Study of core technologies in tree canopy parameter measurements for precision spraying

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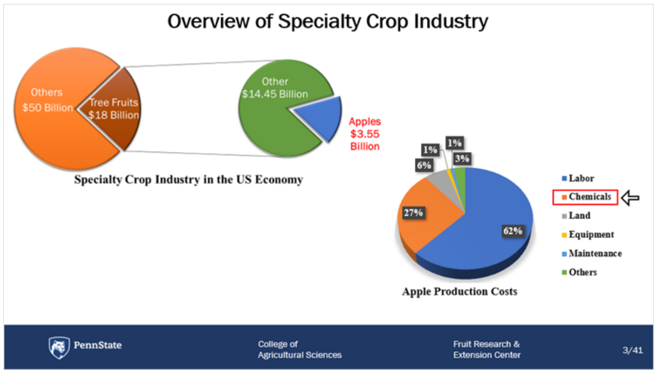
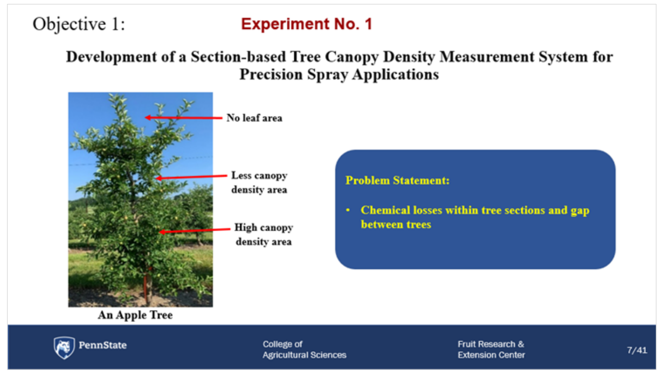
Outline



Overview of Specialty Crop Industry
Others $50 Billion
Tree Fruits $18 Billion
Other $14.45 Billion
Apples $3.55 Billion
Specialty Crop Industry in the US Economy
1%
1%
6%
3%
27%
62%
Labor
Chemicals
Land
Equipment
Maintenance
Others
Apple Production Costs
PennState
College of Agricultural Sciences
Fruit Research & Extension Center
3/41



Objective 1:
Experiment No. 1
Development of a Section-based Tree Canopy Density Measurement System for Precision Spray Applications
No leaf area
Less canopy density area
High canopy density area
An Apple Tree
Problem Statement:
Chemical losses within tree sections and gap between trees
PennState
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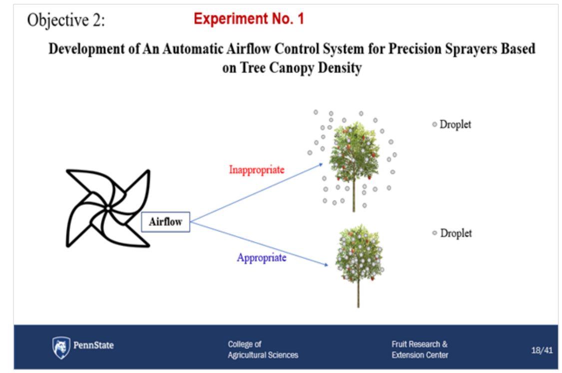
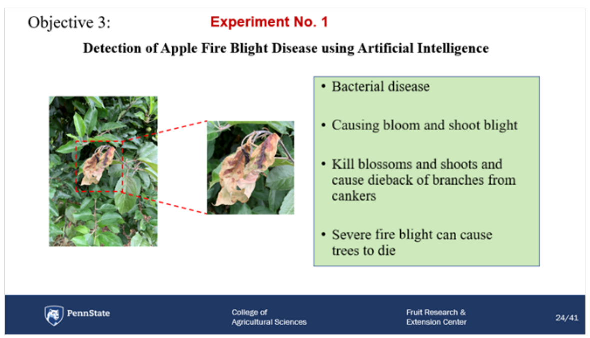


Objective 2:
Experiment No. 1
Development of An Automatic Airflow Control System for Precision Sprayers Based on Tree Canopy Density
Droplet
Inappropriate
Airflow
Appropriate
Droplet
PennState
College of Agricultural Sciences
Fruit Research & Extension Center
18/41



Objective 3:
Experiment No. 1
Detection of Apple Fire Blight Disease using Artificial Intelligence
Bacterial disease
Causing bloom and shoot blight
Kill blossoms and shoots and cause dieback of branches from cankers
Severe fire blight can cause trees to die
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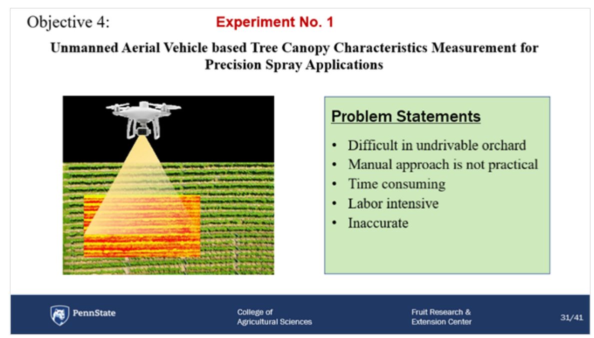

Objective 4:
Experiment No. 1
Unmanned Aerial Vehicle based Tree Canopy Characteristics Measurement for Precision Spray Applications
Problem Statements
Difficult in undrivable orchard
Manual approach is not practical
Time consuming
Labor intensive
Inaccurate
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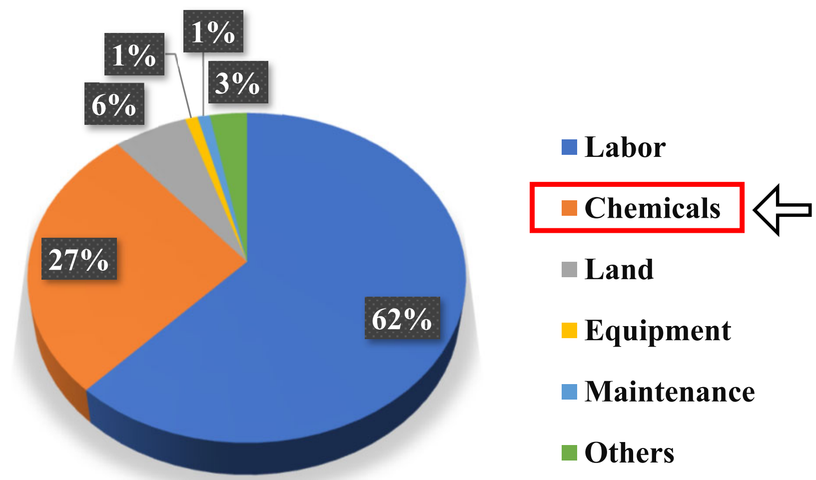
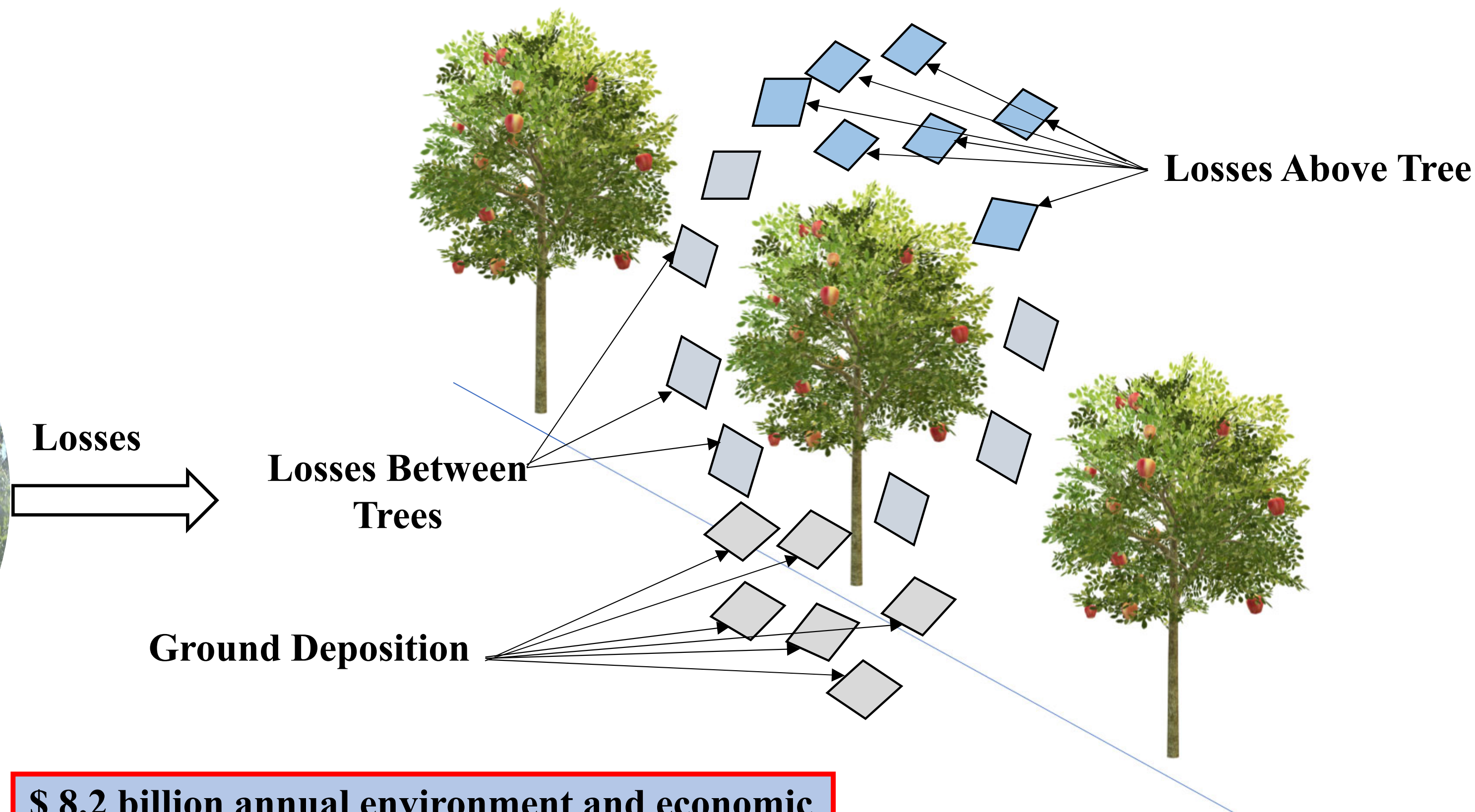
Overview of Specialty Crop Industry

Specialty Crop Industry in the US Economy



Apple Production Costs

Spray Operation in Tree Fruit Orchards



$ 8.2 billion annual environment and economic losses in US (Pimentel & Burgess, 2014)

Precision Spraying in Tree Fruit Orchards

❖ Precision Spraying

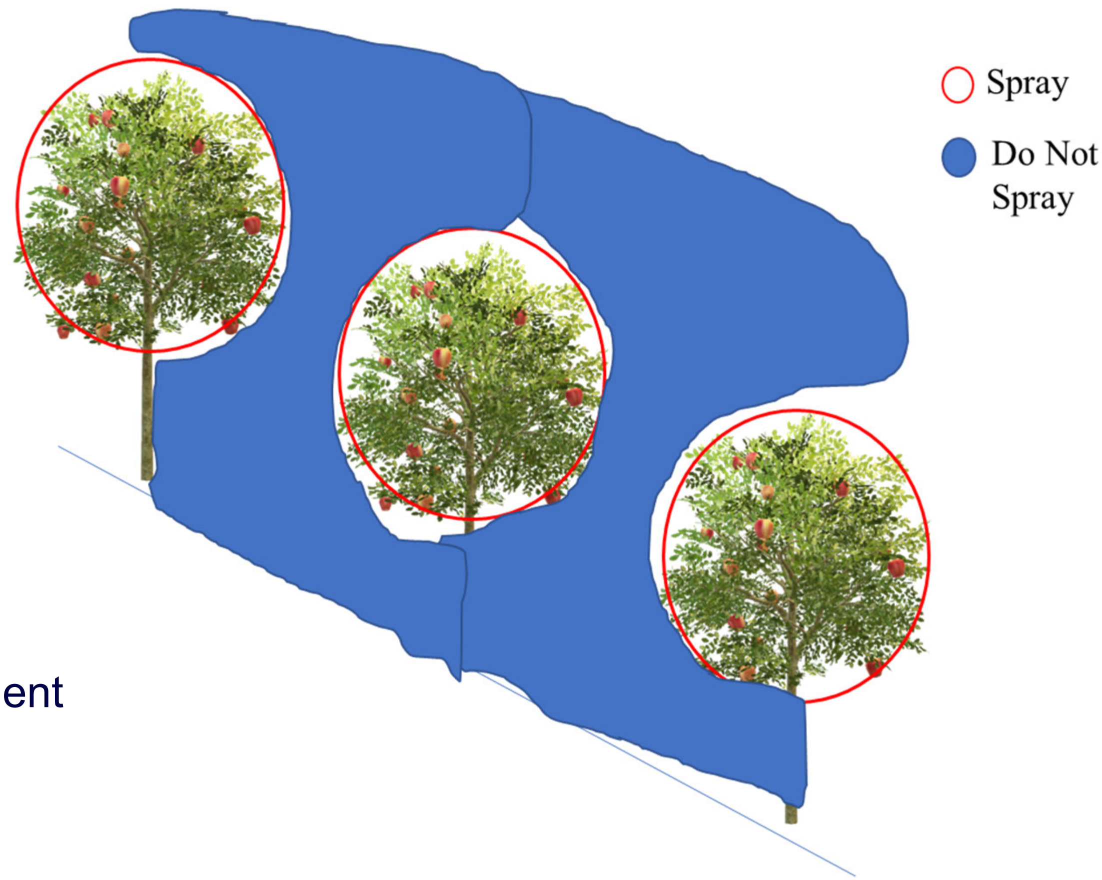
Apply chemical according to the need

❖ Major Advantages

- Accurate spray deposition
- Reduce off-target deposition and drift

❖ Major Tasks

- Sensor application and algorithm development
- Tree canopy characteristics measurement
- Automatic nozzle and airflow control



Goal & Objectives

❖ Overall Goal

Developing core technologies for advancing the orchard spraying system for tree fruits

❖ Objectives

- Development of an accurate tree canopy density measurement system to apply correct spray volume
- Development of an automatic airflow control system to reduce drift
- Advancing sprayer with site-specific management capability for disease management
- Application of unmanned aerial vehicle (UAV) to measure canopy characteristics for undrivable orchards

Objective 1: **Experiment No. 1**

Development of a Section-based Tree Canopy Density Measurement System for Precision Spray Applications

No leaf area

Less canopy density area

High canopy density area

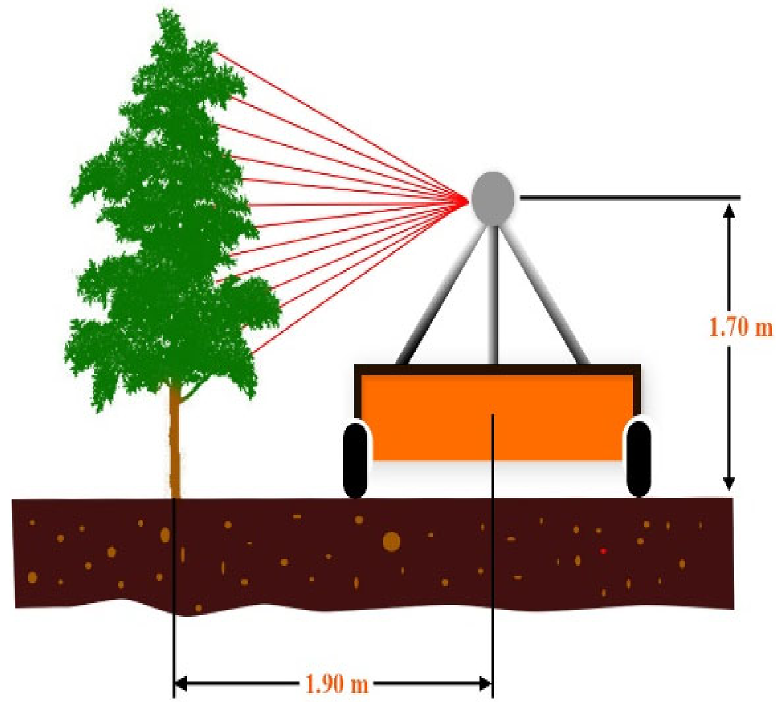
An Apple Tree

Problem Statement:

- **Chemical losses within tree sections and gap between trees**

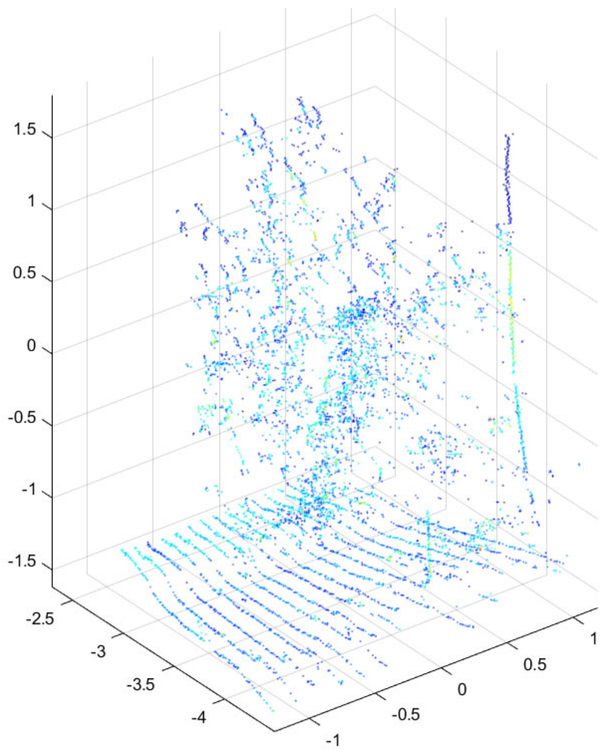
Methodology: **Tree Scanning**

System Development

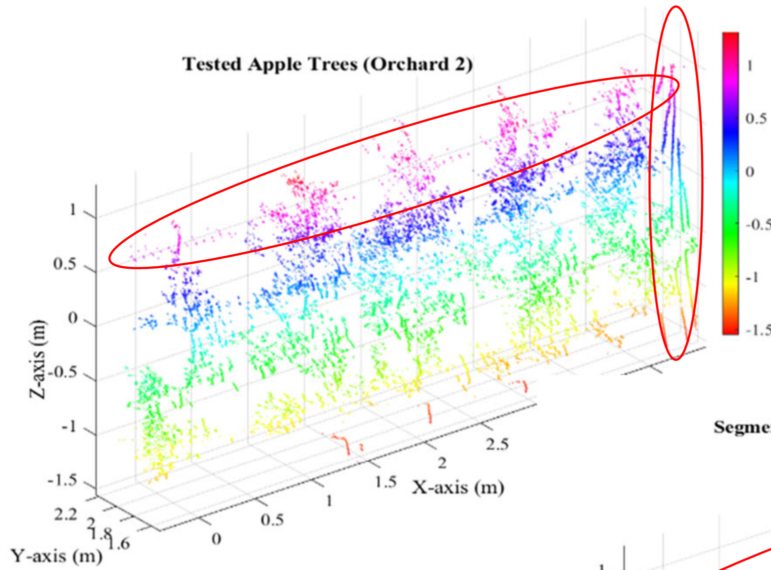


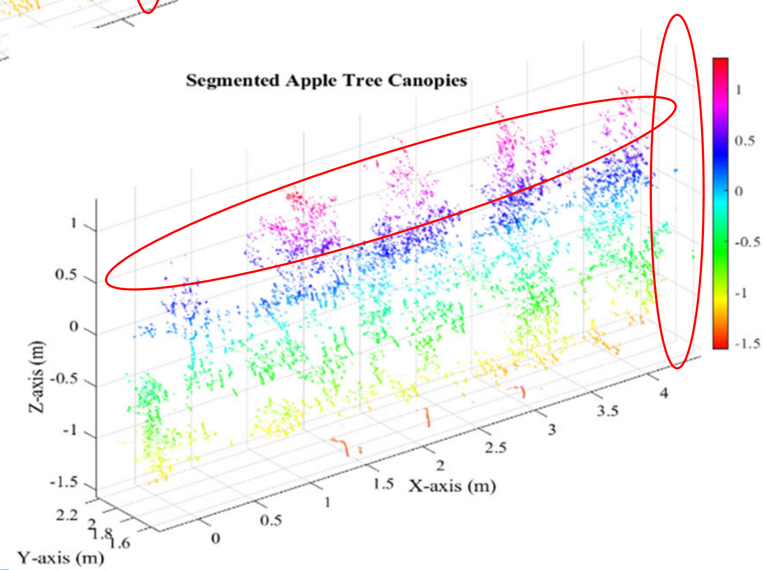
Tree Scanning using LiDAR Sensor

Methodology: **Canopy Points Segmentation**



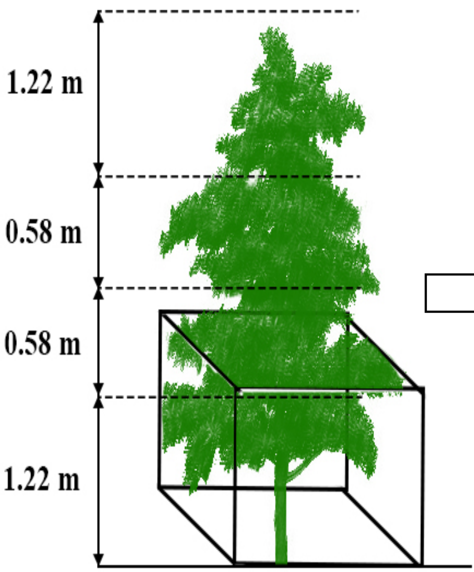
Scanned Tree



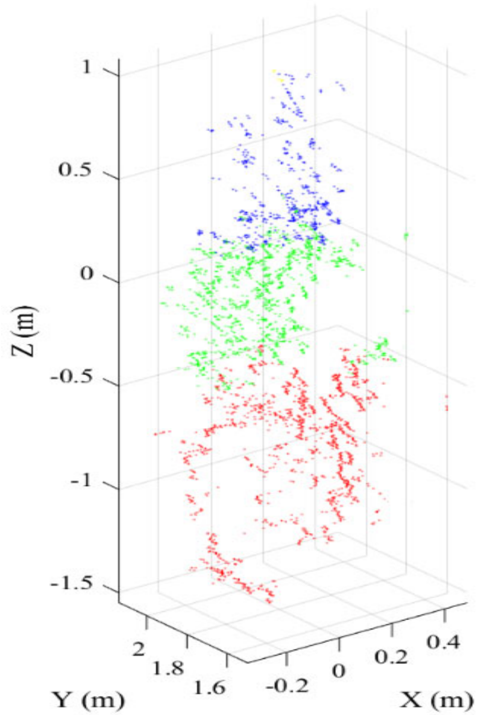


Results: Canopy Density Measurement

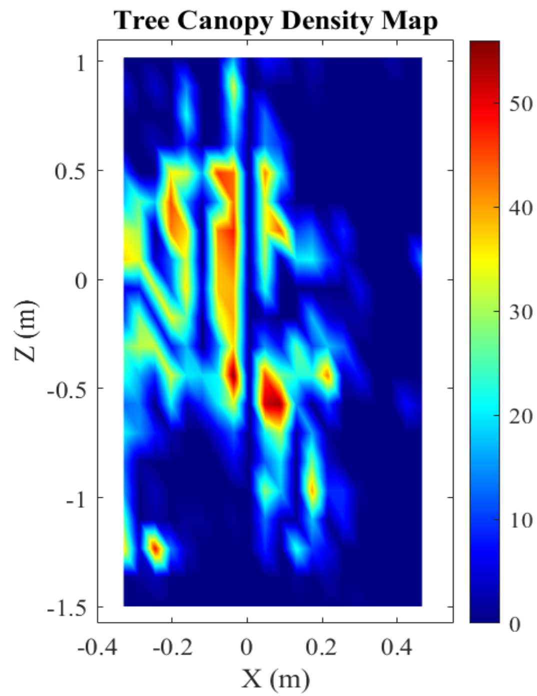
**Scale represents number of leaves per grid area



Tree Divided into Sections



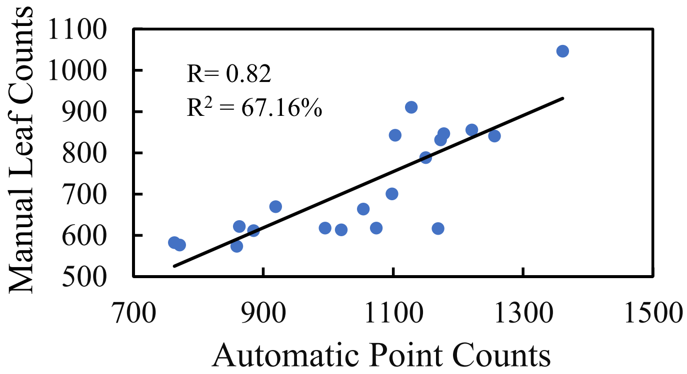
Canopy Points in Sections



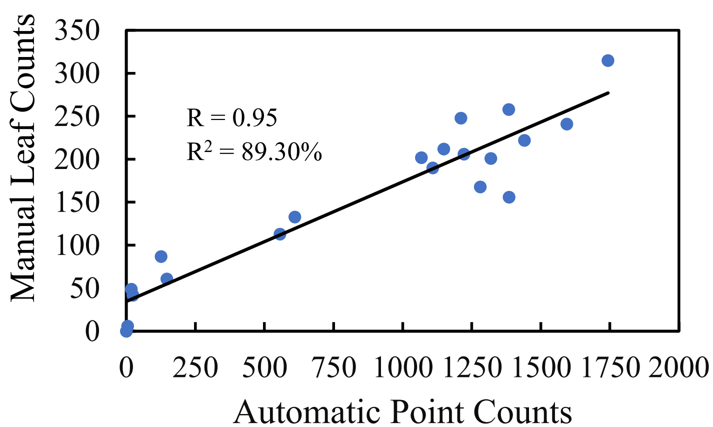
Canopy Density Map

Results:

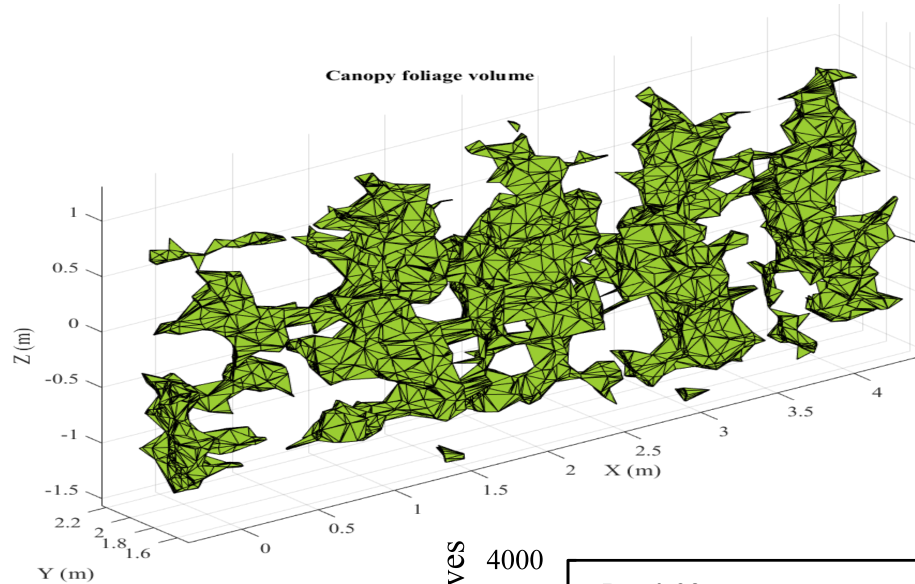
Prediction Models Performance

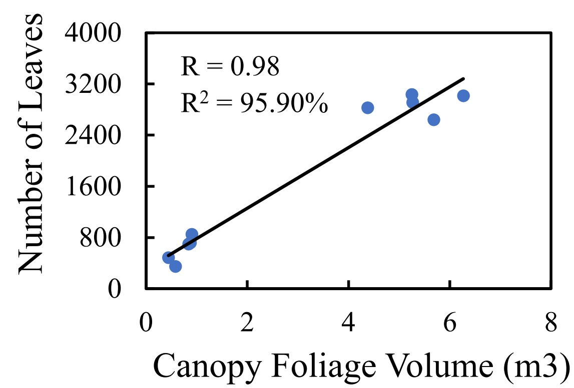


GoldRush Orchard



Fuji Orchard





Conclusions

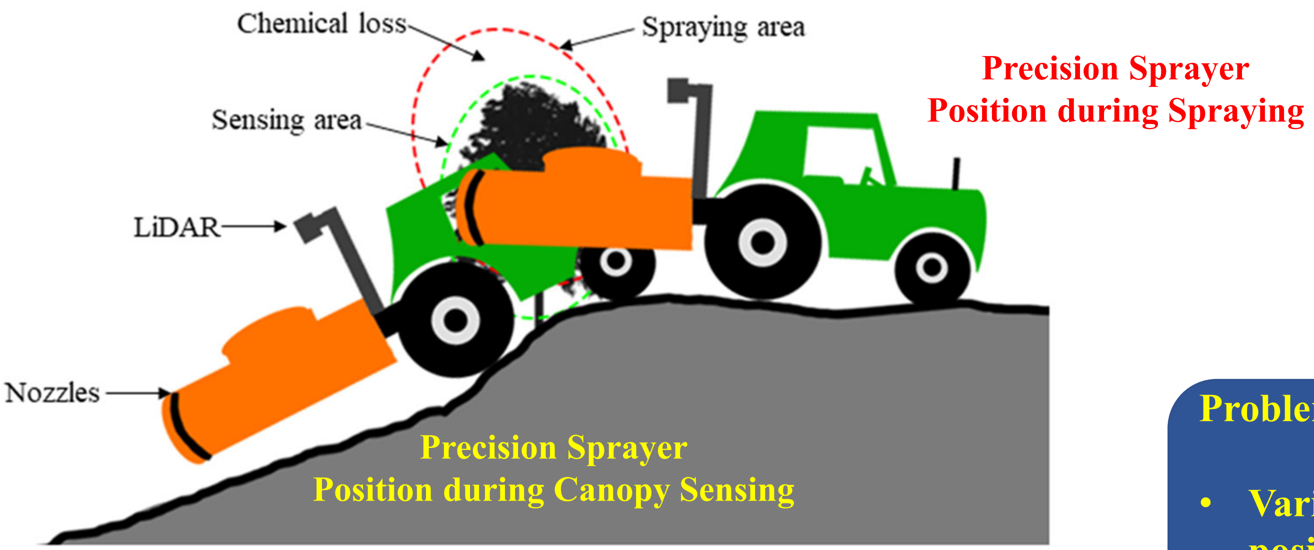
- A strong correlation of 0.95 was achieved between manually counted leaves and acquired point cloud data using Fuji apple tree data (smaller canopy)

- Canopy volume measured by using the alpha shape algorithm showed a very strong relationship with manually counted leaves with a correlation up to 0.98 by using alpha value of 1

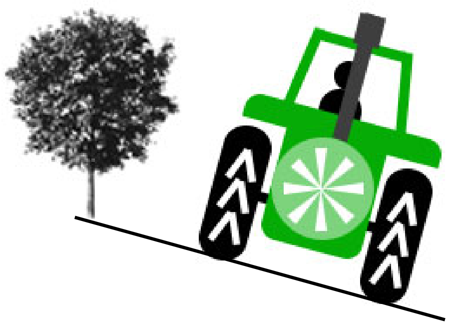
- Generated canopy density map can pinpoint high, moderate, and less density, and no leaf regions within the apple trees, which could be able to guide the precision management systems

Objective 1: **Experiment 2**

Correction of 3D-LiDAR Sensed Canopy Density Information in Sloping Terrains using Sensor Fusion



Problem Caused by Slope Variation



Problem Statements:

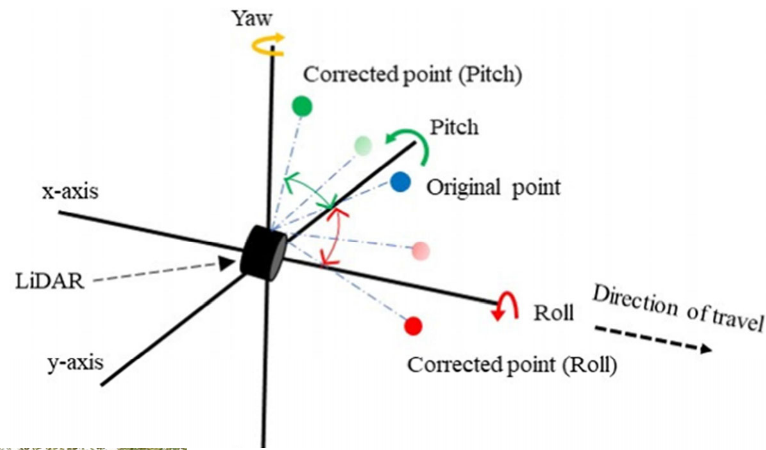
- **Variation between sensing and spraying positions**
- **Adjustment of canopy position is required**

Methodology: **Model for Canopy Correction**

Longitudinal Slope

Lateral Slope

Both Slopes



Euler's theorem

Corrected position at x, y, and z-axis can be described as:

$$P_{C,x} = \cos(\theta_P) \times \{x\cos(\theta_w) - y\sin(\theta_w)\} + z\sin(\theta_P)$$

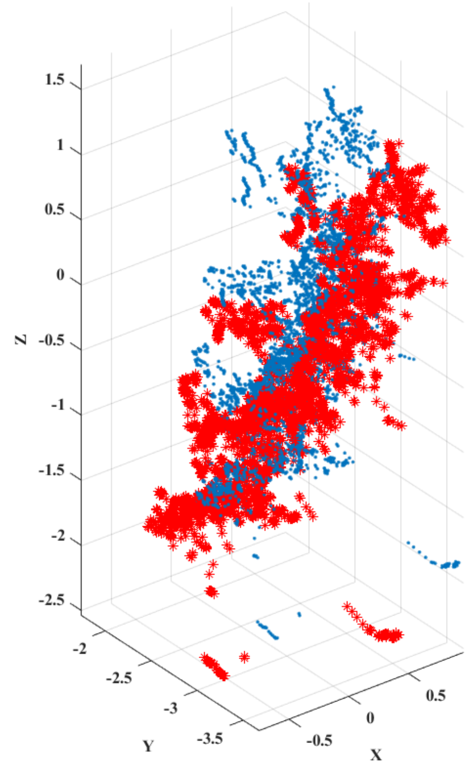
$$P_{C,y} = \cos(\theta_r) \times \{y\cos(\theta_w) + x\sin(\theta_w)\} + \sin(\theta_r) \times [\sin(\theta_P) \times \{x\cos(\theta_w) - y\sin(\theta_w)\} - z\cos(\theta_P)]$$

$$P_{C,z} = \sin(\theta_r) \times \{y\cos(\theta_w) + x\sin(\theta_w)\} - \cos(\theta_r) \times [\sin(\theta_P) \times \{x\cos(\theta_w) - y\sin(\theta_w)\} - z\cos(\theta_P)]$$

Results: Canopy Points Correction

Acquired Canopy Point Cloud Data (m)			Corrected Canopy Point Cloud Data[a] (m)		
X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis
-0.3741389	2.4954416	-1.74862551	-0.949640696	2.863179554	-0.570337959
-0.3719452	2.4838406	-1.73404051	-0.942590976	2.847847258	-0.562131877
-0.3738951	2.4999006	-1.73877065	-0.946041097	2.864230844	-0.560189176
-0.3724327	2.4931417	-1.7276210	-0.940853456	2.854467195	-0.553125488
-0.3724327	2.4961532	-1.72326702	-0.939364306	2.855897707	-0.548250842
-0.3741389	2.5106061	-1.72678237	-0.942169901	2.870409201	-0.545863441
-0.3751138	2.5201662	-1.72688624	-0.943121585	2.879312109	-0.542372064
-0.3758451	2.5280948	-1.72584276	-0.943451814	2.886341669	-0.538503896
-0.3763325	2.5343860	-1.7236605	-0.943163514	2.891495069	-0.534268521
-0.3785262	2.5521810	-1.72925598	-0.947138638	2.909758628	-0.53241819
-0.3821823	2.6039382	-1.70526788	-0.942369816	2.950257216	-0.492359104
-0.2731461	2.6115448	-1.71090064	-0.841835855	2.971970214	-0.529774896
-0.3753576	2.5603585	-1.67035055	-0.924014279	2.898881828	-0.478624863
-0.2721002	2.6045159	-1.6998065	-0.837058641	2.961922016	-0.522718668
-0.3743826	2.5566121	-1.66155238	-0.92008897	2.892647703	-0.472450584
-0.2722745	2.6091491	-1.69634419	-0.836038258	2.965142589	-0.518020714
-0.3746264	2.5611745	-1.65816655	-0.919159989	2.895818268	-0.467822054
-0.2703571	2.5937107	-1.67987378	-0.828603256	2.945566041	-0.509373477
-0.3746264	2.5640646	-1.65369394	-0.917630265	2.897096644	-0.462884147
-0.2682654	2.5765486	-1.6623823	-0.820655227	2.924062007	-0.500470155

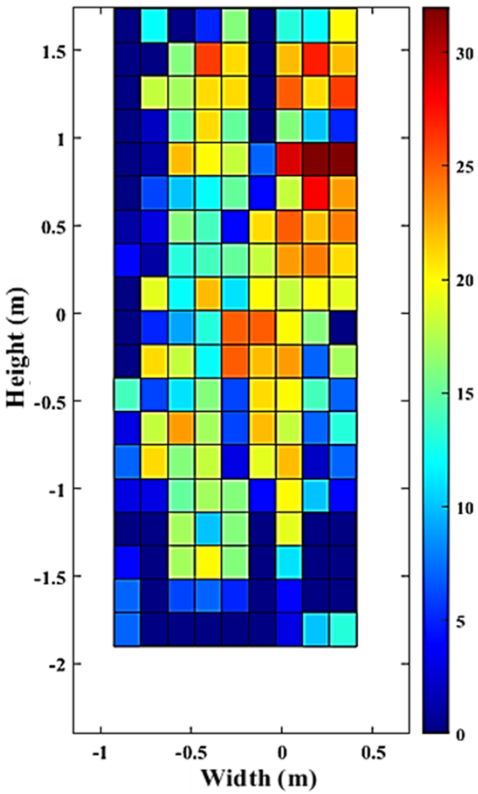
[a]Change of roll and pitch of about 20° (degree)



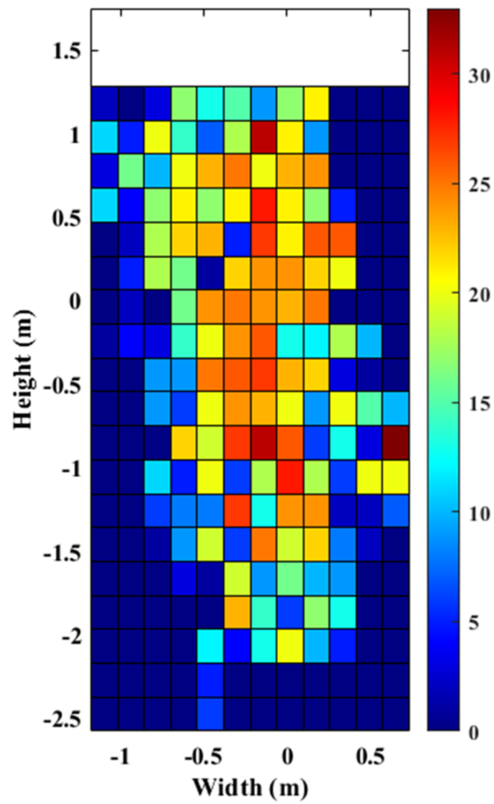
Blue: Sensed Canopy
Red: Corrected Canopy

Results:

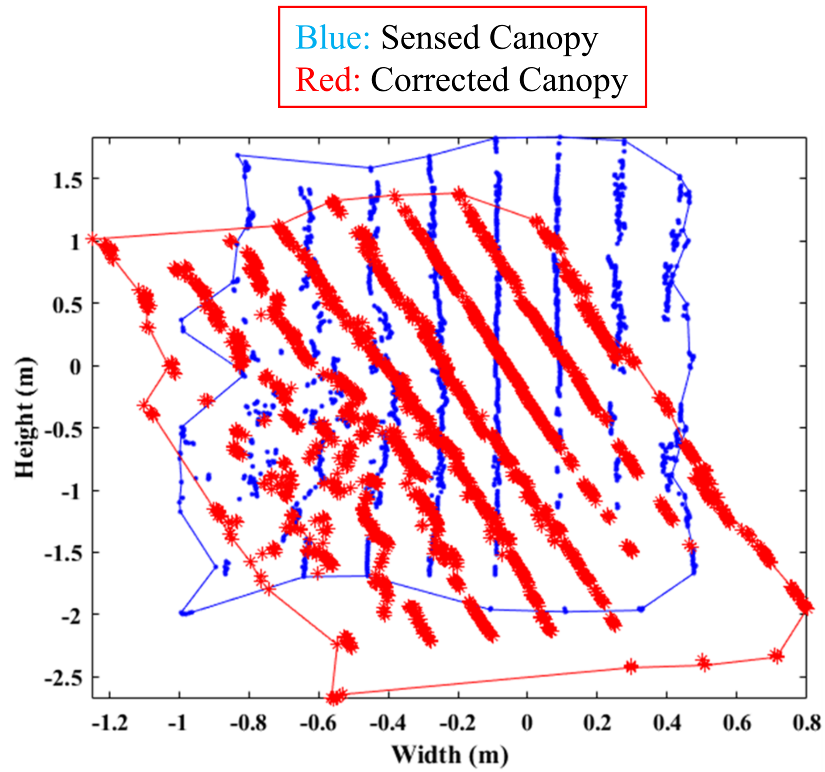
Canopy Points Correction



Before Correction



After Correction



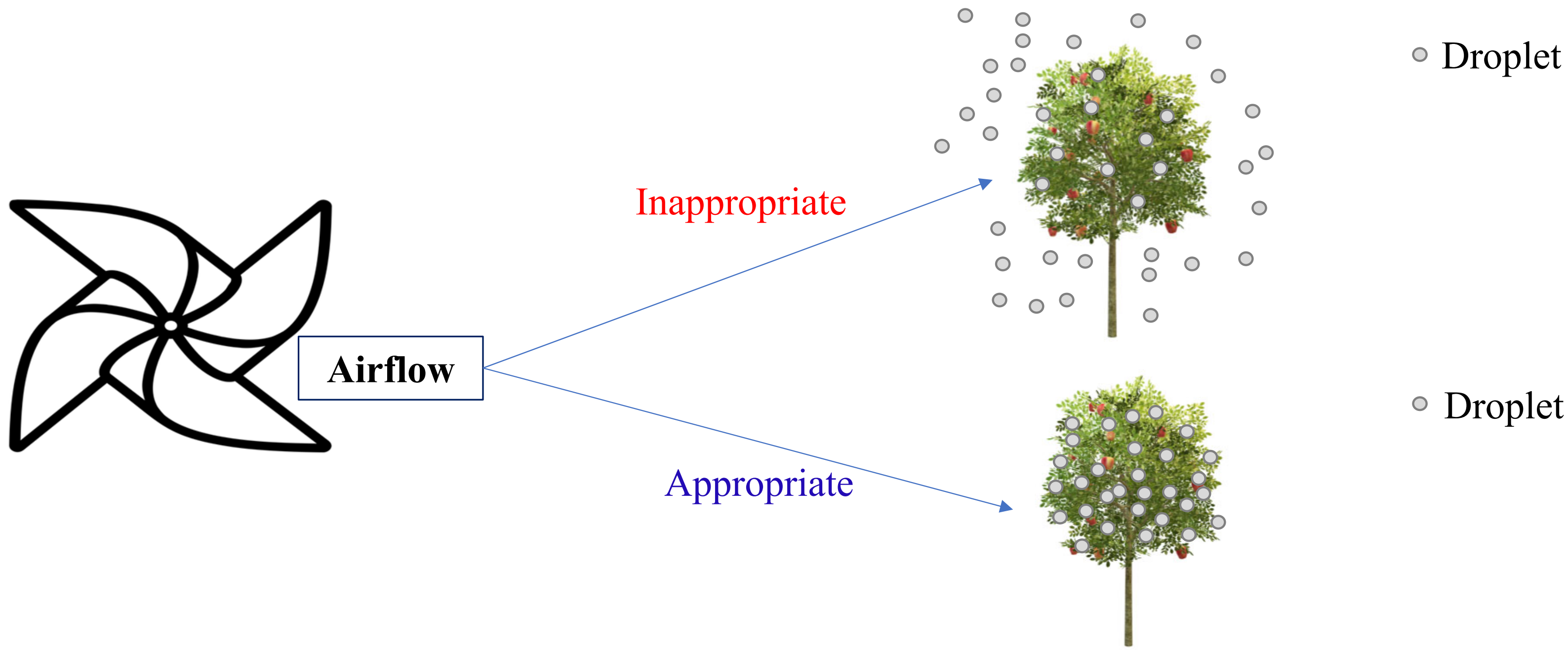
Observation of Possible Off-Target Loss

Conclusions

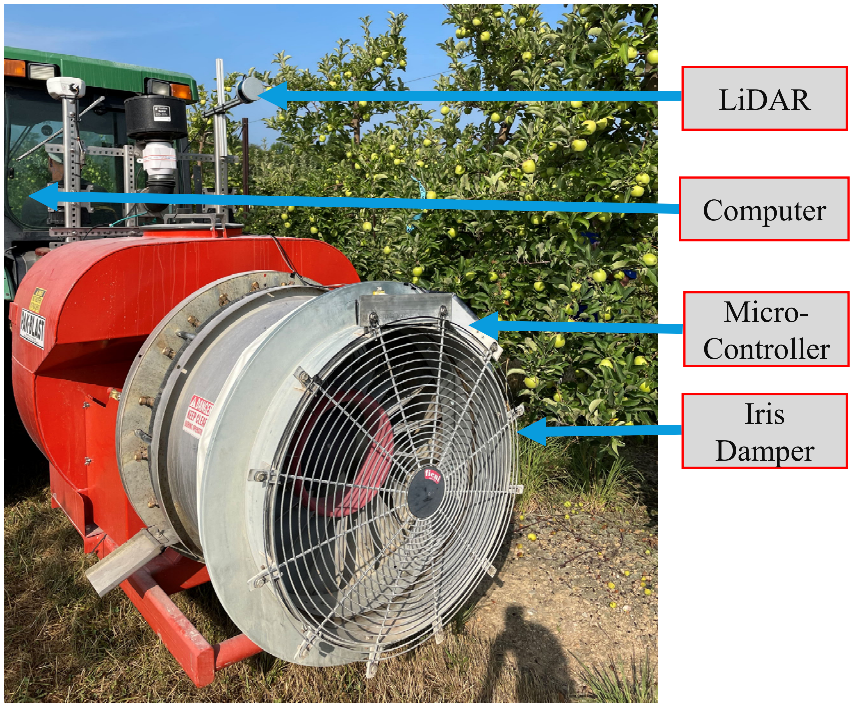
- The simulation results suggested that the model could provide the corrected canopy point location for any change of roll, pitch, and yaw
- Field evaluation results demonstrated that the system was able to correct the apple tree canopy points in different sloping conditions
- The developed system could be able to reduce up to 15.45% of off-target deposition

Objective 2: **Experiment No. 1**

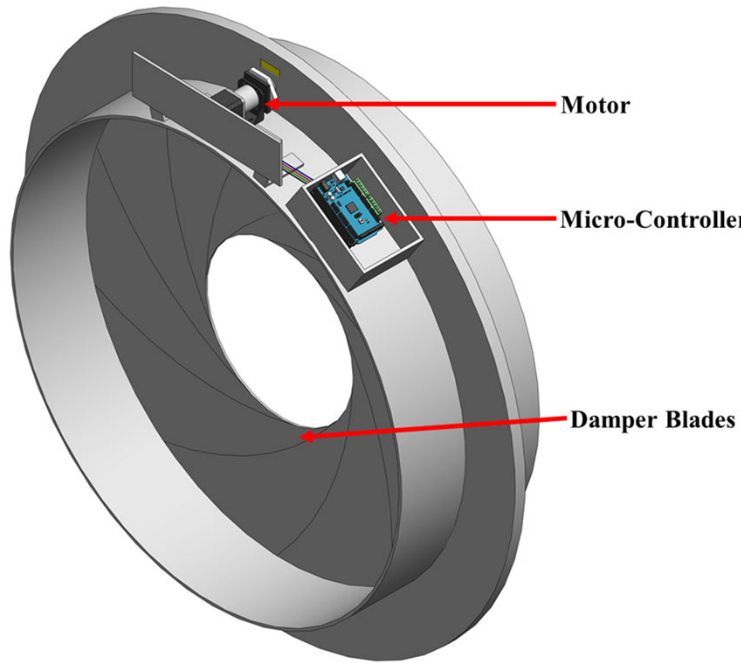
Development of An Automatic Airflow Control System for Precision Sprayers Based on Tree Canopy Density



Methodology: Damper Installation

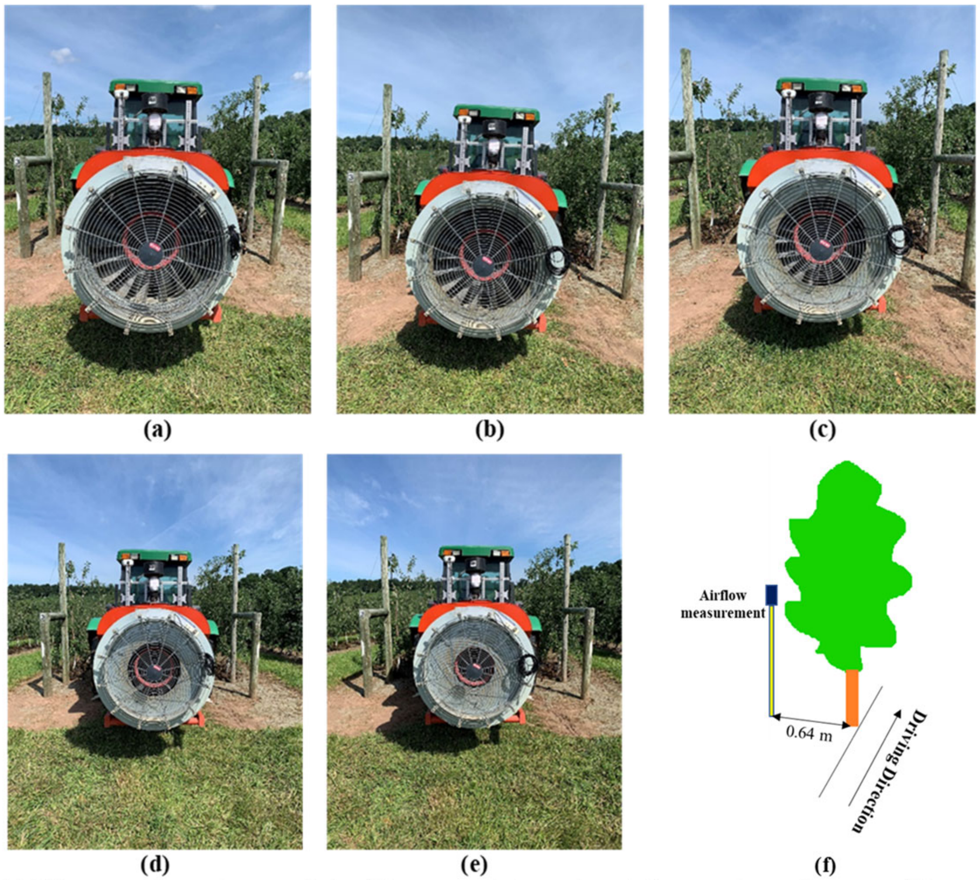


Hardware Integration

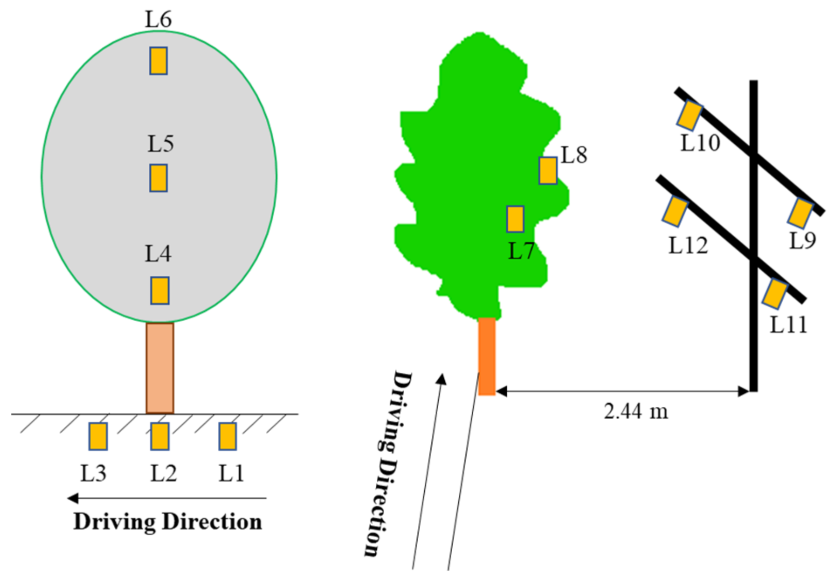


Iris Damper

Methodology: **Airflow Measurement and Spray Deposition**

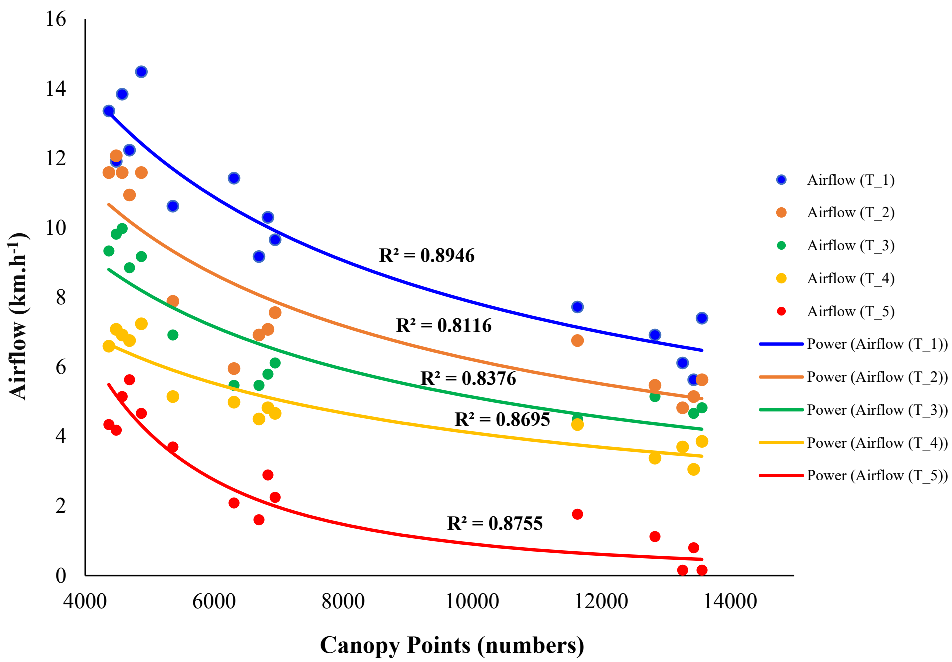


Different Openings of the Damper Tested at Three Tree Canopy Densities

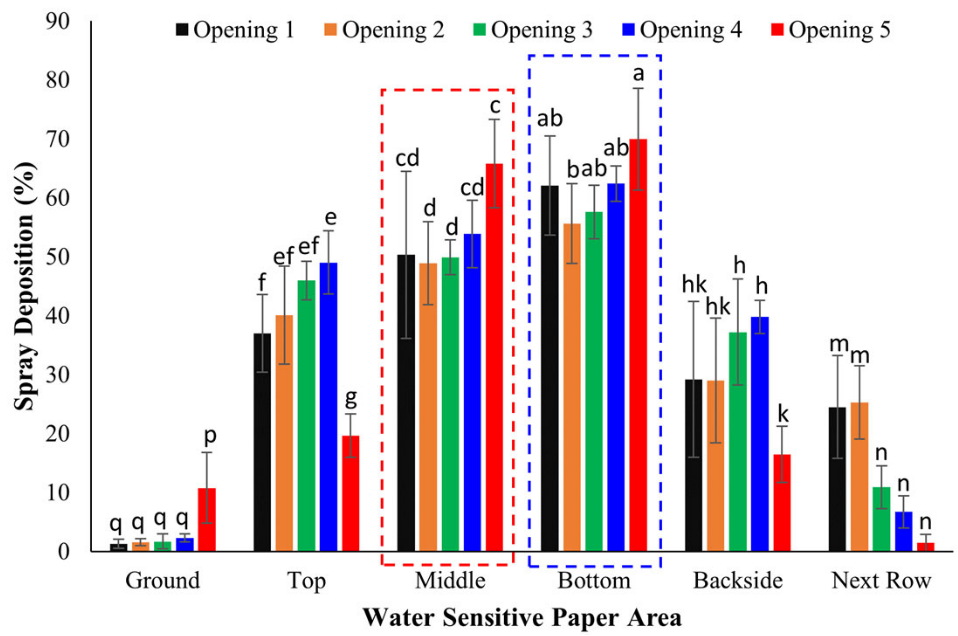


Water Sensitive Paper Locations

Results: **Airflow and Spray Deposition**



Airflow using Different Opening of the Damper

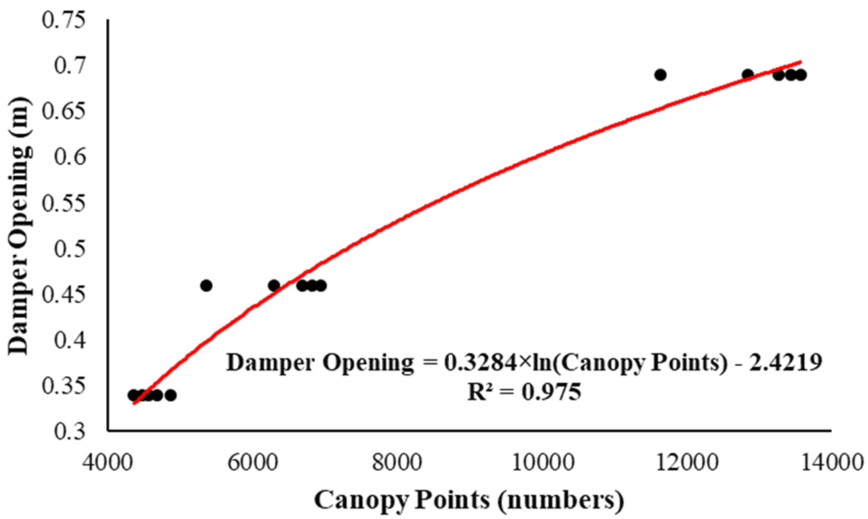


Spray Deposition on Medium Density Trees

Results: Airflow Control Model & Field Evaluation

$$airflow = 2047.2 \times canopy\ points^{-0.65}$$ (for GoldRush)

$$airflow = 2535.9 \times canopy\ points^{-0.653}$$ (for Gala)



Canopy Density Vs Required Damper Opening

Theoretical and Experimental Airflow Measurements

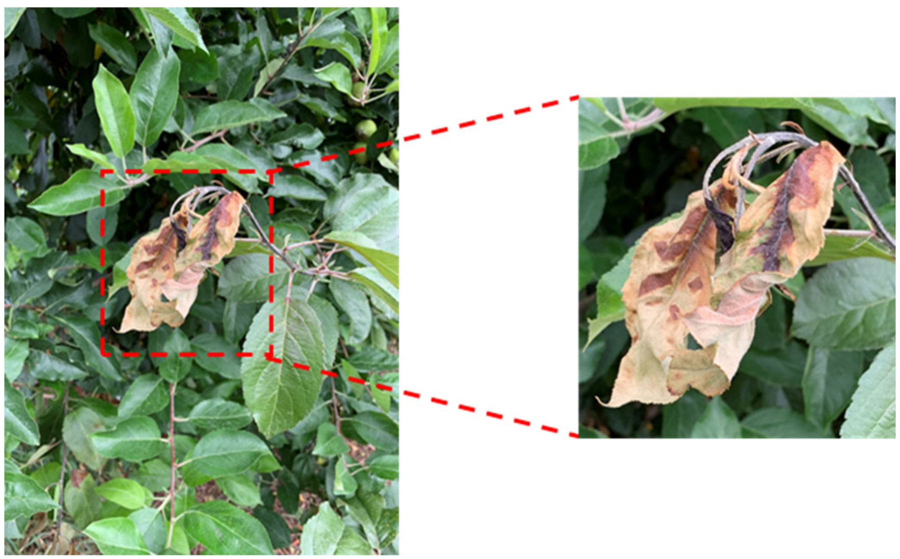
Test Orchard	Tree No	Canopy Points	Theoretical Airflow (km·h⁻¹)	Experimental Airflow (km·h⁻¹)	MAE (km·h⁻¹)	RMSE (km·h⁻¹)
Orchard 1 (GoldRush)	1	10372	5.02	7.89	2.27	2.41
	2	9799	5.21	7.4		
	3	8530	5.7	6.92		
	4	10724	4.91	6.59		
	5	8404	5.76	9.17		
Orchard 2 (Gala)	1	12710	5.3	5.95	1.42	1.6
	2	14111	4.95	3.54		
	3	10291	6.08	8.72		
	4	15795	4.6	2.9		
	5	10735	5.92	6.63		

Conclusions

- Air penetration through canopies was higher in the lower density trees compared to the medium and higher density trees
- The damper opening 2 offered higher spray deposition on high-density trees than the other openings
- The damper opening 4 could be suitable for medium-density fruit trees, and opening 5 for low-density trees
- The airflow control system was able to calculate the required damper opening and the airflow requirement for uniform spray deposition and reduced drift

Objective 3: **Experiment No. 1**

Detection of Apple Fire Blight Disease using Artificial Intelligence



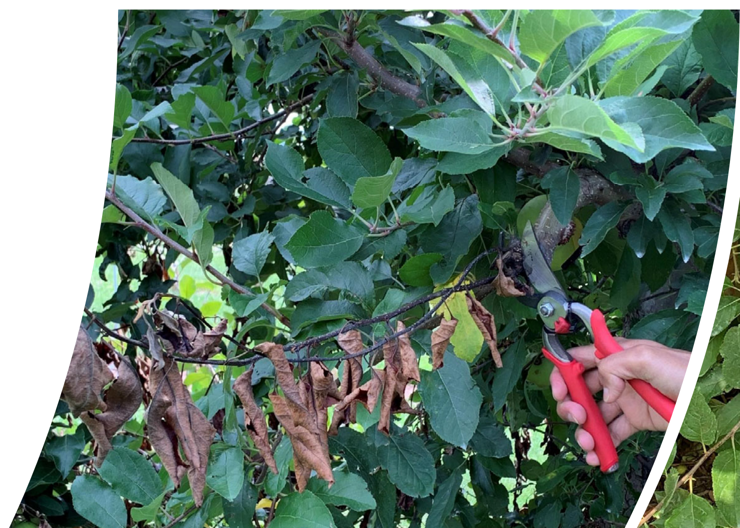
- Bacterial disease
- Causing bloom and shoot blight
- Kill blossoms and shoots and cause dieback of branches from cankers
- Severe fire blight can cause trees to die

Problem Statements

- Manual scouting is time-consuming
- Not practical for large-scale orchard

Objective

- Develop an **automatic fire blight detection system** using artificial intelligence



Methodology: Image Acquisition and Processing

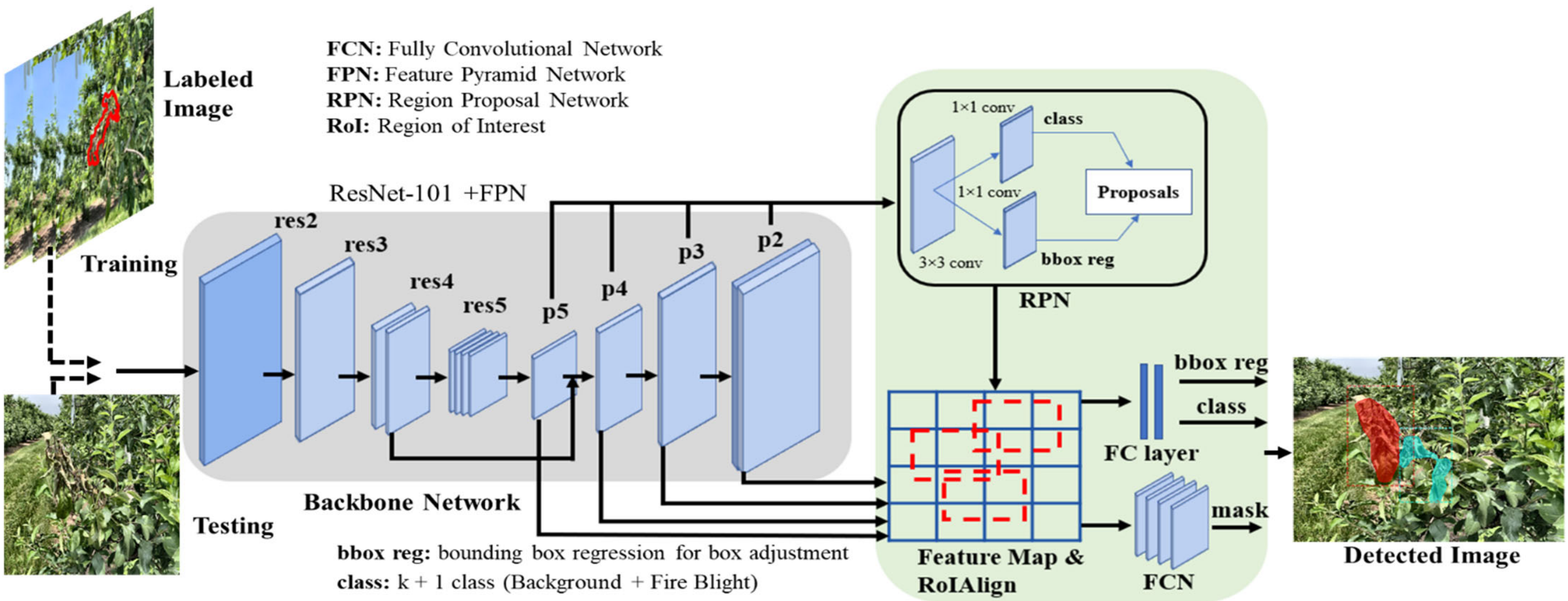
Image Pre-Processing

Image Capture

Raw Image

Pre-Processed Image

Methodology: Deep Learning Application



Results:

Fire Blight Disease Detection

Ground Truth and Detections
GT=green, pred=red, captions: score/IoU

Detected Area Comparison

Evaluation Parameter	Percentage (%)
Precision	92.79
Recall	91.15
F1 Score	91.96

Results:

Fire Blight Disease Detection

Some Examples of Fire Blight Detection

Examples of Fire Blight Misclassification

Conclusions

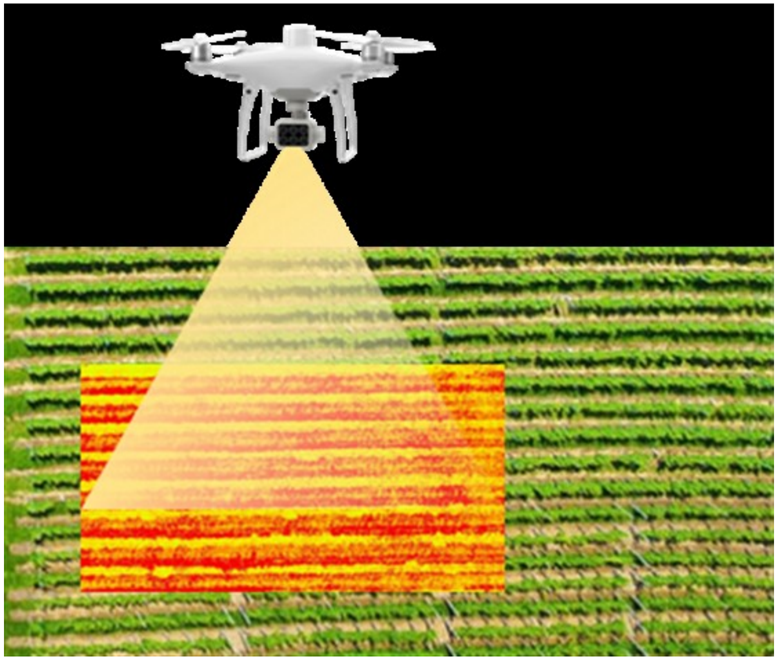
- An artificial intelligence-based fire blight detection algorithm performed impressively with the detection precision, recall, and F1 score of 92.79%, 91.15% and 91.96%, respectively

- Some of the false detections were reported may be due to the illumination variations, shading effects, and complex background

- The IoU value of the detection model was up to 83.5% showing the potential of using this approach for automatic fire blight scouting in the apple orchard

Objective 4: **Experiment No. 1**

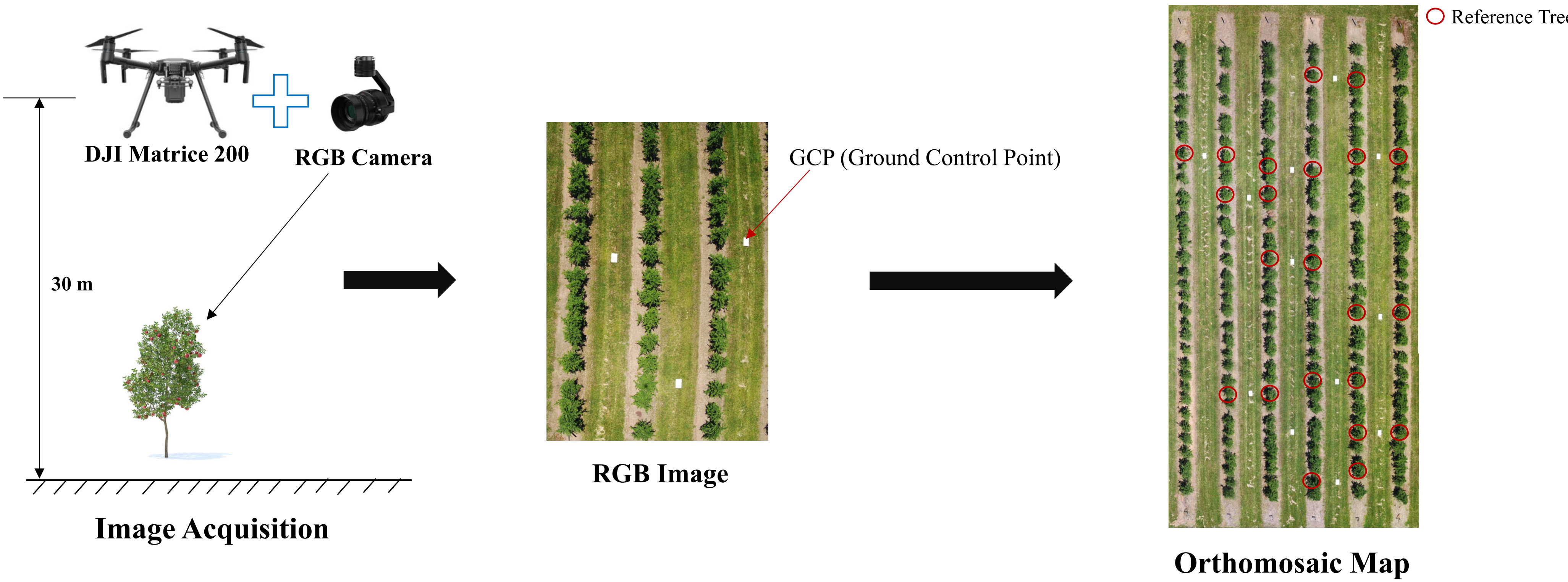
Unmanned Aerial Vehicle based Tree Canopy Characteristics Measurement for Precision Spray Applications



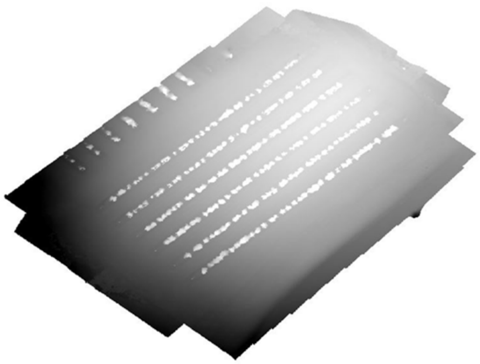
Problem Statements

- Difficult in undrivable orchard
- Manual approach is not practical
- Time consuming
- Labor intensive
- Inaccurate

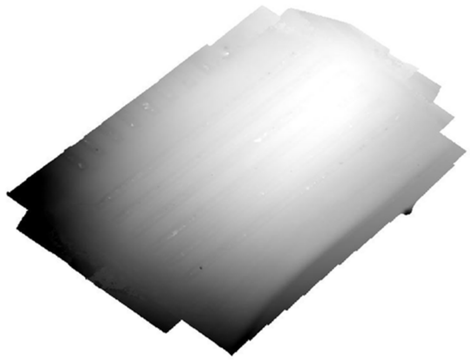
Methodology: Canopy Data Collection and Referencing



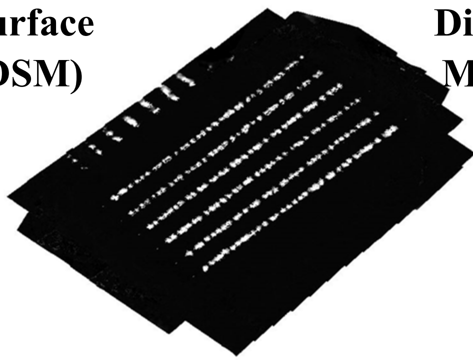
Methodology: Model Generation and Tree Height Map



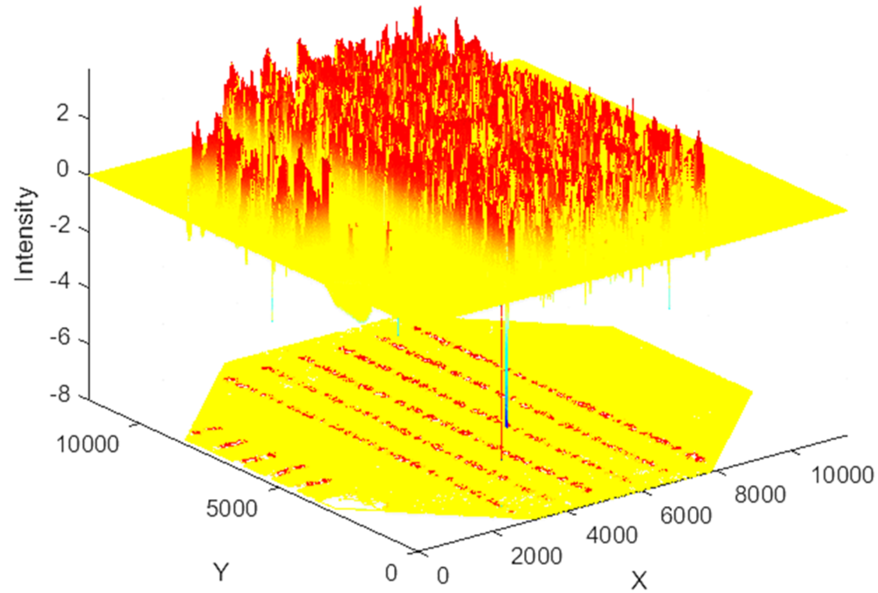
(a)
Digital Surface Model (DSM)



(b)
Digital Terrain Model (DTM)

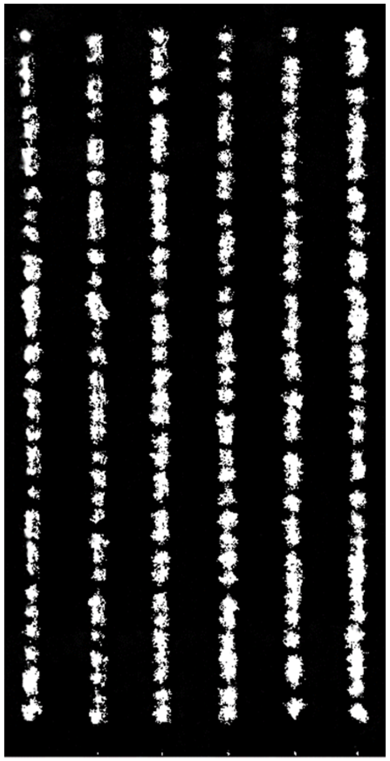


(c)
DSM - DTM

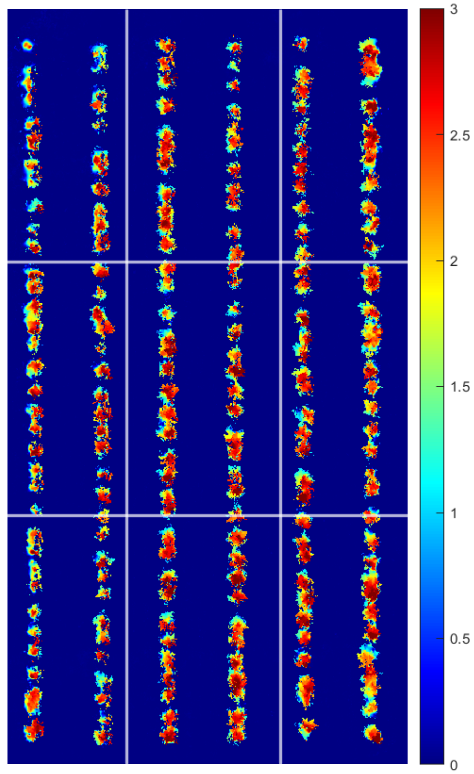


Height Map in 3D Plot

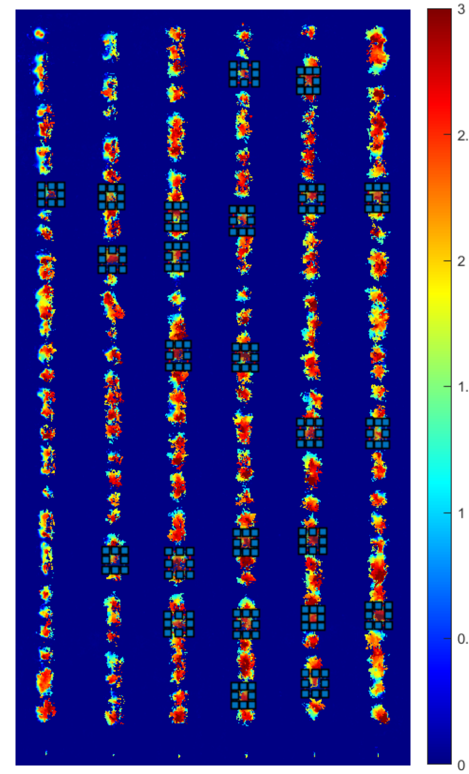
Methodology: Tree Height and Canopy Volume Measurements



DSM Without Ground



Height Map

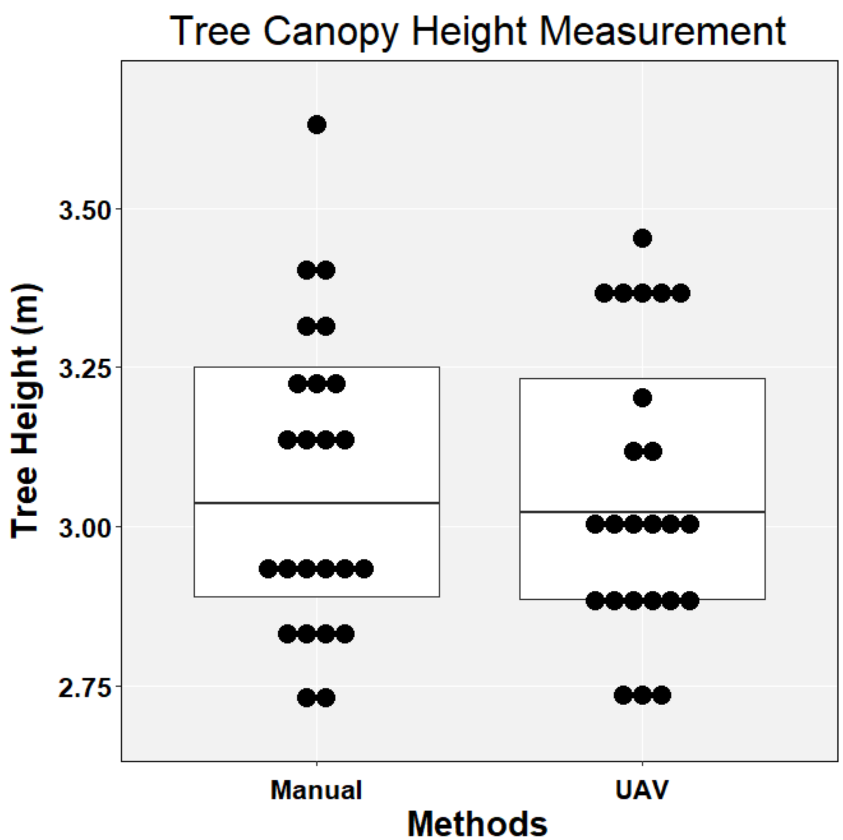


Height Measurement

Results:

Tree Height Measurement

Tree No.	Manual Measurement (m)	UAV-based Measurement (m)	Absolute Error (m)	Absolute Error (%)
1	2.69	2.93	0.24	8.92
2	2.9	3.45	0.55	18.97
3	2.87	3.32	0.45	15.68
4	3.12	3.09	0.03	0.96
5	3.2	2.96	0.24	7.5
6	3.3	2.97	0.33	10
7	3.4	3.36	0.04	1.18
8	3.63	2.9	0.73	20.11
9	2.97	3.02	0.05	1.68
10	2.95	2.88	0.07	2.37
11	2.97	2.69	0.28	9.43
12	2.78	2.78	0	0
13	2.79	3.02	0.23	8.24
14	3.1	3.2	0.1	3.23
15	3.33	3.04	0.29	8.71
16	3.18	3.15	0.03	0.94
17	3.09	2.85	0.24	7.77
18	3.25	3.33	0.08	2.46
19	2.92	3.41	0.49	16.78
20	3.4	3.39	0.01	0.29
21	2.84	2.89	0.05	1.76
22	2.82	2.72	0.1	3.55
23	2.92	2.84	0.08	2.74
24	3.25	3.05	0.2	6.15
Average	3.07	3.05	0.20	6.64

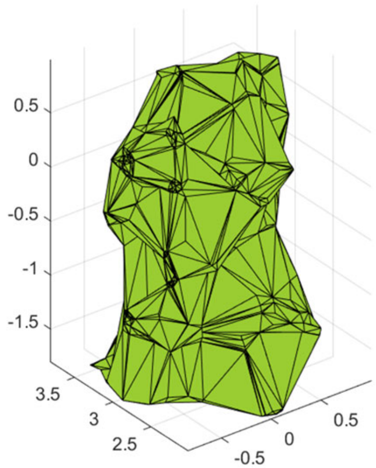


Error between Manual and UAV-based Measurements

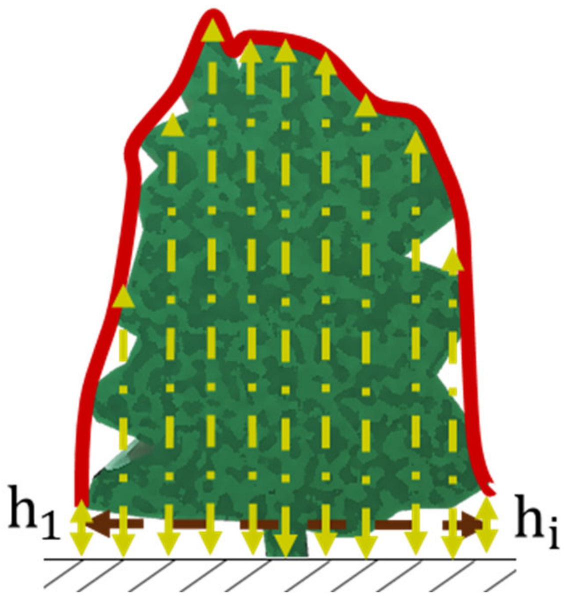
MAE = 0.21 m
RMSE = 0.28 m

Results:

Tree Canopy Volume Measurement



Ground Canopy Volume Measurement

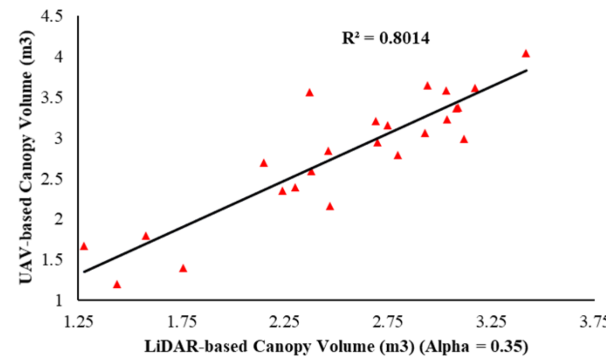


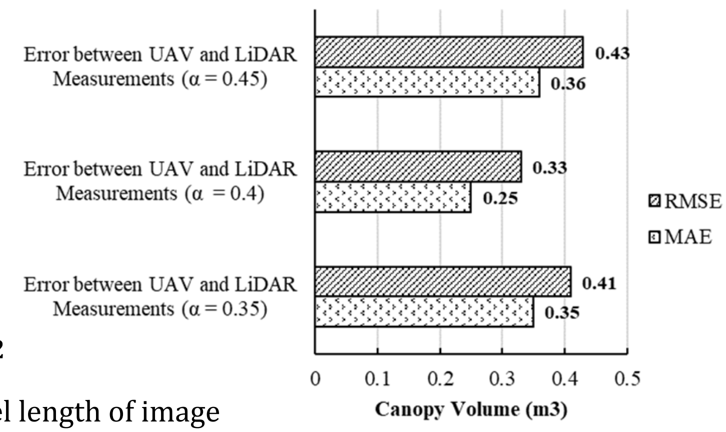
UAV-based Canopy Volume Measurement

Canopy volume (m^3)

$$= \sum_{1}^{i} \text{Height}_i \times \text{Ground Sample Distance (GSD)}^2$$

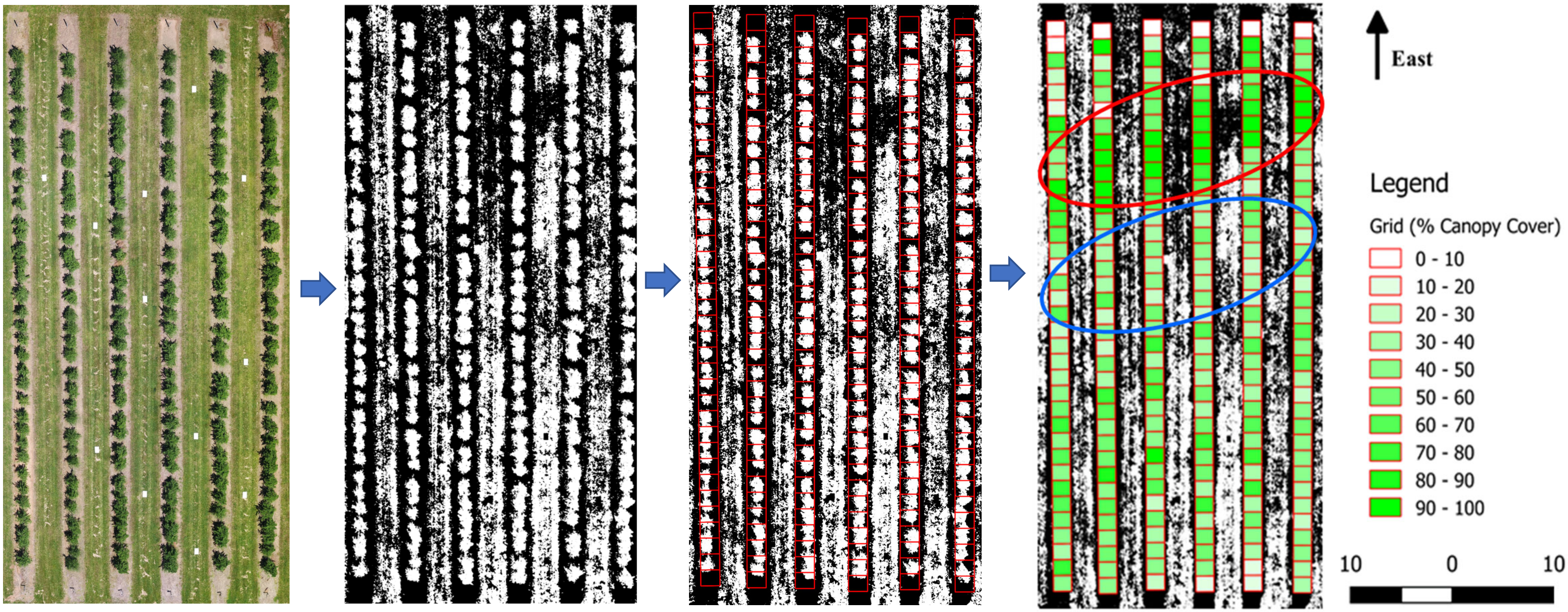
original orchard distance covers by 1 Pixel length of image





Results:

Canopy Cover Measurements



Orthomosaic map → **Extracted canopy pixels** → **Set ROI within trees** → **Canopy cover map**

$$\textbf{Canopy} = \left(\frac{\text{blue}}{\text{green}} < 0.95\right) \text{AND} \left(\frac{\text{red}}{\text{green}} < 0.95\right) \text{AND} \left((2 * \text{green} - \text{blue} - \text{red}) > 20\right)$$

$$\textbf{Canopy cover} = \frac{\left(\sum(\text{GSD}^2) \text{ if Canopy}\right)}{\sum(\text{GSD}^2)} \times 100$$

Conclusions

- Experimental results indicated the potential of UAV-based apple tree canopy height measurement to quantify individual tree height with less than 10% error
- The canopy volume results showed a mean absolute error of 0.25 m3 while comparing UAV with ground measurements
- The UAV-based tree canopy characteristics measurements could be used to quantify the tree canopy characteristics to calculate the pesticide requirement for precision spraying applications in tree fruit orchards

Accomplishments

Awards & Research Grants

1. Outstanding Dissertation Award from College of Ag Sciences
2. Paul Hand Graduate Student Research Achievement Award from College of Ag Sciences
3. Harold V. and Velma B. Walton Doctoral Student Endowment in Agricultural and Biological Engineering
4. Northeast SARE Graduate Student Grant 2020-2022
5. College of Ag Science Graduate Student Competitive Grant 2021-2022

Journal Publications

1. **Mahmud, M. S.,** He, L., Zahid, A., Choi, D., Zhu, H., Krawczyk, G., and Heinemann, P. (2022). Detection and feature analysis of apple fire blight using image processing and deep transfer learning. *Journal of the ASABE (formerly, Transections of the ASABE)* [Under Review]
2. **Mahmud, M. S.,** Zahid, A., and He, L., Zhu, H., Choi, D., Krawczyk, G., and Heinemann, P. (2021) Development of an automatic airflow control system for precision sprayers based on tree canopy density. *Journal of the ASABE (formerly, Transections of the ASABE)* [Revision Requested]
3. **Mahmud, M. S.,** Zahid, A., and He, L., Choi, D., Krawczyk, G., Zhu, H., and Heinemann, P. (2021). Development of a LiDAR-guided section-based tree canopy density measurement system for precision spraying. *Computers and Electronics in Agriculture*, 182, 106053
4. **Mahmud, M. S.,** Zahid, A., He, L., and Martin, P. (2021). Opportunities and possibilities of developing an advanced precision spraying system for tree fruits. *Sensors*, 21, 3262
5. **Mahmud, M. S.,** Zahid, A., He, L., Choi, D., Krawczyk, G., and Zhu, H. (2021). LiDAR-sensed tree canopy correction in uneven terrain conditions using a sensor fusion approach for precision sprayers. *Computers and Electronics in Agriculture*, 191, 106565

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PennState College of Agricultural Sciences

Graduate Student Competitive Grant

Thank you for listening

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