Computers and Electronics in Agriculture 104 (2014) 84–92

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Simulation of image acquisition in machine vision dedicated to seedling elongation to validate image processing root segmentation algorithms

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ARTICLE INFO

Article history:
Received 19 October 2013
Received in revised form 5 March 2014
Accepted 4 April 2014

Keywords:
Machine vision
Numerical validation
Image processing
Simulation
Seedlings

ABSTRACT

This article proposes a methodology for the numerical validation of image processing algorithms dedicated to the segmentation of roots of plants with machine vision. A simulator of plant growth is coupled to a simulator of the image acquisition to generate images of simulated plants associated with a known synthetic ground truth. The simulator incorporates parameters of the plant and parameters of the experimental imaging system acquiring the images. This opens the possibility to assess the impact of these parameters on the performance of any segmentation algorithm on unlimited populations of virtual plants. Illustrations of this approach are given for the segmentation in 2D of seedlings with several classical algorithms and also with an algorithm of recent introduction. The presented results can be easily extended to 3D and are therefore also appropriate for other segmentation algorithms of roots with imaging modalities adapted for 3D root tracking like X-ray or MRI.

1. Introduction

Machine vision applied to plant science is a field of growing interest (see for instance Gwo et al., 2013; Chéné et al., 2012; Belin et al., 2013, for recent studies in this journal). This is linked to the recent need in plant science for automated contactless high throughput measurement methods required to investigate the phenotype of large populations of plants in relation to their genotype under given environmental conditions (Furbank and Tester, 2011). The diversity of plant species together with the different possible observations scales of observation (cell, seed, seedling, meristem, leaf, branching structure, fruit, entire plant, canopy) open the way for the design of a variety of imaging systems dedicated to plant phenotyping (Gupta and Ibakari, 2014). However, certain problems are common throughout plant science such as the study of the growth of the shoot and roots (see Spalding and Miller, 2013, for a recent review), or the recognition of species from their leaves (Du et al., 2007; Soares and Jacobs, 2013; Gwo et al., 2013). And plant models like *Arabidopsis thaliana* or *Medicago truncatula* serve as references for the whole community of plant scientists. This helps define both the scale of observation and constraints for the design of automated imaging systems based on machine vision. Efficient practices in terms of light, choice of optics and imaging technology are being progressively disseminated thanks to the recent development of a network of phenotyping centers at an international scale (Fiorani et al., 2012). Common geometries of imaging systems have been developed by separate research groups for similar problems. In the case of seedling growth, for instance, the imaging system in Subramanian et al. (2013), French et al. (2009) and Benoit et al. (2013) are similar in terms of geometry. On the other hand, a wide range of image processing algorithms (Wang et al., 2009; Kimura and Yamasaki, 2003; Subramanian et al., 2013; French et al., 2009; Benoit et al., 2013) have been proposed and are now referenced on the Web (Lobet et al., 2013), and the performance of these algorithms has not yet been compared. An important reason for the lack of comparison is that the validation of image processing algorithms in plant science requires comparison with ground truth. This ground truth can be manually established by experts. A drawback of this approach is the need to consider inter and intra experts variability when comparing numerical results. Another possible approach would be to build some physical phantoms to establish a synthetic ground truth. One can imagine rigid 3D structures made of wood or plastic that mimic the spatial architecture of plants. This would be possible for adult plants with solid stems but is less feasible for young seedlings. To enable the comparison of the various approaches in terms of image processing, a useful contribution is therefore the numerical simulation. *In silico* experimentation on

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http://dx.doi.org/10.1016/j.compag.2014.04.001
0168-1699/

simulated plants makes it possible to test with unlimited populations of plants the impact of physical parameters of the simulated acquisition system on the accuracy of the information extracted, or the expected performance of image processing algorithms for given tasks. To our knowledge, numerical simulation environments of plant growth together with image acquisition have only been so far developed at the scale of the entire plant for field imaging on assemblies of plants under the OpenAlea software (see Pradal et al., 2008, for an introduction). Here for the first time, we extend this approach to the monitoring of the growth of seedlings. The remainder of the paper is organized as follows. We start with the description of the imaging system dedicated to seedling elongation we intend to simulate. We then detail the simulator of seedling elongation and image acquisition. After, we demonstrate the interest of our simulator by testing a recently introduced algorithm to separate overlapping seedlings. Finally we conclude and discuss the potentiality of this simulation approach for other imaging modalities and other informational tasks in plant science imaging.

2. Image acquisition

The imaging system we use as a generic reference in this paper is composed of a gray level camera and a backlight constituted with green light. Seeds are placed in a Petri dish containing a transparent nutrient (agar gel). The Petri dish is placed between the camera and the backlight. Seeds are oriented so as to respect the vertical gravitropism of plants. The backlight mode is chosen to prevent specular reflection on the cover of the Petri dish without losing information on the external shape of the plants. The imaging system used here is dedicated to heterotrophic growth corresponding to the stage where seeds and seedlings develop in the soil. To mimic obscurity as in the soil, we use a green light, just for image capture. Green was chosen because it corresponds to a minimum of absorption by the different photochromes in plants (Smith, 2000). To limit the influence of light on the development of plants and on experimental conditions (apparition of drops of water inside the cover of the Petri dish, local heating that would encourage the development of fungi, etc.), the light was switched on only during image acquisition. This imaging system, depicted in Fig. 1, allows the acquisition of sequences of images similar to those shown in Fig. 2 which are useful to characterize the continuous development of each seedling from time zero (when the dry seed is placed on the agar gel) at an acquisition frequency determined by the user depending on the time scales being investigated. We tested this imaging system on different species including the model plant *Medicago truncatula*, rape, sugar beet, and wheat as shown in Fig. 3. In the sequel, we propose to simulate the image acquisition step of this imaging system so as to serve as a general framework for the validation of any image processing algorithm dedicated to the extraction of information from a sequence of images produced by such imaging systems.

3. Simulator

3.1. Description

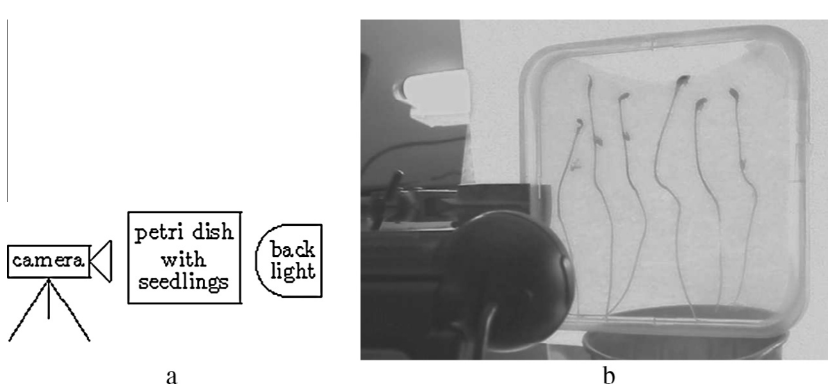
Here we present the numerical validation method of algorithms for image processing of roots. This numerical method, described in Fig. 4 is composed of three stages:

- Stage 1: A seedling simulator establishes a ground truth.
- Stage 2: An acquired image simulator constitutes the images to be processed by the algorithm being tested.
- Stage 3: A comparison between the ground truth and the results produced by the algorithm being tested.

The principal of this numerical validation method can be applied to test any image processing algorithm. In this report, we use seedling segmentation as an illustration. The aim is therefore to objectively assess the performance of good and bad classifications of pixels between the background and the seedlings after a segmentation algorithm.

3.2. Seedling simulator

The seedling simulator is based on the L-system process described in Leitner et al. (2010). As illustrated in Fig. 5, the simulator in Leitner et al. (2010) enables the accelerated elaboration of root systems simulated in 3D without information on root width. We bring two upgrades on this algorithm. The first is the generation of spherical seeds at initial time. The second is the addition of an information on root width. The parameters used by this simulator are the size of the seeds, the width of the roots, the number of roots per seedling and the duration of the simulation. The seedling simulator in Leitner et al. (2010) generates root systems in 3D. The camera used in the imaging system in Fig. 1 does not access information on depth. We have therefore decided to build a plant simulator that generates a synthetic ground truth in two dimensions similar to the one shown in Fig. 6. This adaptation consists in projecting the synthetic ground truth in 3D onto a vertical plane. The synthetic ground truth produced by this seedling simulator is recorded as binary image with zero in seedlings and one in the background. The elongation rate of the root is a fixed parameter in Leitner et al. (2010). We did not modify it since at the scale of a Petri dish this produces sequences of simulated root systems with elongation rates similar to the one observed in real



a b

Fig. 1. The imaging system simulated in this report. Panel (a) schematic description and panel (b) lateral view of the setup. The camera is a Logitech C9600 webcam equipped with Zeiss optics and a CCD sensor with 1500 by 1200 pixels and a 8-bit resolution. The green light is produced by Luxeon LED. Most of the spectrum distribution of the LED is centered on 525 nm.