered area](image)

The blue block describes the scanning area on the ground per rotation, the green block describes one single row. In the dense rows where the width of rows is wider than 0.5 meter, almost all the plants in this row will be scanned, as shown in Figure 6.3 (a). However, in sparse rows where the width of rows is less than 0.5 meter, only part of the plant will be scanned, as shown in the red frame area of Figure 6.3 (b). As mentioned above, the missing plant will be assigned a height value by applying the neighborhood operation which will introduce an error.

Another factor affecting the measurement accuracy is airflow disturbances. It may be caused by the wind in the field. But the UAV’s motion has greater impact. As the UAV flies over the field, the downward airflow will force the plant to bend. (The downward airflow pattern is...
shown in Figure 6.4.) Tall plants and the top part of the crop are most affected. When the plant bends, it causes the measurement result to be smaller than the real height. And the Regression Equation in Chapter 5 has shown that the LiDAR measurement result was smaller than the manual measurement.

![Figure 6.4: Downward airflow pattern](image)

Although the UAV-based LiDAR system is not as accurate as the tractor-based LiDAR system Sun et al. [3] developed, it is far more efficient. The tractor platform took 3 minutes to cover a 90 meters long path. The UAV could cover the same area within 20 seconds. It saved 90% time, which means the UAV could cover nine times the area with the same time compared to the tractor platform, if the battery allowed. As for manual measurements, it took about one week to complete height measurements for the entire field and another week to read the GPS data and then integrate with the height data. The data files occupied 8 MB for the 2 acre experiment field. It took about half a minute to process data in MATLAB. It might take some time to process data in ArcGIS. It was because for an irregular field, it did take some time to create the grid to remove unwanted points, which consumed more than 99% of processing time in ArcGIS. Once the grid was created, it only took a few seconds to process data and visualize
the result in ArcGIS. It would be much more efficient in repeatable measurements and for large scale fields.

Additionally, the UAV-based LiDAR system is less expensive than the tractor-based LiDAR system or manual measurement. The hardware component of the entire UAV-based LiDAR system costs about four thousand and two hundred dollars. By contrast, even a used mid-size tractor costs at least ten thousand dollars. And the hardware component of the data acquisition system, which includes laptop computer, LiDAR sensor, GPS receiver etc., has not been counted. As for the manual measurement, it could be much more expensive. Assume one group, which has two students, works four hours each day. It took two weeks to complete the crop height measurement. The minimum wage in the university is ten dollars per hour. Therefore, it would spend eight hundred dollars on data collection of a 2 acre field. For larger field, the manual measurement will cost more.

The new application exploration test revealed one of the measurement system’s limitation. The system could perform accurate height measurement for row crops, like corn in the field test. However, for the dense crops, like grass in the pasture, the performance of the measurement system is not as ideal as expected. Employing powerful LiDAR sensor with better angular resolution would be a potential solution since it is more likely for the laser to hit the ground so as to generate ground profile as height reference.
CHAPTER 7: CONCLUSION AND FUTURE WORK

This study developed a low-cost, lightweight and portable UAV-based LiDAR system and demonstrated its capability of accurate and efficient measurement for corn height under an uncontrolled outdoor environment. And with the help of the autopilot App (AgVision), the user could control the UAV to complete customized missions easily even without any pre-flight-training or flight experience.

Based on the collected data and post-processing, the height map of the target field will be generated, which makes the high-throughput phenotyping and crop monitoring much more easily.

Through comparison with manual measured data, the RMSE of the height measurement could reach a scale of 0.13 to 0.16 meter. In addition, the system could cover a 2 acre field in about eight and half minutes. The observation indicates the performance of the LiDAR measurement system was as satisfactory. However, the system developed in this study is currently considered as an experimental platform. In order to apply this system to practical production, more research and work is needed.

Future work can be focused on the following field:

1) Improve the measurement accuracy. The tractor-based LiDAR system proved that the accuracy could reach to centimeter level even under a field environment. There was a certain gap between the accuracy of the system built in this study and the tractor-based system. Several parts could be improved to narrow this gap. The first is the accuracy of the GPS receiver. As mentioned above, the build-in GPS receiver on the Matrice 100 has an accuracy of about 0.1 meter. By contrast, the GPS integrated with manually measured data read from RTK-GPS,
whose accuracy could reach to one centimeter. A more accurate and precise positioning system, like RTK-GPS, is required for the UAV platform. The second is the angular resolution of the LiDAR sensor. The angular resolution of the LiDAR sensor used in previous research could reach to 0.33-0.5° [22, 39]. However, the angular resolution of LiDAR sensor in this study was 0.9°, which might cause point missing during scanning, especially for the sparse part. The third is the detection range. The detection range of the LiDAR sensor in this study was about 8 meters which caused point missing in low-lying areas. Thus, a higher angular resolution and wider detection range LiDAR sensor is needed.

2) Extend the cover area. Currently, the system developed in this study can cover a 2 acre field in about eight and half minutes, which almost depletes one battery. However, the fields in the Midwest can consist of dozens even hundreds of acres, which proposes more stringent requirements to the measurement system. To solve this problem, more batteries could be placed on the UAV platform or bring more backup batteries during measurement would be one solution. Increasing the flight height would be another solution. Of course, higher flying height requires wider detection range of the LiDAR sensor as well.

3) Increase the adaptability to outdoor environments. Due to the modulated laser, which is affected by direct sunlight, the system usually conducts measurement during the night. However, it would occupy the field managers time off. And flying during nighttime is a bit dangerous compared to daytime. Also, the UAV platform could carry other equipment or sensors to execute independent missions during the height measurement. Some equipment or sensors may have requirements for light conditions. Thus, a more adaptable LiDAR sensor, which could work at day time is required. Additionally, as the result of application extension test revels, the
system is currently not suitable for very dense field. Employing more powerful LiDAR sensor which has better angular resolution may help to solve this problem.

4) Real time measurement and processing. In this study, the height map of the target field was available after the offline post-processing. It is expected that the system could generate the height map as soon as the system completes the mission. The cell phone/autopilot App has achieved receiving the measured data in real time, through the Data Transparent Transmission. Online processing could be available by transplanting the offline data processing and visualization algorithm to the mobile phone, which will allow the field manager to see the height map just after the UAV completes the mission and lands.

The test result shows the UAV-based LiDAR system’s capability of collecting high spatial and temporal resolution data and generating height map of the target field. The system could also be modified and applied for other crop measurements, like soybean, sorghum, wheat, rice, cotton, and so on.
REFERENCES


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