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Key staff:	Justin Le Louedec
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Industry Representative:	Berry Gardens Growers
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DISCLAIMER

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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GROWER SUMMARY

Headline

This project provides a study to understand the key information for using 3D information and 3D sensing technologies in robotics applications for autonomous soft fruit farming.

Background

Autonomous harvesting is becoming an important challenge and necessity in agriculture, because of the lack of labour and the growth of population needing to be fed. Perception is a key aspect of autonomous harvesting and is challenging for example due to difficult lighting conditions, limited sensing technologies, occlusions and plant growth. 3D vision approaches can bring several benefits for example localisation, size estimation, occlusion handling and shape analysis. To select and pick a ripe fruit from a plant is a simple task for a person, but immensely complex for a machine to replicate. For an autonomous system to achieve this task it must first be able to reliably detect, differentiate, and track fruit in a complex 3D space. This research connects to other work in this and other research groups developing systems for the deployment of robotic platforms in strawberry farms. The overarching objective is to develop systems that can assist pickers, agronomists, and farm managers for a multitude of tasks.

The focus of this work is to study and develop the vision system of robots specifically for the soft fruit industry. This project opens the door to various applications which rely on 3D information. Applications such as improving differentiation and fruit picking, providing more fruit information (e.g. yield and quality) to the growers, recording phenotype information by an autonomous system.

Summary

This project provides preliminary results indicating improvements are needed in current computer vision technology. We developed a method using 3D information for detecting broccoli heads as a model plant based on Convolutional Neural Networks (CNNs). We have completed extensive studies in the field to evaluate sensing technologies and algorithms. Doing so we have found significant limitations in the current sensing technologies while proving the usefulness of our own methods utilising 3D information. Our findings confirm that 3D structure information could be useful for autonomous detection of fruit. We also provide a significant contribution in describing fruit shape information using spherical harmonics. We developed 3D shape descriptors which a machine can use for phenotyping applications. This

work paves the way for advances in automatic phenotyping and will be investigated later in the project.

Financial Benefits

This project is part of a much larger programme to develop robotics for the horticultural industry. The exact financial outcomes of such investment in robotics and computer science is unclear at this early stage. However, it is expected that a fully working robot picker would alleviate labour cost for picking, transporting, and analysing fruits in the grower facility, with an initial investment in the robot.

Action Points

There are no clear action points at this early stage of the project, however investigating new sensing technologies with relevant companies and laboratories to provide better performances of 3D sensing technologies in the field, would provide tremendous assets for future projects and applications in agriculture/horticulture and other fields.

SCIENCE SECTION

Introduction

Autonomous harvesting is becoming an important challenge and necessity in agriculture, because of the lack of labour and the growth of population needing to be fed. Perception is a key aspect of autonomous harvesting and is very challenging due to difficult lighting conditions, limited sensing technologies, occlusions, plant growth, complex changing environment. Utilising 3D vision can bring several benefits which will address these challenges. 3D vision will improve localisation, size estimation, occlusion handling and shape analysis.

Due to population growth and various social and economic factors, the interest in automation of agriculture has grown worldwide. Labour for harvesting is one of the biggest challenges facing this industry. Building autonomous system able to detect, analyse and pick crops is rapidly becoming a necessity, both economically and socially. Perception for harvesting applications presents numerous challenges characteristic to outdoor scenes, such as difficult lighting conditions and occlusions of the target crop caused by the plant growth. There is, however, a strong case for deploying such systems in real-life scenarios and currently it is not clear how well the current state of the art in 3D vision translates into the challenging situations posed by applications such as in agriculture. As part of our research project, we propose a study on the application of modern 3D sensing technology together with the state-of-the-art machine learning algorithms for segmentation and detection of strawberries growing in real farms. The precise information about strawberry fruit location and shape description have a range of applications such as yield monitoring and forecasting, phenotyping or robotic picking. The challenges posed by such a scenario include variable lighting conditions, reflections, occlusions, non-rigid structure of the strawberry plants and relatively small size of the fruit. Since, the current 3D sensing technology has not been deployed widely in such scenarios and most of the modern machine learning algorithms were designed and trained specifically for large and rigid objects, our study aims to assess the usefulness of the sensing and learning methodology for the proposed application.

In this study, we developed a method using 3D information for detecting broccoli heads based on Convolutional Neural Networks (CNNs), exploiting the organised nature of the point clouds originating from the RGBD sensors. The algorithm was tested on real-world datasets and achieved better performances than the state-of-the-art, with better accuracy and generalisation in unseen scenarios, whilst significantly reducing inference time, making it better suited for real-time in-field application.

Shape descriptor and shape reconstruction are two challenges found in computer vision and graphics as well as in perception for robotics, especially for some fields such as agri-robotics (robotics for agriculture). Being able to offer a reliable description of shape that can also translate directly into a high fidelity model of the shape, would be of high importance for many applications such as phenotyping or agronomy. An accurate description of crops shape is an important challenge in horticulture. Automating their creation and allowing a complete 3D reconstruction of the objects from it, would greatly improve phenotyping or other agronomy tasks. In this work, we use the mathematical concept of spherical harmonics to create a representation of strawberries' shape and study their fidelity and accuracy by reconstructing the fruits with them. Furthermore, this new representation offers a more compact and efficient representation of the shape than using directly points. Reducing the volume of data whilst retaining the characteristics that allow a machine to recognise an object is vital to increasing the processing speed of machine vision in real world environments.

Materials and methods

Case study: Broccoli Head Detection

To evaluate sensing technologies, we captured and annotated data from a Time of Flight camera and a stereo camera. We summarize the data captured in the following table:

sensor	stereo	ToF
# point clouds	64	139
resolution	1280x720	1280x720
range	20cm-65m	20cm-70cm
# instances	~ 1000	~1900
% strawberry points	~6%	~ 6%

Figure 1 Strawberries dataset summary

We also use a dataset provided by another project on Broccoli Head detections, as the data presented in this work offer high quality depth information and comparable method performances from previous work. The data available is summarised in the following table:

Dataset Name	Spain	UK1	UK2
#Point clouds	300	300	300
Overlapping	94%	95%	90 %
Average Width	1.10m	0.60m	0.60m
Average Height	0.86m	0.80m	0.80m
Average Distance	0.81	0.75	0.75
Broccoli Species	Titanium	Ironman	Ironman

Figure 2 Broccoli datasets summary

We presented methods for the strawberry data in last year report. For the broccoli data we use a method created to make use of the organized structure from the camera. The global idea can be found in the following figure:

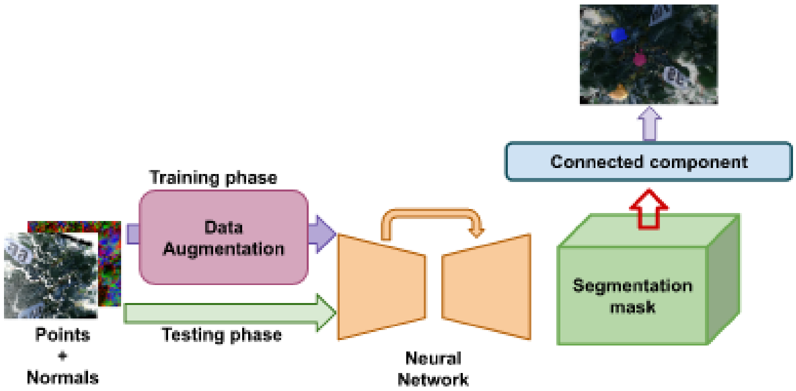

Figure 3 Description of the method used for segmentation of broccoli's head segmentation

The full method, results and experimentation descriptions can be found in the published paper (*LeLouedec et al. 2020b*). The approach for the segmentation and detection of broccoli heads uses organised point clouds originating from RGBD sensors. A CNN autoencoder was trained for the task of semantic segmentation using 3D information. Several data augmentation techniques was used to avoid over-fitting and improve generalisation between different varieties and field conditions. (LeLouedec et al. 2020b)

Shape understanding of strawberry crops

Concerning shape description, we make use of the spherical harmonics mathematical representation to offer a description of the strawberry shape information. We use different level of spherical harmonics to offer different level of precision and details. The full method and results can be found in the published paper (*LeLouedec et al. 2020c*).

Results

Case study: Broccoli Head Detection

The segmentation results on the Broccoli datasets is shown in the following table:

Trained / Tested	FEC	NN	FEC	NN	FEC	NN
	Spain		UK1		UK2	
Spain	0.73	**0.94**	0.64	**0.81**	0.67	**0.85**
UK1	**0.90**	0.85	0.94	**0.95**	0.92	**0.94**
UK2	**0.92**	0.85	0.92	**0.92**	0.94	**0.94**
Mean	0.85	**0.88**	0.83	**0.89**	0.84	**0.91**

Figure 4 Comparison of the Mean Intersection over Union (MIoU) of the segmentation masks for Fast Euclidean Clustering (FEC) method and neural network (NN)

The Fast Euclidean Clustering (FEC) method references a baseline method from the literature (Kusumam et al. 2017) while neural network (NN) represents our proposed method. The best performing method for each experiment is highlighted in bold in figure 4. Overall both algorithms performed well for all training and testing scenarios. However, our method shows on average better results and still offers generalisation and robustness across datasets. FEC achieved poor performances for the Spain dataset. Furthermore, our method is considerably faster than the current state of the art at the time, offering 50 frame per seconds processing speed against 5 for previous methods.

<u>Shape understanding of strawberry crops</u>

For each strawberry model we transform in a spherical harmonics descriptor and use this descriptor to reconstruct the object. The results prove the quality and validity of the reconstruction and the suitability of such descriptor for a strawberry's shape (figure 5 and 6).

Figure 5 Example of strawberry point clouds (left example for each pair) and their reconstructions utilising spherical harmonics (right example for each pair), for two particular shapes.

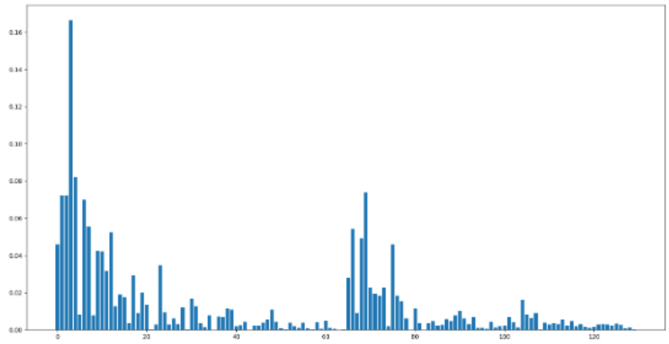

Figure 6 Spherical harmonics coefficients responsible for main shape information

Looking at figure 6, the first coefficient is associated with the first harmonic and is responsible for the round shape of the strawberry. It is present in every strawberry and non-discriminative other than for scale. The first twenty harmonics are more important for the shape and specificity of the global strawberry, while the following harmonics are corresponding to more fine details. Not only is the reconstruction a valid digital representation of the original object, but the quantity of data required to create the reconstruction is considerably less compared to a point cloud, as we can describe the object with a maximum of a thousand harmonics against hundreds of thousands points.

The reconstructed data of the analysis can be found in the following table:

	Original	Reconstructed	Deviation
Volume $(\mu \pm \sigma)\ cm^3$	45 ± 46	45 ± 46	$\sim 1\%$
Surface area $(\mu \pm \sigma)\ cm^2$	280 ± 160	277 ± 160	$\sim 1\%$

Figure 7 The volume and surface area estimation results from the reconstruction process of 15 3D models of strawberries (Note the objects were scaled during capture process).

Discussion and Conclusion

We developed a new method (Convolutional Neural Networks CNN) for processing 3D information acquired through RGB-D cameras in the context of robotic vision for agriculture. We presented new algorithms and strategy opening new investigations on fruit perception in 3D. To evaluate the method and its implications broccoli harvesting application has been chosen due to the availability of high quality data and a state-of-the-art algorithm for processing it. The algorithm was tested on real-world datasets and achieved better performances than the state-of-the-art, with better accuracy and generalisation in unseen scenarios, whilst significantly reducing inference time, making it better suited for real-time in-field application. The new method showed that 3D information to provide accurate and valid segmentation results with agricultural and horticultural type data. Our method achieves similar results on the baseline datasets and better results for the challenging sets, while providing better segmentation of the objects, competitive instance segmentation, better localisation, and faster inference by a factor of 300. However, there are some limits. The difference in size between objects and data sets leads to missed detection, especially on the upper and lower boundaries where the distortion varies the most. Training on intrinsically different object size than the test set (Spain training to UK testing) also affect the results, yielding more false positives. Further investigation (e.g. data normalisation, un-distortion or data augmentation) to solve this problems are required. (LeLouedec et al. 2020b)

The study on determining strawberry shapes with spherical harmonics shows an efficient way of describing and reconstructing strawberry shape information. It offers a compact way of representing the shape of such objects and simplifies future work done on processing this shape information. These preliminary results may lead to investigate new shape descriptors for strawberry and to more complex and generalized representation and reconstruction techniques. The current state of the art sensing technologies require improvement which is a limiting factor for us as it is required to acquire data with sufficient quality for us to process and understand it. We propose some preliminary descriptors for shape which can be used for phenotyping purposes as they offer accurate representation, automatically computed.

In sum, the main aims and results are:

- Study of modern 3D sensing methods
- Experimentations on high quality agricultural dataset to prove the usability of our proposed methods.
- Faster, more accurate and more robust methods than state of the art ones on selected agricultural datasets.
- Novel and performant shape descriptors methods for strawberries, as preliminary work for potential autonomous phenotyping methods.

Ongoing and future work:

We will be working on finalising some previous work on shape completion and reconstruction. This work aims new representation techniques for 3D point clouds of objects and using these new representation for several task such as classification, part segmentation, regeneration. Furthermore, we are planning to introduce a biological aspect to the shape information and generation, using phenotyping and genotyping data with new machine learning techniques. Future investigations include the following:

- Simulating strawberry farm environment to verify algorithms and hypothesis, with data rendered by ideal sensors

- Using segmented fruits to produce shape information
- Reconstructing segmented fruits for a full phenotyping analysis
- Linking phenotype information with genotype

Knowledge and Technology Transfer

- AHDB conference in January 2020:
  - Presentation of recent work and summary of the first year.
- VISAPP conference (Feb 2020), paper published:
  - Presentation of our conclusion drawn from first year work on sensor analysis and state of the art algorithms for unordered point clouds.
- CVPR workshop : The first international workshop and price challenge on Agriculture-Vision: Challenges & Opportunities for computer vision in agriculture :
  - Paper accepted, workshop took place beginning of June 2020
- UKRAS conference (Mars 2020):
  - Presentation/poster on short paper published at the conference
- July 28th 2020: Fruit perception workshop, organized by the Grzegorz Cielniak with the University of Lincoln.
  - Presentation title : Fruit detection in 3D and shape estimation for long term autonomous robotic harvesting
- August 4th 2020: CTP summer meeting, presentation of previous, ongoing and future work. Presentation title :
  - Fruit detection in 3D and shape estimation for long term autonomous robotic harvesting

References

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