Project title:	Soft fruit detection and shape estimation using 3D information and machine learning
Project number:	
Project leader:	Grzegorz Cielniak, University of Lincoln Charles Whitfield, NIAB EMR
Report:	Annual report, 2021
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Key staff:	Justin Le Louedec
Location of project:	University of Lincoln
Industry Representative:	Berry Gardens Growers]
Date project commenced:	September 2018

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

The aim of this project is to study 3D information sensing and determine its potential for use with autonomous soft fruit farming. Provided are published results indicating improvements needed in the technology. In addition, we show that 3D information is a crucial component for crop and fruit detection and analysis, and more generally within the topic of autonomous agriculture. Research from this project on achene counting over strawberry surfaces has also been published.

Background

This work is aligned with a larger project around the deployment of robotic platforms in strawberry farms, to help pickers, growers, and the industry members with various tasks. Specifically, we study the vision system of robots and how they can be used for different tasks such as picking or phenotyping. This project could open the door to various applications utilising 3D information. Such applications, relating to automated machine vision systems, are likely to be tasks such as:

- improving fruit differentiation to assist with picking
- providing information to the growers such as size, weight, quality, and number of fruits
- improving phenotyping accuracy
- autonomous phenotyping

Summary

Extensive field have been conducted to evaluate sensing technologies and algorithms. Doing so we have found strong limitations in available current sensing technologies while proving the usefulness of our methods and 3D information. We also have provided some 3D shape descriptors which can be used in phenotyping applications and will be used in later advances in the project. Finally, we proposed a novel method for achene counting over the surface of strawberries, published at BMVC 2021. This method achieves impressive results, performing better than previous method and manual phenotyping work.

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 are unclear at this early stage. However, it is expected that a fully working robot picker would reduce 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 stage of the project.

SCIENCE SECTION

Introduction

Providing phenotypic data of soft fruits which is both accurate and quantitative, is extremely important for successful breeding programs and visual quality inspection. Currently, strawberry phenotyping assessment is done manually by humans who assess and measure important fruit characteristics.

Image analysis makes use of sophisticated computer algorithms to provide insight (detection, localisation, and description) for 2d images. Although it achieves very impressive results it is quite limited to measure quantities such as size, shape etc.

My PhD project focuses on investigating the use of 3D information for precise measurement and shape analysis

With the work presented here, we address one extremely important task for biologists, agronomists, or breeders, which is the extraction of phenotypic traits from the berries to improve the selection and breeding of the fruit. This project is providing a complete study of the problem and tools and algorithms for the automatic extraction of these phenotypes' traits. Automatic determination of phenotypic traits would be a huge leap forward for the fruit industry due to dramatic increase in data collection and analysis for breeding programmes, and general analysis of soft fruit characteristics. While this thesis is focusing on strawberries the technology and methods are applicable to other fruits and crops.

Being focused on technology, this project is intrinsically different from other projects funded by the CTP, which makes it a unique approach to research and challenges in the soft fruit industry.

Some of the traits that are used for quality assessment and breeding purposes are surface and shape features such as bruises, shape, deformities and seed number or density. Using 3D scans of berries and providing tools and algorithms to analyse the surface and shape of the fruits autonomously and precisely would alleviate the extremely long and difficult process of manual assessment by breeders, biologist, and agronomists. This work is inspired by the preliminary work of Li et al. [1], of using 3D imaging of berries to predict phenotypic traits.

Method

My PhD project focuses on three different aspects of 3D information in horticulture and soft fruits:

- Studying 3D cameras and their suitability in the field for detection and analysis of fruits. This led to two publications [4,5], with direct implication in the industry with the investigations and conclusion provided.
- Providing algorithms and solutions for phenotypic analysis of soft fruits, in particular strawberries, using state-of-the-art techniques and technologies.
- Creating novel techniques for the reconstruction and shape analysis for fruits directly in the field, with simple cameras mounted on robots (see Figure 1).

Figure 1: The Thorvald robot in the strawberry polytunnels, with camera mounted for fruit analysis.

Using the 3D scan of the berry it is also possible to provide insights into the shape and particularity of a given species of berry or a precise selection of genes. For example, in the next figure, it is possible to visualize the roundness/sphericity of a given berry and compute its deviation or compare it to other selected strawberries.

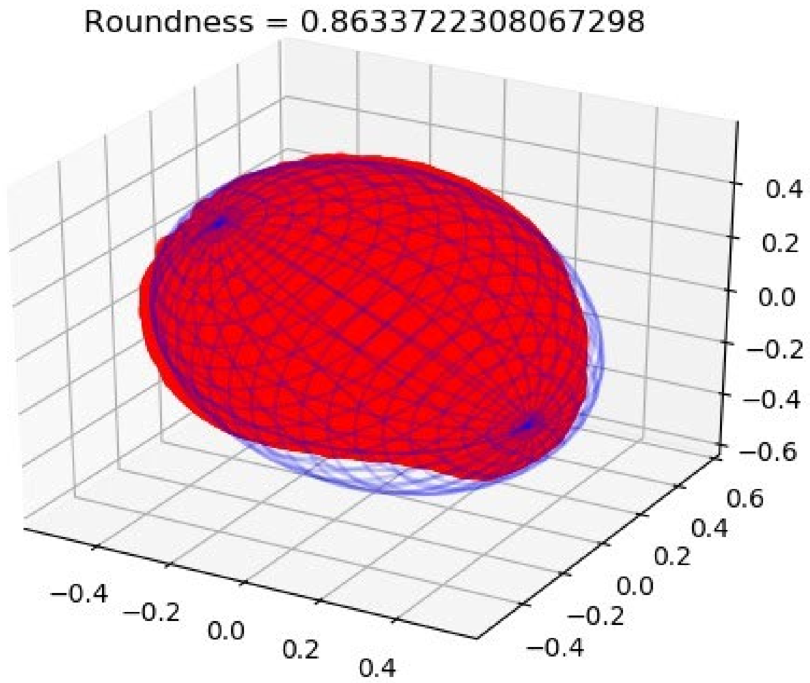

Figure 2: Using the 3D scans, one can easily compute some attributes such as roundness, here of 0.86 (1 being a perfect ellipsoid)

In this report, we focus on presenting our work on creating a novel method for phenotypic analysis of strawberries.

It is based on this idea that the surface of a strawberry in 3D can be represented differently and processed efficiently to extract meaningful information. We propose to use a spherical projection of the berry surface on a 2D surface and to use artificial intelligence to extract seed locations and numbers, which also allows us to provide insightful information about the surface, defects, and particularities of the berry.

We present in Figure 3 a 3D scan for a strawberry as an example of data we use for phenotypic analysis.

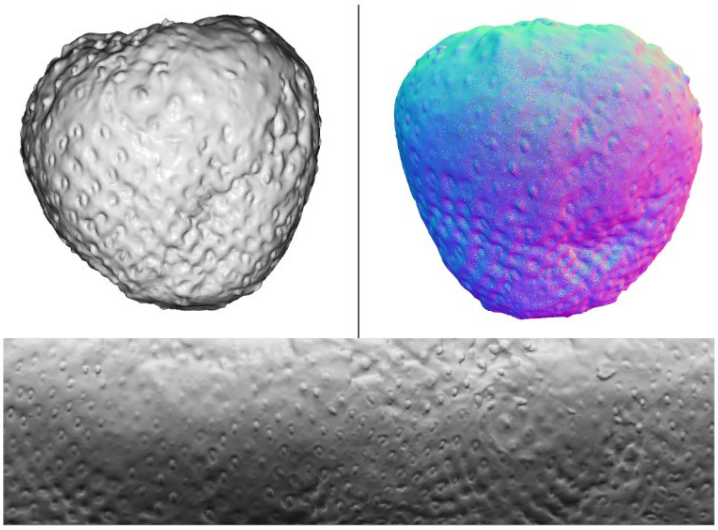

Figure 3: Illustration of (1). On the top left the 3D scan of the strawberry, on the top right the points sampled over its surface, and the bottom image is the planar projection of these points.

This type of data is then used by state-of-the-art algorithms to predict and summarize phenotypic traits over the surface of the berry. Figure 4 shows a summary of the process.

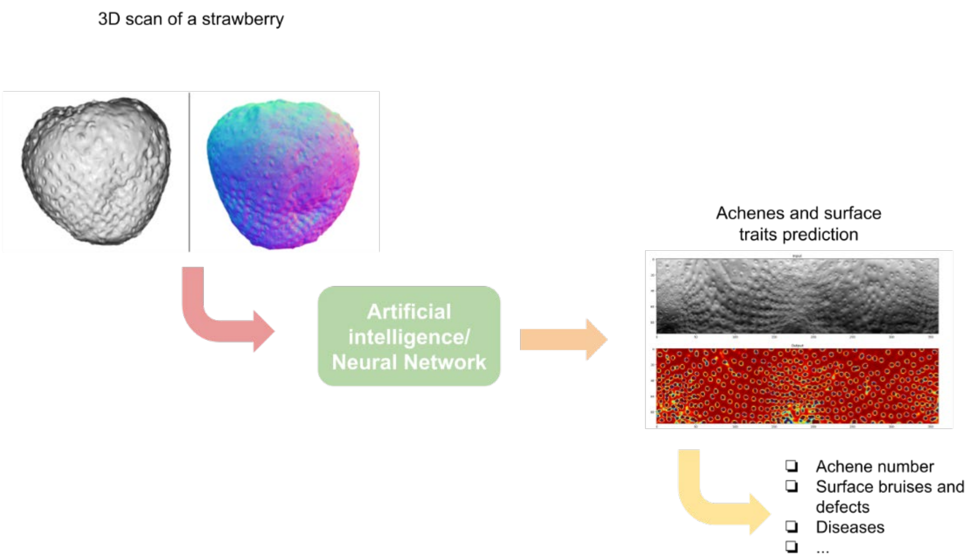

Figure 4: 3D scans of strawberry are fed to state-of-the-art algorithms in charge of inferring summaries of phenotypic traits.

Results

Achenes number prediction

To evaluate our method, we use the dataset presented in Durand-Petiteville et al. [2]. They provide a dataset of thousands of strawberry scans from multiple species and locations.

We show the results for the achene number prediction in the following Figure. The prediction is very close to the actual number of seeds, with errors most of the time below 8% with some hard examples still below 13%. These error rates are very good considering a large number of seeds in some examples and difficulty induced by bruises and defects.

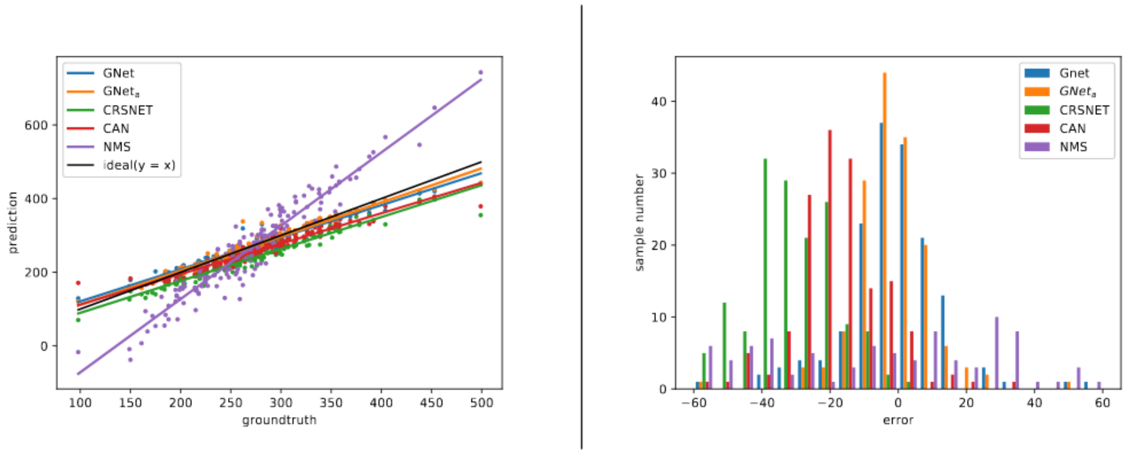

Figure 5: The linear regression between the ground truth and prediction counts [of what? Fruit, achenes?] for all considered methods (left) and distribution of errors (right). (From Le Louedec et al. [3]*)*

We present some quantitative results in Table 1. The RMSE (root mean square error) and MAE (mean absolute error). We also use False Positive rates (FP%) and False negative rates (FN%).

Table 1: Quantitative results for our method GNet, compared to other state of the art methods. (From Le Louedec et al. [3]*). Values highlighted by bold style are the best score for each metric.*

Arch.	Δ	RMSE	MAE	FP%	FN%
GNet	0.5	14.30	9.80	1.55	2.06
GNet$_a$		**12.86**	**8.40**	1.34	**1.75**
CSRNet		36.42	32.90	**0.00**	12.13
CAN		24.62	20.03	0.41	6.97
NMS		71.64	57.37	11.41	10.45
GNet	1.0	**16.10**	**10.89**	0.87	3.15
GNet$_a$		17.60	10.10	2.65	**1.07**
CSRNet		39.84	35.55	**0.24**	12.87
CAN		39.65	30.48	0.28	10.96
NMS		71.16	55.75	7.51	13.74

Arch.	MSE	MAE	FP%	FN%
UNet	13.69	9.21	**0.94**	2.45
UNet$_t$	14.24	9.71	1.38	2.19
GNet$_a$	**12.86**	**8.40**	1.34	**1.75**

The results obtained prove our method to be very efficient for the achene counting task, providing accurate and precise counts.

For comparison, the following figure is taken from Bo Li's paper **[1]**:

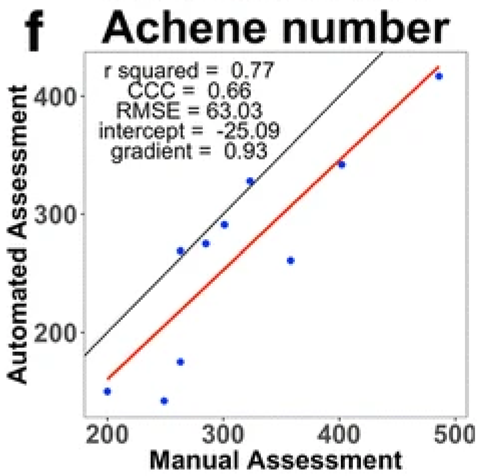

Figure 6: Achene number prediction from Bo Li et al. [1]

We achieved very good results with higher accuracy and streamlined the process to a lot of data samples.

We show in Figure 6 some examples of the seed location predictions that we use for counting them. With easily identified seeds we achieve very good accuracy and performances, as shown in the first example. Some examples on the other hand are very much more difficult, as seen in the second example. The difficulty is mostly due to inconsistency in surface continuity inducing higher seed density in some areas, as well as some defects and bruises on the surface.

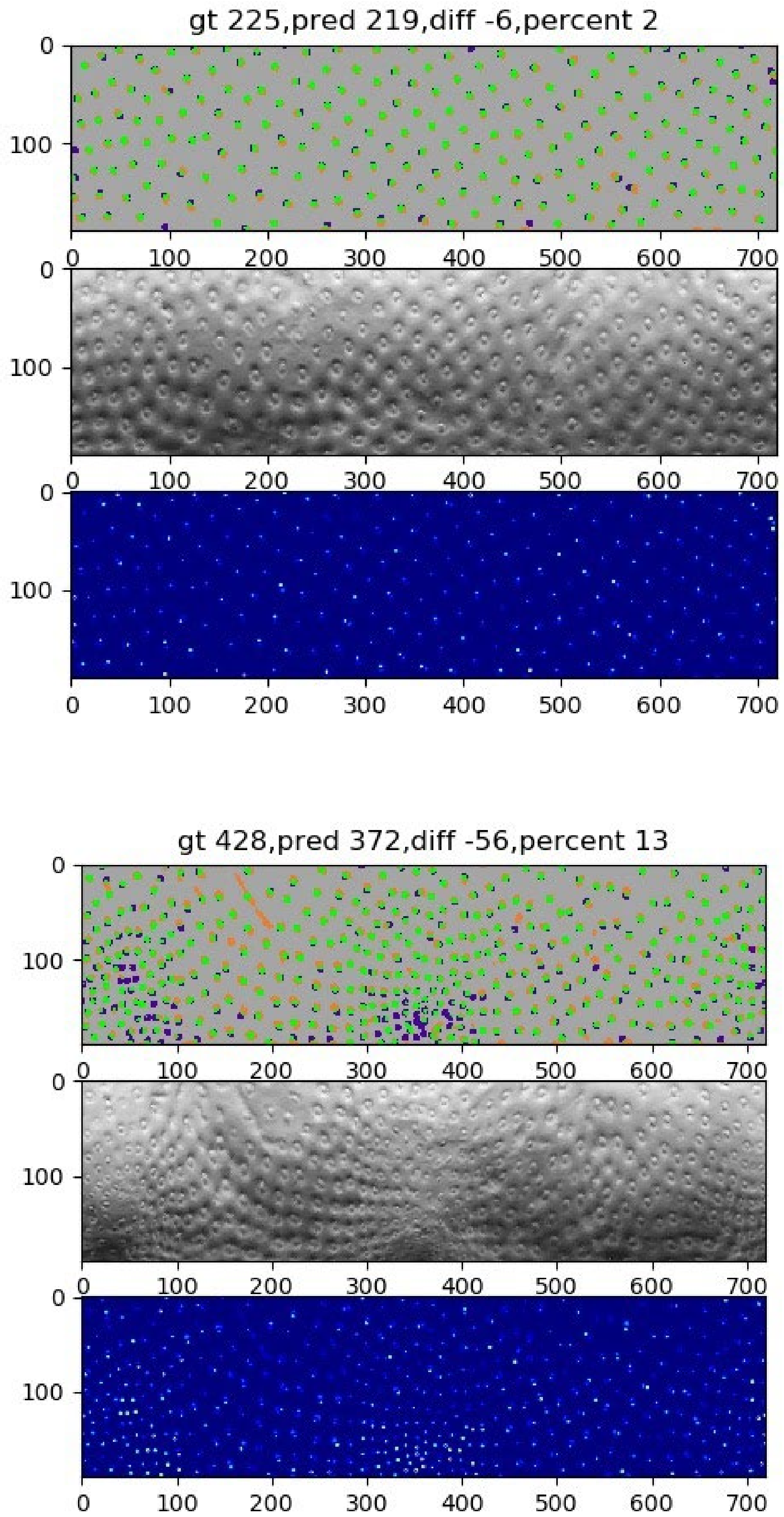

Figure 7: Two examples of seed location predictions. Green indicates correctly predicted areas, orange areas predicted as seeds, but which are not, and purple areas missed. The top example showcases and easier example with very good performances, and the bottom one shows a more difficult surface with very dense areas and bruises.

Surface quality assessment

In the following figure, we show how the prediction for the location of the achenes is also helping in understanding better the surface bruises and defects. With achenes very accurately highlighted, brighter areas indicate disturbances over the flesh of the berry.

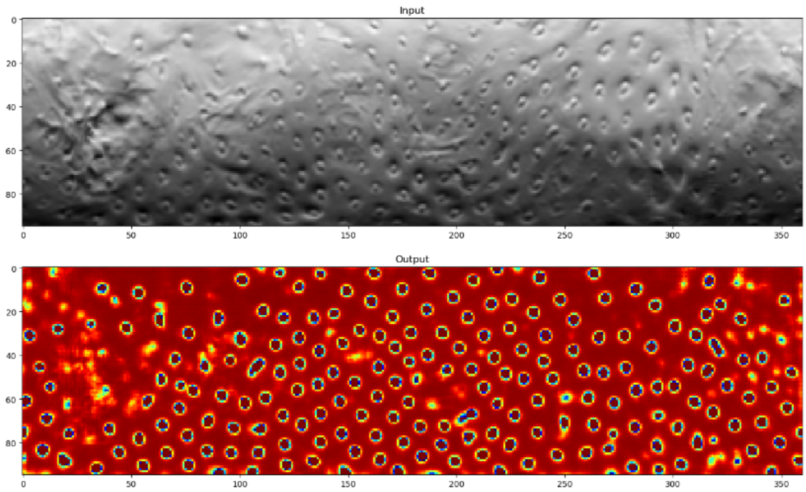

Figure 8: Comparison between the surface of the berry (Top) and the prediction of the seed locations (Bottom). Seeds become easily identifiable, and it is also easy to identify bruises and defects.

Achene density and continuity of the 3D surface

Using the achenes prediction, we can also visualize the density of the seeds over the surface directly on the 3D berry, providing lots of insight for agronomists, biologists, or breeders to analyse their product. For example, in the following figure, with a scale from blue to red, we can easily identify defects or bruises in blue and regular continuous flesh with red/orange.

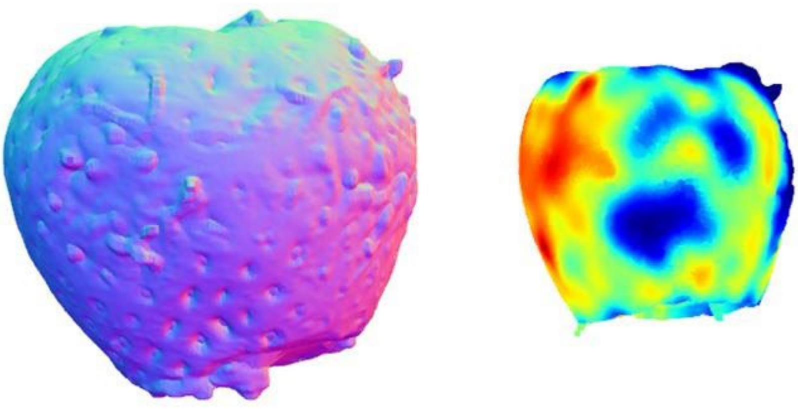

Figure 9: Using such prediction one can visualize for a given berry (Left), the density of achenes over its surface (Right)

Conclusion

We presented in this report the advances made in autonomous phenotyping for soft fruits and agriculture/horticulture. We present a novel technique to process 3D surface information of strawberries to predict and provide advanced phenotypic information. With very promising results, we not only provide a reliable automatic way of counting achenes on the berry but also predict and give insights on other phenotypic traits found on the surface.

Furthermore, this type of method opens the door to phenotypic traits prediction to other plants, fruits and organisms found in the industry.

Concerning the direct application of this method, it offers a lot of advantages compared to traditional fruit/plant manual inspection, from the huge amount of time saved, and amount of samples analysed, to the precision of information extracted. It also alleviates the need for expertise and experience from the inspector, only during defining the model and annotation we need to know about what is needed. Once trained the model can process all the data and deliver detailed reports, requiring analysis without the hard labour of going through all the data.

To conclude, with far greater output than doing it manually, it would provide a fast, reliable, and almost fully automatic and autonomous 3D analysis of the fruits, saving countless hours and labour, accelerating breeder analysis and production.

Future work would take two separate directions:

- Providing scanning technology as part of the software as a whole package ready to be used. This would mean out of the box phenotypic analysis of the fruits, with advanced analysis and in-depth phenotypic traits extraction.
- Breaching the gap between phenotyping and genotyping work, by also providing analysis of the genome and combining both as a comprehensible report for the biologists.

Both directions would provide huge advantages to biologists and breeders, accelerating the production and selection of fruits adapted to the market or climate demands. For complete results and method explanations, it can be found in our publication [3].

Knowledge and Technology Transfer

- Paper entitled "*3D shape sensing and deep learning-based segmentation of Strawberries*" submitted at Computers and Electronics in Agriculture in November 2020 and accepted in July 2021.
- Paper entitled "*Gaussian map predictions for 3D surface feature localisation and counting*" submitted at BMVC in June 2021 and accepted in October 2021. It tackles the task of counting achenes over the surface of 3D strawberries.
- 06/05/2021: I partook in the LAR (Lincoln Agri-Robotic group) bi-weekly meeting where I presented my work on achene counting.
- 7/07/2021: Presented my third-year work at the CTP summer event as part of my founding.

References

[1] Bo Li Joe Q. He, Richard J. Harrison. A novel 3d imaging system for strawberry phenotyping. In Plant Methods, 2017

[2] A. Durand-Petiteville, D. Sadowski, and S. Vougioukas, “A strawberry database: Geometric properties, images and 3d scans,” 2018.

[3] Justin Le Louedec, Grzegorz Cielniak, Gaussian map predictions for 3D surface feature localisation and counting, BMVC, 2021

[4] Evaluation of 3D Vision Systems for Detection of Small Objects in Agricultural Environments, J Le Louëdec, B Li, G Cielniak,15th International Conference on Computer Vision Theory and Application

[5] 3D shape sensing and deep learning-based segmentation of strawberries, J Le Louëdec, G Cielniak, Computers and Electronics in Agriculture 190, 106374

