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Research Paper

In-field automatic observation of wheat heading stage using computer vision

Yanjun Zhu, Zhiguo Cao, Hao Lu, Yanan Li, Yang Xiao*

National Key Laboratory of Sci. and Tech. on Multi-Spectral Information Processing, School of Automation, Huazhong University of Sci. and Tech., Wuhan, PR China

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Growth stage information is an important factor for precision agriculture. It provides accurate evidence for agricultural management as well as early evaluation of yield. However, the observation of critical growth stages mainly relies on manual labour at present. This has some limitations because it is time-consuming, discontinuous and non-objective. Computer vision technology can help to alleviate these difficulties when monitoring growth status. This paper describes a novel automatic observation system for wheat heading stage based on computer vision. Images compliant with statistical requirements are taken in natural conditions where illumination changes frequently. Wheat plants with low spatial resolution overlap substantially, which increases observational difficulties. To adapt to the complex environment, a two-step coarse-to-fine wheat ear detection mechanism is proposed. In the coarse-detection step, machine learning technology is used to emphasise the candidate ear regions. In the fine-detection step, non-ear areas are eliminated through higher-level features. For that purpose, scale-invariant feature transform (SIFT) is densely extracted as the low-level visual descriptor, then Fisher vector (FV) encoding is employed to generate the mid-level representation. Based on three consecutive year's data of seven image sequences, a series of experiments are conducted to demonstrate the effectiveness and robustness of our proposition. Experimental results show that the proposed method significantly outperforms other existing methods with an average value of absolute error of 1.14 days on the test dataset. The results indicate that automatic observation is quite acceptable compared to manual observations.

1. Introduction

Information about growth stages is an important factor for precision agriculture. It can help to analyse the relationship between field management and agrometeorological conditions so as to provide effective agricultural guidance (Bannayan & Sanjani, 2011; Jannoura, Brinkmann, Uteau, Bruns, & Joergensen, 2015). Besides, knowledge of the growth stages of crops allows farmers to perform field operations properly and in a timely fashion. The optimum timing of fertiliser, irrigation, herbicide and insecticide applications are best determined by crop growth stage rather than calendar date (Cook & Veseth, 1991). Among the crops, wheat is an indispensable cereal grain cultivated worldwide. A sound understanding of its growth status and development is an

* Corresponding author.
E-mail addresses: yjzhu@hust.edu.cn (Y. Zhu), zgcao@hust.edu.cn (Z. Cao), poppinace@hust.edu.cn (H. Lu), yananli@hust.edu.cn (Y. Li), Yang_Xiao@hust.edu.cn (Y. Xiao).
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essential element of efficient, economical wheat management systems. Heading stage, extending from the time of emergence of the tip of the head from the flag leaf sheath to when the head has completely emerged but has not yet started to flower (Administration, 1993), is one of the most important periods in wheat crop management. Growers need to pay attention to the observation of heading stage in order to make adequate management decisions.

However, growth stage information mainly depends on labour-intensive manual observation at present. It is a time-consuming procedure since observations need to be carried out every two days, even every day at key stages (Administration, 1993). The manual approach is not objective because observers may have different understanding of the same criterion, which may result in errors. In addition, the manual approach may damage crops when technicians come into fields to observe. Another way to acquire growth stage information is extracting from other indicators. Some researchers have studied the relationship between crop growth stage and thermal time, and thus formulated models of phasic developments based on temperature (Angus, Mackenzie, Morton, & Schafer, 1981). As an indirect regression model, the use of thermal time depends on the linearity of the response to temperature and a knowledge of the base temperature. However, there are many other environmental factors that can influence the prediction of growth stages, such as photoperiod, vernalisation, drought, nutrition, solar radiation, etc.

Methods based on computer vision can be effective for monitoring growth status because of their low-cost, intuitive nature and non-contact features. Computer vision greatly facilitates the development of precision agriculture on observing, measuring and responding to inter and intra-field variability in crops. There are numerous applications of computer vision technology in agricultural automation, such as yield estimation (Gong, Yu, He, & Qiu, 2013; Payne, Walsh, Subedi, & Jarvis, 2013), disease detection (Polder, van der Heijden, van Doorn, & Baltissen, 2014; Pourreza, Lee, Etxeberria, & Banerjee, 2015), weeds identification (Guerrero, Pajares, Montalvo, Romeo, & Guijarro, 2012; Tellaeche, Burgos-Artizzu, Pajares, & Ribeiro, 2008) and quality control (Valiente-González, Andreu-García, Potter, & Rodas-Jordá, 2014). Continuous monitoring of crop status (Sakamoto et al., 2012; Vega, Ramírez, Saiz, & Rosúa, 2015; Yeh et al., 2014) is one of them. There are also many applications for wheat, such as counting wheat ears after milk stage (Cointault et al., 2012; Liu et al., 2014), weeds identification (Tellaeche, Pajares, Burgos-Artizzu, & Ribeiro, 2011; Zhang & Chaisattapagon, 1995), nutritional status estimation (Sun, Berman, Coward, & Osborne, 2007), disease and pest monitoring (Cheng, Hu, & Zhang, 2007; Zayas & Flinn, 1998). Recently, research on automatic observation of growth stage has made some progress. Wang, Cao, Bai, Yu, and Li (2013) described an automatic detection method for emergence stage of wheat through image segmentation. Yu et al. (2013) detected emergence stage and three-leaf stage of maize using AP-HI model, and Ye, Cao, and Yu (2013) proposed an approach on HOG/SVM framework with spatio-temporal saliency map to detect tasselling stage of maize. Fang, Chang, Zhai, and Wang (2014) adopted HI colour segmentation method to recognise rape emergence stage following Yu et al. (2013). Nevertheless, little research has been conducted on ground-based observation of wheat heading stage. The above mentioned methods can detect objects whose colour is quite different from the background, but are not applicable in this task since more challenges emerge when observing heading stage in the wheat field. Firstly, unlike emerging plants showing a striking contrast with the background, the new ears are almost indistinguishable since they are nearly the same colour as the leaves. Secondly, due to the statistical requirements (Administration, 1993), the cameras need to be installed 5 m from the ground to collect enough samples. Therefore, the newly emerging ears only occupy a small number of pixels in the whole image. It is quite a challenge to emerging ears under low spatial resolution with a fixed camera shooting angle. Thirdly, image colour varies significantly as natural lighting conditions change. And except for the crop, some interference also exists in the image, such as soil, shadows, straw, pipes, and other equipment. Therefore, an emerging ear detection algorithm robust enough to both outdoor light conditions and complex environments is needed.

Our goal is to explore the feasibility of automatically observing wheat heading stage based on computer vision. In this paper we proposed a novel automatic observation system for wheat heading stage, which is efficient, continuous and non-destructive. A schematic diagram of the proposed method is shown in Fig. 1. Heading stage, a sensitive stage of development, shows obvious changes in plant ontogeny, with developing ears appearing. The proposed method directly detects newly emerging ears in pictures since indirect ways are easily effected by other indicators. The main contributions of this work can be summarised as follows:

- We propose a novel automatic observing system for wheat heading stage using computer vision technology;
- A novel coarse-to-fine wheat ear detection mechanism is applied for observing heading stage;
- We characterise wheat with the mid-level representation to eliminate non-ear areas.

This work may benefit farming management and yield estimation. And it may be used to provide helpful feedback information for agricultural robots.

The remainder of the article is organised as follows. In Section 2.1, we briefly introduce the experimental field and image acquisition device in this study. Section 2.2 shows difficulties and challenges of automatic observation. The overall automatic observation strategy compared with the manual approach is introduced in Section 2.3. The two detection steps, coarse-detection and fine-detection, are detailed respectively in Sections 2.4 and 2.5. A series of experiments conducted to demonstrate the effectiveness of the proposed automatic observation system are shown in Section 3. Finally, we draw conclusions and discuss possible future work in Section 4.

2. Materials and methods

2.1. *Experimental field and image acquisition*

In this study, the three experimental fields with a total area of 670 m^2 are located in Taian, Shandong province, China