Monitoring the growth status variability in Onion (*Allium cepa*) and Garlic (*Allium sativum*) with RGB and multi-spectral UAV remote sensing imagery

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Abstract

Traditional ways of monitoring the growth status of crops in the early and middle seasons rely on manual methods involving sampling and laboratory analysis, which are time-consuming and costly. In addition, a diagnostic method based on human eyes has a limitation in identifying invisible symptoms of crops with internal defects. Since UAV remote sensing allows fast and detailed mapping of crop growth due to the ability to obtain high-resolution images flying at low altitudes, an UAV platform is appropriate for collecting the images of onion and garlic vegetables with relatively small leaf areas in the early season. In this study, an experimental plot was prepared growing garlics and onions based on different planting timings and fertilizer rates, and the RGB and Multi-spectral UAV images of the onions and garlics on a spatial resolution of < 1 cm were collected to build relationships between the UAV images and various biophysical parameters of garlic and onion. Two spectral indices, i.e., vegetation fraction and 3D-based height estimation, obtained with a RGB camera were used to estimate the fresh weights of garlic and onion, and the nutritional status of the crops was studied based on NDVIs calculated using multi-spectral imagery obtained with a multi-spectral camera in order to investigate the potential for variable-rate fertilizer application. Image pre-processing techniques and crop segmentation methods for effectively extracting the images of garlic and onion were developed. The multi-linear regression models to estimate the average fresh weights of onions and garlics built based on RGB images showed the coefficients of determination>0.9 and >0.7 for onion and garlic, respectively. However, there was little effect of fertilizer application rates on the NDVIs in the early stage.

Background

Biophysical parameter estimation in the early and middle growth stage is crucial for yield prediction of crops and high quality production of crops by taking appropriate actions. Precision cultivation management techniques are also important for the growth stage of crop and the conditions of the agricultural field (Mulla, 2013). Remote sensing technology, which can monitor the agricultural fields using aerial platforms, can be used as a crop cultivation management method to determine the amount of agricultural inputs, such as agrochemicals and fertilizers based on such non-invasive monitoring of growth status of the crops. Unmanned Aerial Vehicles (UAVs) have been commonly used for low-altitude and high resolution-based remote sensing applications in precision agriculture, due to several advantages such as its versatile, light-weight, and low operational costs (Hunt et al., 2010). Especially, UAVs have been successfully used to assess the vegetation status of crops and predict its yields because the operating flexibility of vertical taking off and landing platforms with various image sensors make it easy to fly over agricultural fields acquiring aerial images with high spatial and temporal resolutions (Torres-Sánchez et al., 2014).

Onion (*Allium cepa*) and garlic (*Allium sativum*) are ones of the most consumed vegetables in Korea. Since onion and garlic vegetables have small and sharp leaf areas in the early and middle growth stages, the UAV platform flying at low altitudes is appropriate to observe their growth status on a finer spatial resolution. The acquired high-resolution UAV images can help farmers to evaluate the status of onion and garlic growth. In addition, it could provide useful information about canopy greenness, leaf area, water stress estimation and various geographic conditions such as crop areas, crop surface models (CSMs) and depth contour lines (Zhang and Kovacs, 2012). However, when using the UAV technique for monitoring the growth of the onion and garlic, it is difficult to effectively extract their images from the background due to their own geometric characteristics of thin and small leaves as well as an illumination interference by plastic mulching films commonly used for suppressing weeds.

In this study, statistical models to estimate the growth of garlic and onion were developed by relating the RGB and multi-spectral imagery to various biophysical indexes. A test plot was prepared growing onion and garlic plants under different planting timing and fertilizer application treatments. Images of the RGB and NIR were taken using a multi-rotor UAV flying over the test plot at an altitude of 10 m on a two-week interval.

Multiple linear regression models were developed using the index of vegetation fraction and DSM-based height estimate using the images of the garlic and onion vegetables obtained with a RGB camera as predictor variables and their fresh weights as response variables. Various image pre-processing techniques including radiometric calibration and crop segmentation methods for effectively extracting the images of garlic and onion from the field in the presence of soil and plastic mulch were studied. Ultimately, the goal of this study was to develop mathematical models to quantitatively estimate biophysical indices, such as fresh weight, leaf length, and leaf area, based on UAV-based RGB imagery, which can be employed in a real-time monitoring system for onion and garlic vegetables grown in fields. As one additional task, the nutritional status of garlic and onion crops grown based on different fertilizer application rates was studied to investigate the potential of using NDVIs obtained using multi-spectral imagery for variable rate application of fertilizers.

Methods

Test site and UAV-based image collection

UAV remote sensing was conducted in a garlic and onion test field of the National Institute of Crop Science, Rural Development Administration, in 2016. The garlic field was located in 199, Muan-ro, Muan gun, Jeollanam-do, Republic of Korea (267448E, 3872370N, UTM zone 52N). The size of the garlic and onion field was 1044 m^2 and row spacing was set to 0.65 m. The test bed was constructed by varying the number of fertilizer application (0, 1, 2 and 3 times) for side-dressing to investigate the effect of fertilizer application rates on its growth status. A hexa-rotor airframe model (F550, DJI, China) was used as the aerial platform to acquire images. The UAV flight was manually controlled using an R/C controller (NAZA M Lite, DJI, China) on the ground through a 2.4 GHz radio frequency communication. With the Mission Planner software, the flight path was designated for the UAV to perform user-defined waypoint flights above the test field. As the image sensor, a RGB digital camera (Canon Powershot S110, Canon, Japan) and a Multi-spectral camera (Sequoia, Parrot, France) consisting of Red (660 BP 40), Green (550 BP 40), Red edge (735 BP 10) and NIR (790 BP 40) bands were attached to the UAV. The RGB camera resolution was set to be 12 megapixels to achieve a ground resolution of approximately 0.0037 m/pixel at a flight altitude of 10 m while the multi-spectral camera resolution was 0.0095 m/pixel. Flight missions were performed on four days during the early and middle growth seasons, referring to BBCH scale (bulb vegetable) of 204, 400, 406 and 408 (Feller et al., 1995). In each mission, aerial images were captured with an intended overlap of 80% to ensure image redundancy. The overview of the flight missions is given in Table 1.

Table 1. Overview of flight missions performed including BBCH scales and the number of images taken, flight altitude, image ground resolution, mission time, illumination and the average velocity of wind.

Date	BBCH code		Images(count)		Scheduled Altitude(m)	Time	Illumination	Wind
	Onion	Garlic	RGB	Multi				(m/s)
17/03/24	204	204	261	1998	10	11-12 am	Clear sky	3.2
17/04/04	400	400	209	1944	10	11-12 am	Cloudy	3.4
17/04/14	406	406	204	1772	10	11-12 am	Cloudy	5.2
17/04/28	408	408	205	1952	10	11-12 am	Clear sky	3.1

Image processing and vegetation index calculation

Imagery and corresponding UAV flight information were used to generate each ortho-image of the entire garlic field with the Pix4D mapper software (Pix4D, Switzerland). All selected images were aligned, mosaicked and geo-referenced using functions of the software Structure from Motion algorithm. Based on the corresponding and initial GNSS image locations, the SfM algorithm reconstructed the 3D scene forming four ortho-images of the entire garlic and onion field.

A radiometric calibration method is the prerequisite in digital image processing to remove the noise and offset from the sensor, especially when imagery is acquired for biophysical analysis, change detection across date, and comparison across sensor. In this study, the empirical line method (Wang and Myint, 2015) was used to calibrate remotely sensed images of digital number to surface reflectance based on our reference tarps. Spectral response curves of the RGB and multi-spectral cameras obtained from a preliminary experiment based on the reflectance of reference tarps were applied to all of the UAV images taken to ensure that the images could be compensated for a change in reflectance between the images obtained under different sunlight conditions.

Crop segmentation was performed prior to the calculation of vegetation fraction of ROI (Region of Interest). Especially, in Korea since plastic films were commonly used to suppress weed growth and protect crops from cold weather, it was necessary to extract only crops from the background consisting of a mixture of soil, the plastic film and other residues. As shown in Figure 1, from the preliminary analysis of distributions in RGB, HSV and CIE L*a*b* color space, it was found that a* band in the CIE L*a*b* color space was the optimal band for separating crops from soil and plastic film when using the Otsu's threshold method. The overlap region between crop, soil and plastic film was not wide in a* band, thereby providing the threshold selection for Otsu's threshold method. As a result, only crop pixels were successfully extracted by applying the Otsu's threshold using the a* band as shown in Figure 2. The image processing of contrast adjustment and morphological operations were also conducted to increase the accuracy of the crop segmentation. Before calculating the vegetation fraction, eighty images (1 m x 1 m) were sampled and compared with the results obtained by manual segmentation to evaluate how well the crop segmentation was done. The segmentation error calculated was an average of 11.39%, which was better than that obtained with the ExG-Otsu's threshold combination used in other previous studies.

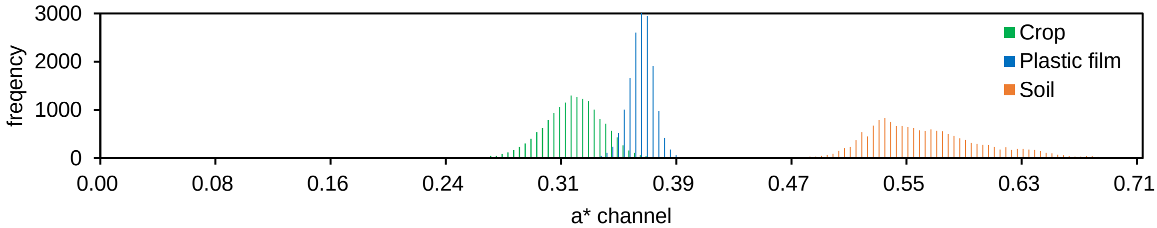

Figure 1. The histogram of a* band in CIE L*a*b* color space for observing the distribution of crops, plastic films and soil

The optimal ROI of 1 m x 1 m was selected to represent the average value of the coverage and height for the each treatment region (Figure 2). That is, vegetation fractions of ROI in each treatment (4 treatments x 3 iterations x 4 days) were calculated using the following equation 1. The averages of NDVI (equation 2) in each ROI were calculated to monitor the nutritional status for garlics and onions.

$$\text{Vegetation Fraction(VF)} = \frac{Number\ of\ classified\ crop\ pixel\ in\ ROI}{Number\ of\ total\ pixel\ in\ ROI} \quad (1)$$

$$\text{NDVI} = \frac{NIR-RED}{NIR+RED} \quad (2)$$

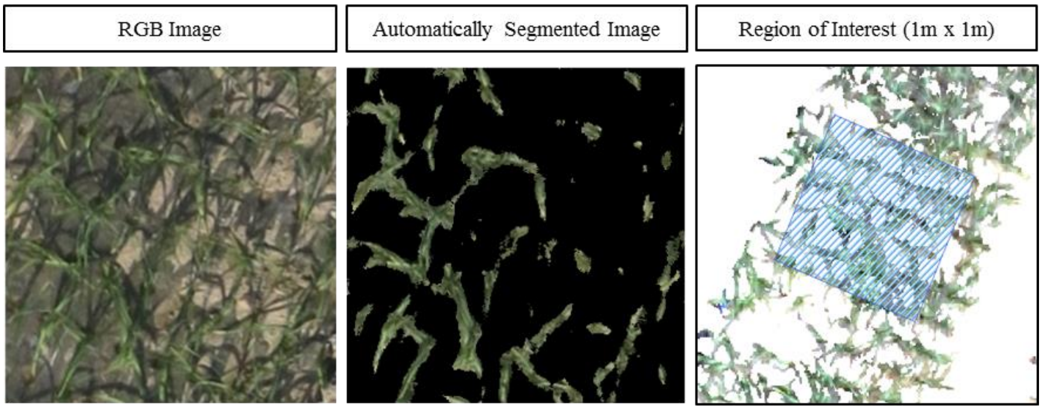

Figure 2. The result of the proposed crop segmentation method in CIE L*a*b* and the ROI (1mx1m) to calculate the Vegetation Fraction

Crop height estimation

The digital terrain model (DTM), was acquired by taking images of the test field without crops. Changes in plant height in the form of multi-temporal digital surface model (DSM) of crops were calculated based on the DTM (Bendig et al., 2014). DSMs were obtained when the images were mosaicked by matching of feature points in Pix 4D mapper software. When two images contained the same object, the relative heights of the objects could be estimated based on the change in the positions of the object in each image. The crop height estimates were obtained by subtracting the DTM from the DSM.

Ground biophysical parameter modeling

To develop models to estimate biophysical parameters (upper fresh weight, lower fresh weight and total fresh weight) for the garlic and onion crops, ground-truth fresh weights were destructively measured using an electronic balance after the UAV images were obtained. The model development procedures and statistical analyses were executed in the SAS software (SAS 9.4, SAS Institute, USA). Multiple linear regression models were developed using the vegetation fraction and plant height as independent variables. The models were developed based on the form of the following equation 3,

$$Y = A \times X_{VF} + B \times X_{PH} + C \times X_{VF} \times X_{PH} + D \qquad (3)$$

where Y = Biophysical parameters, X_{VF} = Vegetation fraction, X_{PH} = Plant height, (A, B, C, and D) = parameters.

Results and discussion

Biophysical parameter modeling

The multiple regression models relating the vegetation fraction and plant height estimate to biophysical parameters of garlic and onion vegetables are shown in Table 2. The biophysical parameters used in the study were the upper fresh weight, lower fresh weight and total fresh weight for onion and garlic. Since the onion and garlic used in the study were bulb crops, the upper fresh weight was the fresh weight of the rest except the bulb above the ground, and the lower fresh weight was the fresh weight of bulb under the ground. The total fresh weight of all part was modeled with vegetation fraction value and crop height. As shown in Table 2, overall, the coefficients of determination for onion (> 0.9) were higher than those for garlic (>0.7), implying that the UAV images of onion would have better potential used for estimating their biophysical parameters as compared to those obtained with the UAV garlic images.

Table 2. The biophysical parameter models of onion and garlic; Y=Biophysical parameters (g); X_{VF} = Vegetation fraction value; (ratio) X_{PH} = Plant height value (m); n = Number of samples; R^2 = Coefficient of determination, SE = Standard error (g)

Crop	Biophysical parameter	Multiple regression model	n	R^2	SE
	Upper fresh weight(g)	$Y = 65.3 \times X_{VF} + 22.6 \times X_{PH} + 70.5 \times X_{VF} \times X_{PH} + 4.1$	48	0.91	11.1
Onion	Lower fresh weight(g)	$Y = 5.3 \times X_{VF} – 18.9 \times X_{PH} +148.8 \times X_{VF} \times X_{PH} + 1.7$	48	0.90	8.0
	Total fresh weight(g)	$Y = 69.2 \times X_{VF} + 2.8 \times X_{PH} + 222.6 \times X_{VF} \times X_{PH} + 6.1$	48	0.94	15.1
	Upper fresh weight(g)	$Y = -7.3 \times X_{VF} + 36.0 \times X_{PH} + 38.2 \times X_{VF} \times X_{PH} + 33.2$	48	0.74	8.8
Garlic	Lower fresh weight(g)	$Y = -3.1 \times X_{VF} + 3.9 \times X_{PH} + 12.0 \times X_{VF} \times X_{PH} + 8.0$	48	0.71	1.7
	Total fresh weight(g)	$Y = -9.8 \times X_{VF} + 39.7 \times X_{PH} + 48.0 \times X_{VF} \times X_{PH} + 41.0$	48	0.75	9.9

Multi-temporal vegetation fraction images and changes in NDVI

Figure 3(a) shows multi-temporal changes in NDVIs of the garlic and onion obtained with the multispectral camera after radiometric calibration and crop segmentation. The images obtained on a two-week interval showed that the NDVIs were increased over time. The empty regions in the middle of the field was the part where the crops were removed for ground-truth investigation. At the same time, the NDVI values of each treatment bed were almost the same regardless of the times of fertilizers at the early growth stage of onion and garlic while it appeared that there was a difference in NDVI values between garlic and onion vegetables of different fertilizer treatments from the middle growth stage. However, in the case of the test bed of this experiment, since basic fertilization was provided to all of the test sub-field, it was thought that the additional fertilization did not strongly affect the NDVIs.

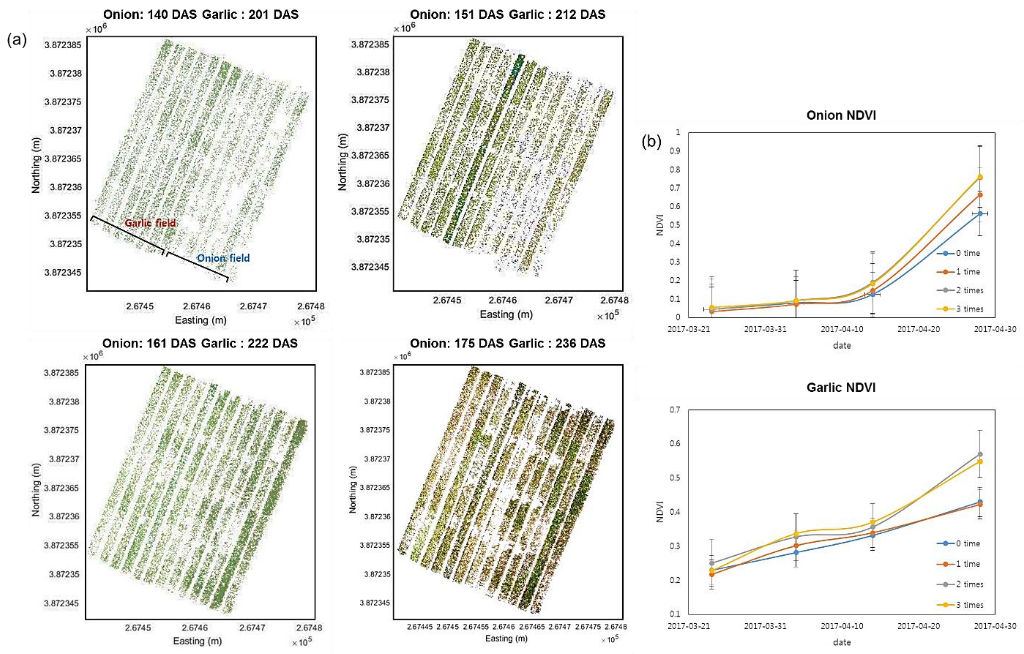

Figure 3. (a) Multi-temporal onion and garlic field images taken with our UAV after radiometric calibration at the different days after seeding or transplanting and (b) changes in NDVI

Conclusion

The objectives of this study was to develop mathematical models to estimate the growth status of onion and garlic crops, known as bulb crops with thin and small leaves at the early and middle growth stages. In order to develop a prediction model, the crop segmentation method based on a band in L*a*b color space was proposed to separate crop pixels from plastic films, soil and other residues, providing the separation error of about 11.4%. To compensate for the temporal and spatial illumination density variations of the images, the radiometric calibration method was applied. After the image pre-processing, the vegetation fractions of all treatment regions were calculated and plant heights were estimated using a digital surface model. The vegetation fraction and plant height were used to develop the crop fresh weight estimation model of garlic and onion. The coefficients of determination for the models were > 0.9 (onion) and > 0.7 (garlic).

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