Comparison of 3D Imaging Technologies for Wheat Phenotyping

Imran Mohamed and Richard Dudley
National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, United Kingdom

Email: imran.mohamed@npl.co.uk

Abstract The in-field measurement of phenotypes or traits of wheat such as ear size is important data for use in the development of newer wheat varieties. The data is currently gathered manually from hundreds of test plots by random sampling of the wheat within each plot. To improve the data quality and data collection speed, we investigate and compare the use three different 3D imaging technologies: multistereo imaging, time-of-flight and structured light laser scanning to produce point clouds of a wheat plant in-situ. Measurements of the wheat plant’s ear is made from the generated point clouds.

1. Introduction

Plant phenotyping is the quantification of a plant’s physical traits, genetics and ontogeny. For wheat, key phenotypes include yield, ear size and disease resistance [1]. Phenotype data is used to guide cross-breeding programmes for new varieties and an efficient process requires large phenotype data sets, recorded in a quantifiable and accurate way [2]. Phenotype data ideally should take place in-situ on outdoor plots with variations in locations, soil type, drainage etc.

Capturing data for just wheat ear size, currently relies on manual sampling with a ruler [3]. Measurements are repeated on hundreds of plots in the same field, each growing different wheat varieties. Data collection is time-consuming, and the quality of the data limited by the sample size within each plot, creating a bottleneck in capacity. 3D imaging of field grown crops plots expands the quantity of data that can be collected, is faster than making measurement manually and enables more post processing for additional plants trait information. Measurement data on ear size is obtained by shape fitting to 3D point clouds, a virtual representation of a scene, created by commercial imaging hardware [4] and software [5][6].

In this paper we present trials of the three of the most promising imaging technologies for field phenotyping deployment, multi-stereo imaging, Time of Flight cameras (ToF) and Structured Light Laser Scanning (SLLS). All the technologies have been demonstrated for indoor plant trait analysis [7], [8] but some of their application outdoors is less well reported.

2. Imaging Technologies

Multi-stereo imaging uses multiple images of a scene taken from multiple positions. Using stereo matching algorithms, the images are analysed with information about the cameras’ positions and internal parameters such as focal length. Pixels in captured images are assigned an x,y,z location using stereo-matching algorithms resulting in a point cloud representation of the image. Stereo matching algorithms
include those found in commercial software such as HALCON [5] or open source libraries such as Point Cloud Library [6]. In this study the multigrid stereo matching algorithm implemented in HALCON was utilised.

A time-of-flight camera is more comparable with radar than conventional cameras. TOFs use pulses of near-infrared (NIR) light to illuminate a scene, with pulse lengths in the order of 10 ns. A high-speed CCD records the reflected NIR images and the time of arrival, and a distance can be calculated. Each pixel on the CCD sensors thus records intensity and distance enabling a point cloud of the scene to be produced in real time at typically 20 fps and with a resolution of 640×480 pixels.

SLLS is the latest variation on laser projection scanning and uses a moving pattern of stripes projected onto a scene using a high-brightness laser. A CCD camera captures the changing patterns on the scene and converts the distortions around surfaces directly into a point cloud. From the observed distortions it is possible to calculate the 3D structure of the scene and convert this data into a point cloud.

3. Image Capture

Obtaining 3D images of wheat outdoors is challenging. Variable lighting conditions and wind influence the quality of the image and/or the ability of the instrument to acquire an image. At NPL we constructed a 2 x 2 m wheat trial plot enclosed by two linear motion rails and two A-frame camera mounts. The rails were placed on the north and south side of the plot to allow the A-frames to move in an east-west direction, which we define as the x-axis, Figure 1.

Our study initially focussed on imaging a single wheat plant to validate and calibrate imager operation. The wheat plant was chosen due to its location in the less densely populated end of the plot which allowed easier imaging without occlusion from neighbouring wheat plants. The imaging instruments were mounted onto the A-frame and images captured during the afternoon, with ambient light levels varying between 3000 to 4000 lux. CloudCompare [9] was used to view and post-process measurements from the produced point clouds.

For multi-stereo imaging, four 2.3-megapixel monochrome Basler cameras were used to capture images of the wheat plant. Prior to mounting on to the frame, the cameras’ internal parameters were calculated using the calibration routine in HALCON. The routine involves the use of a 32 cm × 24 cm calibration plate consisting of 5 mm white circles arranged hexagonally on a black background, with the centre to centre separation of each circle being 1 cm. Images of the calibration plate placed in a variety of positions and orientations are taken. By comparing the size and position of the dots seen across in the camera’s field of view from what is expected the software calculates the: focal length, radial lens
distortion parameters, decentring lens distortions, the centre of the radial lens distortion, and sensor’s physical dimension.

The same calibration plate used for camera calibration was placed on the southern side of the wheat and was used to calculate the external camera parameters of position and orientation. Figure 2 shows the imaging set up during assembly of the experiment with one pair of monochrome cameras mounted to the southern A-frame. The remaining pair of monochrome cameras were mounted on the northern A-frame. The lens to lens centre distance between each camera pair was 10 cm. The cameras were positioned so that all four were able to see the wheat plant and calibration plate.

Figure 2: Imaging setup with pair of monochrome cameras and ToF camera attached to A-frame on southern side (left in the figure) of plot. Also visible is the calibration plate used for the multistereo imaging placed on the southern side of the wheat plant being imaged.

With an exposure time of 5 ms, images from the four cameras were captured, then the two A-frames moved approximately 5 cm and capture repeated. This was carried out for as long as the calibration plate was visible from all the four cameras, example frames are shown in Figure 3. The captured images were processed using the multigrid stereo matching algorithm implemented in HALCON to produce a point cloud.

Figure 3: The view of the wheat plant under investigation and calibration plate from the four monochrome cameras.
The larger leaves and stems structures were recreated well by the algorithm as seen in Figure 4. However, wheat ears often were not well-formed image focus, crop movements and algorithm pixel-correlation challenges within the captured images. The greater the number of input images taken from different positions and orientations improve the quality point cloud at the expense of computational and capture time. The point cloud of Figure also contains significant noise from structures that were not fully formed by the algorithm. Simple denoising techniques such as CloudCompare’s Statistical Outlier Removal filter can improve the final quality of the point cloud but does at this stage require manual optimisation.

For Time of Flight trials, a Basler ToF camera was mounted on the southern A-frame at the same time as the monochrome camera pair shown in Figure 2. The ToF camera’s default processing mode, High Dynamic Range (HDR), was used which allows the camera to take both short (4 ms) and long (20 ms) exposures and combine them into a single image. This allows the camera to achieve a more even NIR illumination across the scene which in turn allows for more accurate distance measurements.

The ToF camera produced the point cloud shown in Figure 5 with the structure of the wheat plant clearly visible for most of the stems and leaves, but not all the ears are visible. In contrast the larger structures around the wheat plant such as the calibration plate, the imaging frame and the ground itself are visible highlighting the ToF cameras low resolution and inability to resolve the smaller structures of the wheat plant.
The final imaging technology used a structured light laser scanner (SLLS), the Photoneo PhoXi 3D. Due to its larger size it was mounted separately from the monochrome and ToF cameras. The scanners longer acquisition time of 1 to 2 seconds, compared to the 10 ms of the monochrome and ToF cameras, meant more care was required to ensure image capture was taken when the wheat was stationary.

The structured light laser scanner, having a higher resolution, was able to produce point clouds of the wheat, Figure 6, including stem, leaves, ears and even florets. Less of the surroundings are seen in the point cloud due to the smaller scanning volume.

4. Imaging Technology Comparisons
Comparing the three imaging technologies, the SLLS produced the best quality point cloud out of the three presented technologies. It captured the stems, leaves and ears in high resolution and minimal noise. Multistereo imaging was next best due to it also being able to recreate most of the wheat plant’s structure,
albeit with noise. ToF performed the worst, only being able to discern the main structure but without enough detail to be of use.

Based on these initial results, multistereo imaging’s advantages compared to ToF and SLLS are its ability to produce point clouds at low cost (each monochrome camera cost in the order of GBP 100) and function under direct sunlight. An ability to obtain images with exposure times in the order of hundreds of milliseconds means motion blur caused by wind can be minimised without the use of wind shield. Being able to “freeze” any motion in this way will also be advantages should the technique need to be used from a moving platform. Disadvantage of multistereo imaging is the computing time and resources required to process the input images into a point cloud. The presented point cloud required over 20 seconds for the stereo matching algorithm to complete on an Intel i7-7500U processor, reaching a peak RAM usage of 1.7 GB. This would increase as the imaging volume increased (e.g. imaging a row of wheat plants versus a single wheat plant) and the number of input images (e.g. to capture more wheat plants or to improve the point cloud of a single wheat plant). Setup time was longer than ToF and SLLS due to the number of monochrome cameras that required mounting on to the imaging frame.

The ToF camera, despite not producing a usable point cloud, has the advantage that it can produce a point cloud in real-time at up to 20 frames per second rather than requiring offline processing of images. Exposure times can be reduced to 300 μs which allows for mitigation against motion blur of the wheat plants caused by light wind although the monochrome cameras can reach exposure times as low as 40 μs which allow for even less motion blur provided there is sufficient lighting. Its cost is in the order of GBP 1000. The two primary disadvantages are the camera’s low resolution which impeded it from resolving as much wheat structure as the other technologies achieved and its inability to work under strong or direct sunlight (the camera specifications state a maximum ambient light level of 15 000 lux). In future uses these effects will be mitigated by moving the ToF camera closer to the scan subject and using a screen to block excess ambient light.

The advantage of the SLLS is the high quality of the produced point cloud, short setup time and being able to produce a point cloud directly. The disadvantages to using the SLLS are its high cost (over GBP 10 000), an inability to work under direct sunlight and acquisition times in the order of seconds which make it susceptible to wheat movement caused by wind. A screen could be used to limit the effects of sunlight, as can performing the scan at night or when light levels are low. The screen would also mitigate effects of wind during the seconds long image capture, but only if the SLLS is stationary. Using SLLS to phenotype large fields from a continuously moving imaging platform would not work.

### 4.1. Ear Height Measurement

Measurements were only carried out using the SLLS produced point cloud because it was the only one where almost all the wheat ear’s height was recreated. Manual measurement on the wheat plant of interest was carried out with a tape measure and a virtual point cloud measurement was carried out using CloudCompare (Figure 7). The manual measurement on the left wheat ear in Figure 7 was 83 mm in height from ear base to the top of the spike. The point cloud measurement taken from the lowest and highest visible wheat ear points came to 82.4 mm. The right wheat ear in Figure 7 came to 86.7 mm when measured manually and 81.7 mm when measured from the point cloud, a lower value caused by the bottom most floret and the stem not being imaged in the point cloud leading to an under measurement.
Figure 7: Measurement of the wheat ear of interest in the field (left) and with the SLLS produced point cloud (right).

This demonstrates that measurements of wheat ear height carried out with point clouds can be as accurate as those obtained manually in the field if the point cloud closely reproduces the structure of the wheat ear. To take the method further, more than a single wheat plant needs to be imaged and measured. With greater number of wheat ears in a point cloud this also necessitates a way to automate the detection and measurement of wheat ears in a point cloud. An expanded measurement campaign is planned for the next growing season with the intent of producing point cloud based measurements of more of the plot.

5. Conclusions
An investigation into the use of multistereo imaging, ToF and SLLS to produce point clouds for in-field dimensional phenotyping was completed. The preliminary results based on the imaging of a single wheat plant show that multistereo imaging and SLLS are both capable of producing point clouds that show the structure of the wheat plant. However only the SLLS point cloud was detailed enough to obtain a measurement of the ear height. Due to the SLLS high cost and the advantages possible with it, suggestions on how improvements to the point cloud produced via multistereo imaging were given.

Acknowledgements
This work is supported by the UK government’s Department of Business, Energy and Industrial Strategy (BEIS).

References
[1] Walter A, Liebisch F and Hund A 2015 Plant phenotyping: from bean weighing to image analysis Plant Methods 11 14
[2] Aruas J L and Cairns J E 2014 Field high-throughput phenotyping: the new crop breeding frontier Trends Plant Sci. 19 52–61
[3] Torres A and Pietragalla J 2012 Crop morphological traits Physiological breeding ii: a field guide to wheat phenotyping eds A Pask et al (Mexico, D.F.: CIMMYT) p 106
[4] Photoneo. https://www.photoneo.com/
[5] HALCON. MVTec Software GmbH
[6] Rusu R B and Cousins S 2011 3D is here: Point Cloud Library (PCL) IEEE ICRA
[7] Rose J C, Paulus S and Kuhlmann H 2015 Accuracy analysis of a multi-view stereo approach for phenotyping of tomato plants at the organ level \textit{Sensors} \textbf{15} 9651–65

[8] Wang Y, Wen W, Wu S, Wang C, Yu Z, Guo X and Zhao C 2019 Maize plant phenotyping: comparing 3D laser scanning, multi-view stereo reconstruction, and 3D digitizing estimates \textit{Remote Sens.} \textbf{11} 63

[9] CloudCompare. http://www.cloudcompare.org/