Studentship Project Interim Progress Report
Reporting period: Oct/2018 to Nov/2019

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Project Title:	**Development and demonstration of an automated selective broccoli harvester**		
Lead Partner:	**Prof Simon Pearson, Lincoln Institute for Agri-Tech (LIAT), University of Lincoln**		
Supervisor:	**Prof Tom Duckett, Lincoln Centre for Autonomous Systems (L-CAS), University of Lincoln**		
Start Date:	**18/09/2017**	**End Date:**	**18/12/2020**

1. Project progress update including milestones

This PhD research is concerned with robotic perception using state-of-the-art 3D sensors for real-time detection and size estimation of broccoli crops. This project incorporates findings from work previously carried out at the University of Lincoln to accurately identify broccoli plants in the field based on low-cost 3-D structured light cameras, as well as measure the size of each plant head in order to determine whether or not it is suitable for cutting.

a) Progress to date

In previous state-of-the-art work carried out at L-CAS, a 3D system pipeline for broccoli detection was developed and the results were reported in a journal paper by Kusumam *et al*. [1]. The system was evaluated using sensory data collected under real-world field conditions in farms in the UK and Spain. Two main key performance indicators were used to measure the capabilities of the system, namely *average precision score* (APS) and *processing time per frame*. The experimental results showed a precision score of 95.2% on the UK data and 84.5% on the Spain data, and an average processing time of 5-6 seconds per frame running on an Intel i7 CPU, 3.4 GHz [1].

Model based segmentation. One of the first objectives of the work reported here was to research 3D imaging methods to accurately separate and identify crops of broccoli heads from their background in planted fields. To this end, we developed a 3D segmentation method based on local surface features and the available data from both the UK and Spain was used to conduct an extensive evaluation and comparison with the experimental results published by Kusumam *et al*. [1]. The method, as shown in Figure 1, processes the depth data in a pipeline of four stages:

1) Depth filtering. Removes soil and other elements located too far deep from the sensor.
2) Feature extraction. Determines a numerical descriptor using the angular difference of each point's surface normal.
3) Model matching. Each descriptor is compared to descriptors of broccoli heads.
4) Classification. The points are labelled as broccoli or non-broccoli using a decision function. The points with the same label are grouped to form the final segments.

Similarly, an example of the process is showed in Figure 2. The main contribution of this work was an increased precision rate of 95.6% on the UK data, and 88.2% on the Spain data. However, because the method examines features in every data point, the average processing time still needed to further improve. The findings of these experiments have been published in the recent TAROS (Towards Autonomous Robotic Systems) 2019 conference [2].

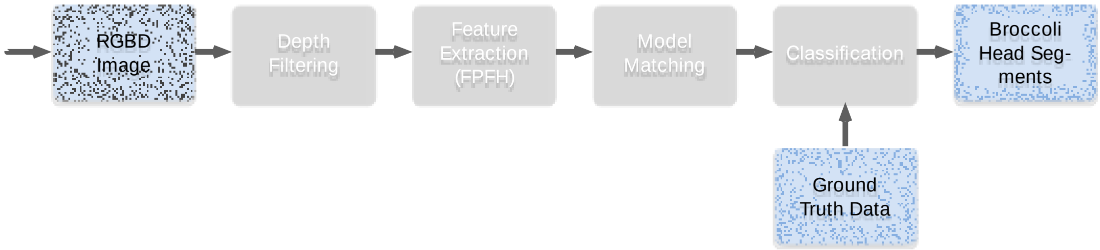

Figure 1. The broccoli data points are first filtered by depth. Then features are extracted from each point and matched to reference models. The points are then classified using a decision function. Points with the same target class are grouped to form the final segments.

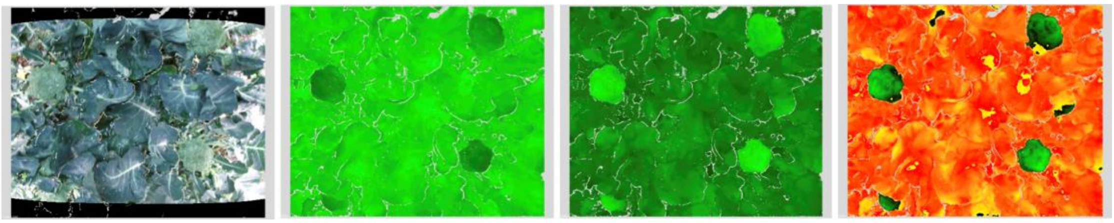

Figure 1. Our method processes 3D data of broccoli plants (far left) are analysed based on local angular features (middle frames) to segment broccoli heads (far right).

Organised Edges Segmentation. One of the goals of this PhD project is to develop a 3D perception system which robustly detects and classifies the target crops in real time, resulting in 3D locations that can be then used by a robotic system for physically harvesting the crop. Using the results from Kusumam *et al*. [1] and from Blok *et al*. [4] as reference baselines, a new method has been developed that takes advantage of the inherent organized structure of the input data.

First, to ensure a more complete and fair evaluation of our system, we implemented a slightly modified, yet faster version, of the method presented by Kusumam *et al.* in [1] dubbed Fast Euclidean Clustering (FEC). The original detection pipeline from [1] included a statistical outlier removal step, depth filtering, Euclidean cluster extraction, normal estimation, feature extraction, classification, and an additional temporal filtering step to improve the overall classification results. In our FEC pipeline, the outlier removal and the temporal filter steps were removed, as the former is computationally expensive and the filtered points do not affect the clustering step, and the latter is a step added to further improve the classification performance. Additionally, one of the key steps, the normal estimation process, was replaced by a similar but much faster method for estimating normal called Integral Images Normals Estimation (IINE). As a result, the APS for broccoli detection improved to 98.0% on the UK data and 91.9% on the Spain data and the average processing time also improved to 0.367 seconds per frame (or 2.72 frames per second) running on an Intel i7 CPU, 3.7 GHz.

Both our FEC pipeline and the results from Kusumam *et al.* in [1] are then compared with the new developed method to detect crops of broccoli heads in real-time at a high precision rate. The new 3D detection pipeline achieves high performance in both detection and running time by using the organized structure of the input data, i.e., data of 3D points that are indexed from a 2D matrix layout. This is an inherent property of the sensors used to collect the broccoli data. The main advantage of this organized data is that the location of neighbouring points of any other point within the matrix grid can be retrieved in constant time, making it unnecessary to run costly searches and, thus, drastically speeding up processing times. The new 3D detection pipeline involves five main steps: (1) An edge detector of organized data that uses the depth information of neighbouring points to estimate edge boundaries. (2) An edge-based segmentation method that yields a particular segmentation depending on the depth level used by the edge detector. (3) An integral images normals estimation method that takes advantage of the organized structure of the input data. (4) Feature extraction, and (5) classification.

This new detection method is been named *Organised Edges Segmentation (OES)* and an overview of its pipeline is shown in Figure 3.

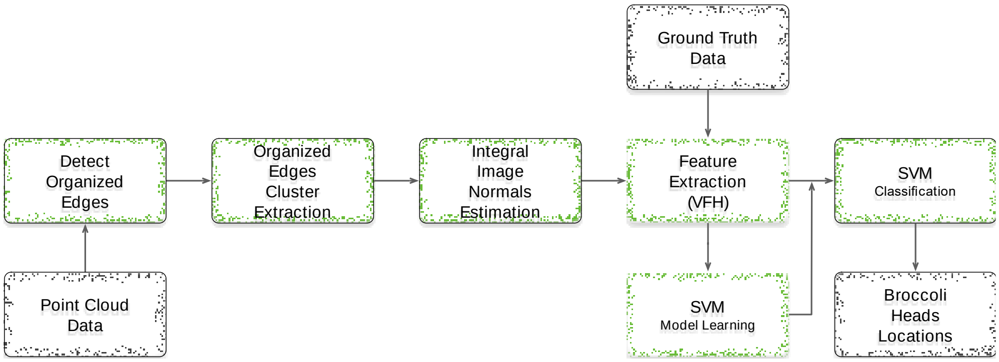

Figure 2. Real-time broccoli detection system pipeline. First, the edge detection algorithm labels points as edges based on point depth discontinuities. Then data points that are not part of an edge are grouped together by adding points in the immediate vicinity to form clusters. Normals are then estimated by using the organized structure of the data. Features are then extracted from each cluster and classified to determine whether they are a broccoli head or not.

In addition, the system's performance was evaluated using multiple datasets acquired in open field conditions in locations in three different countries, namely, the UK, Spain and the USA. The data from both the UK and Spain is the same data used in the experiments reported by Kusumam *et al.* [1]. Different broccoli heads are visible in the three datasets. In the Spain set only one row of the crops is visible, whereas in the UK set two appear on each frame. The entire three row planting scheme of broccoli commonly used by farmers is visible in the California dataset. The challenge is to test all these different schemes to evaluate the generalization performance of our system, and also to help to decide hardware configurations for the robotic harvester.

The OES detection system was first evaluated and compared with the segmentation pipeline published by Blok *et al.* [4]. These segmentation results were evaluated using the data of 200 images of two broccoli varieties, acquired with an RGB camera (2448×2050 resolution) in fields in The Netherlands. We also included in the evaluation the results from our FEC detection pipeline. To ensure a fairer comparison, the broccoli data used are from both the UK and Spain as those show the closest similarities to Blok's images in terms of both visibility and broccoli head size. Our results showed that Blok *et al.* [4] achieved a precision rate of 76.8%, the FEC pipeline precision was 96.1%, and the OES precision rate was 96.9%.

Then we compared the detection performance of the OES system to the results by Kusumam *et al.* [1] described above. Our experimental results showed that the OES detection pipeline delivers an improved APS of 98.8% on the UK data and 95.1% on the Spain data as well as a higher processing time of 0.069 seconds per frame, equivalent to nearly 15 frames per second, running on an Intel i7 CPU, 3.7 GHz. This evaluation performance showed that the method exhibits the required detection precision and real-time performance needed for autonomous robotic harvesting applications.

The results of both the FEC and the new OES were reported in a paper that has been submitted to the upcoming International Conference on Robotics and Automation (ICRA) 2020 entitled "*Real-time detection of broccoli crops in point clouds for autonomous robotic harvesting*" [3].

b) Current work

A new method for the detection of crops of broccoli heads that also uses the organized structured of the input data as well as constraints of local features to segment broccoli crops is currently being experimentally tested. Preliminary results have produced an APS of 97.7% and an average processing time of 0.098 seconds per frame (or 10.2 frames per second). Note, however, that it is expected that additional experimental refinements will further improve these initial results. Additionally, an extensive error analysis on the influence of object characteristics on detection performance will be included. This analysis will help to properly determine the size of the broccoli heads detected to ensure that it meets market specifications for size and shape, which is in line with the overall goals of the PhD work.

The results of these experiments will be included in a paper to be submitted to the upcoming International Conference on Intelligent Robots and Systems (IROS) 2020.

c) Planned development

For the last stage of this PhD research work, the goal is to develop a version of the system based on state-of-the-art machine learning techniques and compare its result with the methods already developed. Methods such as Convolutional Neural Networks (CNN) and similar *deep learning* techniques will be implemented as they have become the method of choice for problems similar to the one been address in this project. The key performance indicators APS, processing time per frame, and error analysis of the detector will also be used to make fair comparisons an to determine the best broccoli detector.

Milestone	**Target date**	**Achieved date**
Optimization and evaluation of a previous study by Kusumam *et al.* 2017.	August 19	August 19
Develop and evaluate new approaches for accurately clustering 3D data that are both size and point density invariant.	January 19	January 19
Develop and evaluate new approaches for detection of broccoli heads beyond the current state-of-the-art.	May 19	June 19
Develop and test an approach for 3D size estimation of broccoli heads robust to occlusions and partial data to determine if a head is ready to be harvested.	October 19	December 19
Develop and test an approach based on state-of-the-art machine learning techniques, such as CNN's, and compare its result with the methods already developed.	April 20	
Start thesis write-up	July 20	
Thesis submission	December 20	

2. Issues arising / Risk management:

N/A

3. Knowledge transfer (KT) activities/resources delivered and future KT opportunities:

(please attach any KT outputs relating to the project e.g. presentations, articles)

- Experiments with a method based on local features for 3D segmentation were carried out and its results have been published in the recent TAROS (Towards Autonomous Robotic Systems Conference) conference, hosted by the Centre for Advanced Robotics at Queen Mary University of London in July 2019 [2].
- A method for real-time detection of broccoli crops has been developed and a paper has been submitted with the results to the upcoming ICRA 2020 conference [3]. These experimental results are in line with the overall goals of my PhD research.
- Currently a method for 3D segmentation that delivers a high precision detection and performs in real-time it is been experimentally tested. The immediate goal is to submit a paper with the results to the IROS 2020 conference.

4. Placement requirements (if applicable)

N/A

References

[1] *K. Kusumam, T. Krajnik, S. Pearson, T. Duckett, and G. Cielniak*, "3D-vision based detection, localization, and sizing of broccoli heads in the field", Journal of Field Robotics, vol. 34, no. 8, pp. 1505–1518, 2017.

[2] *H. Montes, and G. Cielniak, T. Duckett*, "Model-based 3D point cloud segmentation for automated selective broccoli harvesting". In: 20th Annual Conference Towards Autonomous Robotic Systems (TAROS). Lecture Notes in Artificial Intelligence 11649, pp. 448–459, 2019. https://doi.org/10.1007/978-3-030-23807-0_37.

[3] *H. Montes, and G. Cielniak, T. Duckett*, "Real-time detection of broccoli crops in point clouds for autonomous robotic harvesting". International Conference on Robotics and Automation, 2020. *In review*.

[4] P. M. Blok, R. Barth, and W. van den Berg, "Machine vision for a selective broccoli harvesting robot", IFAC-PapersOnLine, vol. 49, no. 16, pp. 66–71, 2016, 5th IFAC Conference on Sensing Control and Automation Technologies for Agriculture AGRICONTROL 2016.