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Vision-based judgment of tomato maturity under growth conditions

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To determine the picking time of tomato and design the control strategy for the harvesting robot, the judgment of tomato maturity under natural conditions is required. Tomato samples were collected based on the fruit growth conditions which were divided into five different stages in this article: breakers, turning, pink, light-red, and red stages. The visible CCD camera VS-880HC was adopted to shoot visible images, while the near-infrared images at a wavelength of 810 nm were screened by MS-3100 multi-spectral camera. The variations of samples, about color features, were analyzed. The tests indicated that with the changes in maturity, the hue-mean of tomato decreased and the red-green color-difference image mean increased. The standard deviations of the hue-mean and red-green image mean were the largest values for tomato in the pink stage, but the intensity mean of the near-infrared image for tomato in the pink stage had the lowest value. Hue-mean and red-green color-difference image mean can be used as a criterion for the judgment of tomato maturity, and the tests indicated that the red-green mean method was more satisfactory than that of the hue-mean in the maturity recognition methods of tomato fruit with an accuracy of over 96%. The intermediate divisions of five different maturity stages, which were divided by red-green color-difference image mean, were 0, 23.5, 42.5 and 70. The judgment errors of the two methods are mainly caused by the recognition of tomatoes at the pink stage.

Key words: Tomato, maturity, image, judgment.

INTRODUCTION

The research of tomato-harvesting robot has been a widespread concern of international scholars. The research contents mainly include target recognition, judgment of tomato maturity, spatial location and flexible picking control (Kondo et al., 1996, 2007, 2008; Zhang et al., 2001; Zheng et al., 2004; Yin et al., 2006, 2009; Jiang et al., 2008; Li et al., 2009). To determine the picking time, judgment of tomato maturity on the growth state in the field becomes very important, because it directly affects the design of the control strategies for the harvesting robot.

Tomato maturity is closely related to its surface color feature, so evaluating their levels of maturity by visual analysis of the tomato's surface color features is a feasible mean (Choi et al., 1995; Gejima et al., 2004). Generally, tomato maturity is divided into six stages: Green stage, breakers stage, turning stage, pink stage, light red stage and red stage (USDA, 1991). The harvesting of tomato is usually implemented after the turning stage. After harvesting, the different maturities of tomato are also inconsistent (Takashi and Kataoka, 1981). At present, international scholars have conducted a series of studies to judge the maturity of tomato by visual recognition technology. Based on the image of the top part of tomato in HSI (Hue, saturation and intensity) color model, Choi et al. (1995) calculated the hue values cumulative relative frequency of all pixels in artificial illumination chamber, by visual assessment with six different maturity stages of tomato. However, its accuracy achieved 77%. Gejima et al. (2003, 2004) adopted L*a*b* and RGB color model to classify the decision of five different maturity stages of tomato, and proposed G's and a*'s Eigen-Value. Its accuracy achieved 70% (by using the G (36) number of

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pixels to decide the tomato's maturity) and 96% (by utilizing the a* mean). Syahrir et al. (2009) used a* to evaluate tomato maturity based on the L*a*b* image, and then infer the shelf-life of tomato. Zhang et al. (2008) took advantage of PCA and LDA means to classify three different maturity stages of cherry tomato with machine vision, and its accuracy was up to 94.4%. Zhang et al. (2001) extracted the histogram parameters of hue values from tomato HSI image, and then used the multilayer feed-forward neural networks, accomplished by GA, to determine tomatoes that were fully ripe, half-ripe and immature, automatically with its accuracy up to 94%. However, the tomato images were all collected in light box during these studies. Only Yin et al. (2009) discussed, decisively, tomato maturity under natural conditions. He used the difference between area percenttage of red component and yellow green component as the main group characteristics, then the neural network model was established to decide the maturity stages and its accuracy up to 95.26%, but he did not give the explicit expression of different maturity stages.

In a nutshell, the research of tomato maturity decision is mainly conducted in the artificial light box, and its purpose is to meet the requirement of tomato grading line, but the factors of fruit identification under natural conditions is not put forward and can not meet the control requirement of the harvest robot. Moreover, two or three levels of maturity (full-ripening, half-ripe and immature stages) are usually selected by the existing literatures. Obviously, this can not provide sufficient information to the harvesting robot.

In this paper, the authors selected the images of tomato samples, based on the fruit growth state, which were at five different stages: Breakers stage, turning stage, pink stage, light red stage and red stage. The information of tomato images were gathered, and some color features (for example, HSI, RGB, and red-green chromatic aberration) were selected according to the efficient color components of tomato images. These color features were often applied to the segmentation and recognition of tomato images (Zhao et al., 2004; Zheng et al., 2004; Yin et al., 2006; Jiang et al., 2008; Dong et al., 2009). The authors conducted the research of deciding the different maturity stages of tomato by analyzing the variations of the color features. As such, this research provided the decision-making means for the tomato-harvesting robot to achieve the selectivity of harvesting.

MATERIALS AND METHODS

Materials for test

Tomato samples, (*Lycopersicon esculentum* Cooperation 907#) for the test, were provided by Zhenjiang Ruijing Agricultural Science Demonstration Park. Images were acquired from nine in the morning to five in the evening. Decision of the tomato maturity was artificially made by the technical staff working for the park. Taking the harvest of tomato for commercial usage, after the turning stage, into consideration (Takashi and Kataoka, 1981), tomatoes were collected in five different stages: Breakers stage (there was a definite break in color from green to red on not more than 10% of the surface, but the top of the fruit became light white), turning stage (the color gradually turned into red, from the top of the fruit, but most of them were green, even though the red color level achieved 10~30% in the aggregate), pink stage (the orange-red extended from the top of the fruit to the abdominal, and the red color level achieved 31~60% in the aggregate), light red stage (the red color of the fruit expanded to an almost full color, but the bottom was still green and the red color level achieved 61 ~ 90%), and red stage (more than 90% of the surface, in the aggregate, showed red color) (USDA, 1991). The maturity of every twenty (20) samples was analyzed by the image system for each stage.

Tomato image acquisition

The tomato images should be taken under natural illumination conditions in the greenhouse. When more fruits grow on one branch, the image of tomatoes often overlap and the profiles of these fruits are prone to incompletion. A white paper should be placed behind the selected tomato to highlight the fruit's goal in this case. The purpose is to simplify the extraction of a complete fruit image outline in order to obtain the image features of a fruit surface. This lessened the times of image processing, but the filming was ensured in the natural environment. A VS-880HC visible light CCD camera (Microvision Digital Image Technology Co. Ltd.) was chosen to capture the visible light color digital image of the tomato, using RGB image signal formats. A MS-3100 3-chip multispectral digital camera (Duncam Technologies, Inc.) was used to capture the near-infrared image in 810 nm band, which was used for comparative analysis. The image acquisition system also contains image acquisition card, desktop computers, image acquisition and processing software, etc. The computer used for the image process and analysis is an Intel Core2 Due CPU, 2.1 GHz main frequency, 2GB memory, Microsoft Windows XP, operating system.

Selection of tomato image shooting angle

The tomato's orientation and position, to a large extent, are different for the growth state in the field and the grade line. The blossom end seldom appears, but the fruit stalk faces the observers. A total of 135 tomato pictures were randomly taken at different growth states in greenhouses. According to statistics, there were 174 pictures with fruit axis that were basically perpendicular to the camera's axis in 175 fruit images with various maturities. Only one tomato's blossom end towards the camera was found. Therefore, the shooting angle of the tomato's image was chosen perpendicularly to the axis between the blossom end and the fruit stalk, and three shooting points were selected along the circumference direction of the fruit at equal spacing (Figure 1). So, it can cover most of the fruit's surface area. However, we calculated the average of the relevant color component of three images as the corresponding sample value.

Image processing method of tomato samples

Tomato image segmentation based on color difference

Through the gray histogram analysis of the components in tomato image, under different color spaces, it was found that the red-green color-difference gray histogram of tomato image was a bimodal distribution under RGB color space, which was suitable for the Otsu method of segmentation processing (Yin et al., 2006; Dong et al., 2009). Through the computing target class and background class of

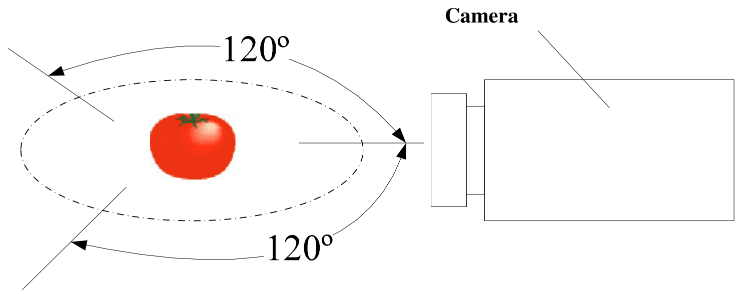

Figure 1. Image shooting angle of the tomato's growth state in the field.

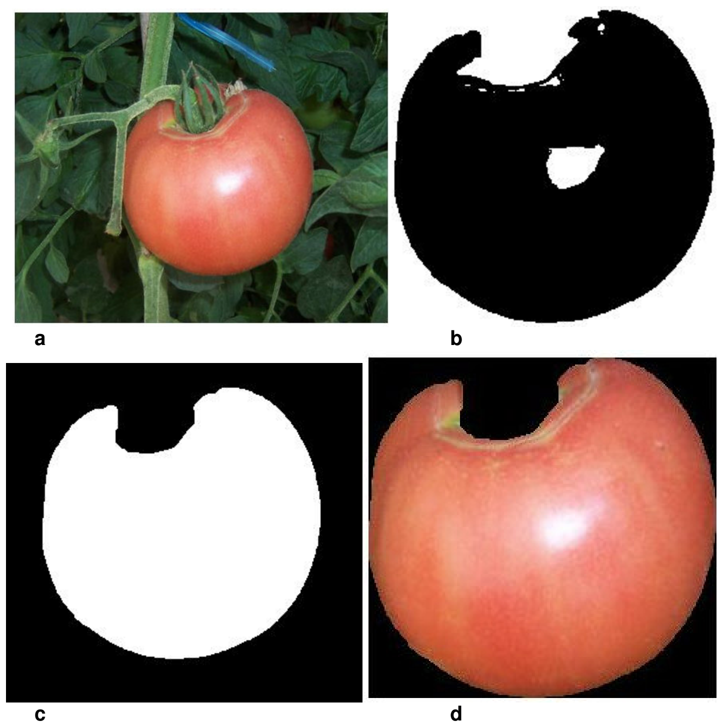

Figure 2. Tomato fruit regional image segmentation based on red-green color-difference method. a, the original image; b, the binary image after segmentation; c, the binary image with a removal of empty holes after segmentation; d, the full fruit area image.

the image, as the smallest intra-class variance and maximum inter-class variance, the Otsu method automatically derives the fruit's goal. Therefore, the red-green color-difference gray image can be obtained from the RGB color image first by subtraction, after which the Otsu method can implement the segmentation and extraction of the tomato fruit regions. Due to the factors, such as noise, imaging surface reflection and fruit maturity differences, the binary image contained small pieces of the non-target area, as well as the empty holes that existed in the goal's area. These small areas should be removed according to the area threshold method, and then the empty holes should be filled, so that the regional contour images fruits could be obtained. The full fruit area image could be obtained by removing the background of the original image via logic processing. The original image, the processed binary image and the full fruit area image are shown in Figure 2. The methods used such as the Otsu method, logical processing and area threshold, were implemented by image processing functions under Matlab.

Selection and calculation of the color features of tomato images

The percentage of the tomatoes' surface red coloring degree is the basis for determining its maturation by humans. In digital images, the number of pixel is usually used to describe the area. The coloring degree of the ripening tomato can be described by the number that sums the red component gray value of each pixel, multiplied by the corresponding number of pixels which have the same gray value, and then divided by the total number of all pixels in the fruit area. Thus, coloring degree is also expressed by the average of grey level components.

Which color component should be chosen to express the degree of tomato maturity? The literatures of several studies have shown that both red-green color-difference and hue component methods were availed to segment fruit images for the robotic selective harvesting process, and were used to identify the mature tomato satisfactorily (Zhang RH et al., 2001; Zhao et al., 2004; Zheng et al., 2004; Yin et al., 2006; Jiang et al., 2008). Based on these researches, several components, such as R, G, B, R-G, H, S, I (red, green, blue, red-green, hue, saturation and intensity), were analyzed in the article. With the use of MATLAB, the characteristic of these components (such as average and standard deviation) were extracted in separate fruit regions under the RGB and HSI color models.

RESULTS AND DISCUSSION

Characteristic analysis of tomato visible images in HSI color model

Both the averages and standard deviations of each color component of the tomato's surface, under different maturity stages, were counted in HSI color model. Figure 3 shows their changing trend. In Figure 3, as the tomato grows up from the breakers stage to the red stage, the average of the hue component tends to decrease. Its variation gets close to linearity. This will be propitious to decrease the errors in judgment of various maturity samples. So, the average of the hue component can be used to judge the degree of maturity. However, the average of the intensity component does not vary obviously before the pink stage, although, the intensity value is easily affected by environment light. The average of the saturation component shows, nonlinearly, that it has a large change range. Moreover, the test of this study used samples of red tomatoes cultivar (*Lycopersicon esculentum* Cooperation 907#). The hue component is appropriate more than the saturation and the intensity components for judging the maturity stage of the used tomato samples.

When Figure 3 was further considered, the standard deviation value of the hue component average at the pink and light red stages increased largely than in other stages. This appearance showed that the hue component averages of these two kinds of maturity stages have a divergent range, which led to large errors of judgment, about fresh tomatoes, in the maturity stage. Judging the range of the coloring area and the large non-uniform color distribution on the surface of tomatoes, at the pink and light red stages, cause a large error.

Features analysis of tomato visible images change in RGB color model

We measured the averages and standard deviations of each color component for all fresh tomato sample images in RGB color model. Figure 4 shows their changing trends at different maturity stages. With the increase of tomato maturity, the averages of both the red and red-green components tend to increase, while the average of the green component tends to decrease. However, the average of the blue color component changes nonlinearly. The average of the red component is similar at the pink and light red stages. Thus, the averages of the blue and red components are not appropriate in judging the maturity degree. The average variations of the green and red-green components are all close to linearity, but a change of the red-green component is better than the green component before the light-red stage. When growing from the pink stage to the light-red stage, the average of the green component tends to decrease strongly. The average of the red-green color-difference component has a better actual value and is more suitable for judging tomato maturity. Furthermore, as shown in Figure 4, the standard deviations of the red and green components at the pink stage are maximal also. The averages of the red, green and red-green color-difference components distribute most divertingly. This distribution is similar to the features in HSI space and it causes an increase in the error of judging tomato maturity at the pink stage.

Intensity change of tomato near-infrared images

The near-infrared images of fresh tomatoes on 810 nm wave length were extracted by using a MS-3100 multi-spectral camera. Near-infrared images of five samples with different maturity stages are shown in Figure 5. Intensities of these images are hard to differentiate one from the other by the unaided eye. The intensity's averages of all samples at five maturity stages were calculated with the image processing and statistical methods in Matlab. As shown in Figure 6, the change of the intensity's averages at five maturity stages is not monotonic. In other words, the average of near-infrared image can not be used to judge directly, maturity of all tomatoes at all stages. However, when the intensity averages of near-infrared images of tomato samples for all maturity stages are considered, the minimum is at the pink stage, while the maximum is at the red stage. The averages of the near-infrared image's intensity are fit for judging the maturity of the pink and red stages, so as to improve the accuracy rate of other judgment methods.

Vision-based judgment of five maturity stages

Figures 7 and 8 show the statistics of the hue component average and the red-green color difference average of 100 samples in five maturity stages. A total of 100 samples were chosen at random in five maturity stages, ranging from the breakers stage to the red stage. Each maturity stage was distinguished by an average value of hue component in Figure 7, and each distinguishing middle point of the hue average was 43, 33, 23 and 16. Judging the accuracy rates of each stage: The breakers stage was 100%, turning stage was 90%, pink stage was 85%, light red stage was 95%, red stage was 95% and the average accuracy rate was 93%. Error was made mainly by samples at the pink stage and samples adjacent to the pink stage. Nonetheless, when the average value of hue

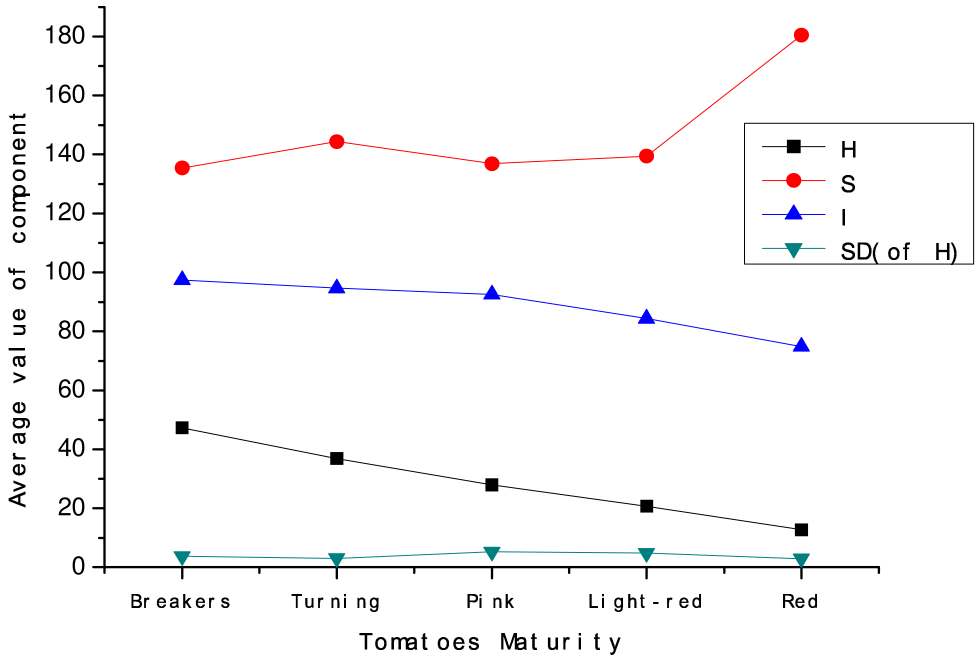

Figure 3. Average value of each HSI components of fresh tomatoes at different maturity stages.

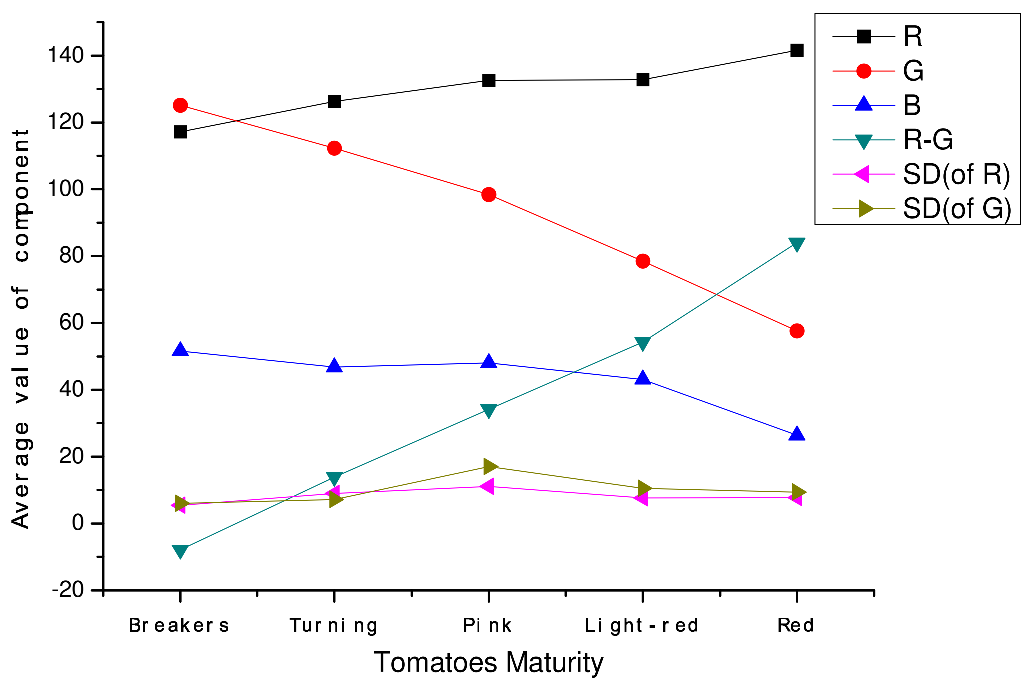

Figure 4. Average value of each RGB components of fresh tomatoes at different maturity stages.

is 43, the tomatoes can be totally distinguished between the breakers stage and turning stage, or above maturity.

When the average of the red-green color difference component is used to distinguish the five maturity stages, the distinguishing middle points of the red-green component average are: 0, 23.5, 42.5 and 70. When the average value of the red-green is 0, the breakers stage and turning stage or above maturity can be separated.

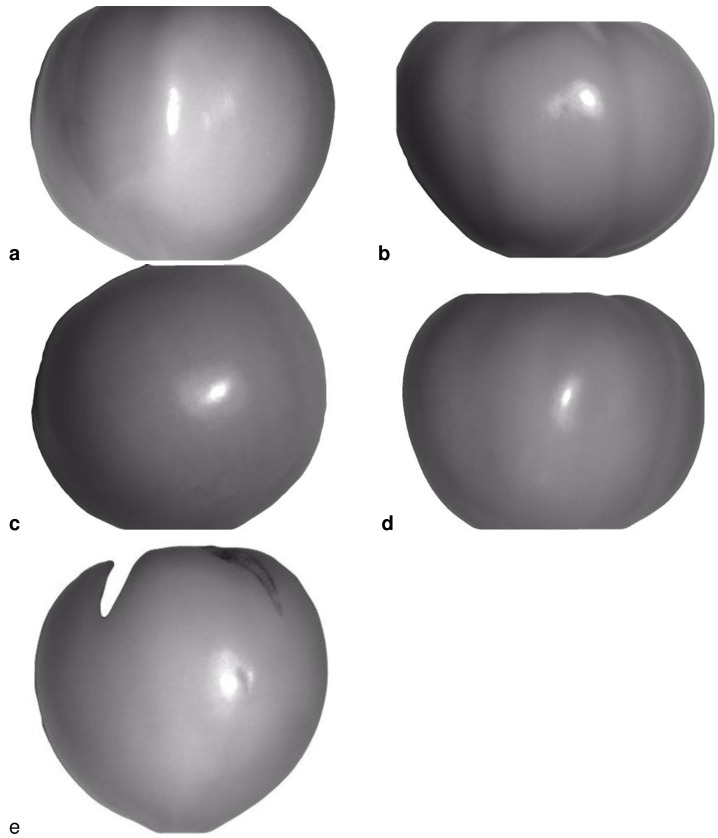

Figure 5. Near-infrared images of five tomato samples for five maturity stages (at 810 nm). (a) Breakers stage, (b) Turning stage, (c) Pink stage, (d) Light-red stage, (e) Red stage.

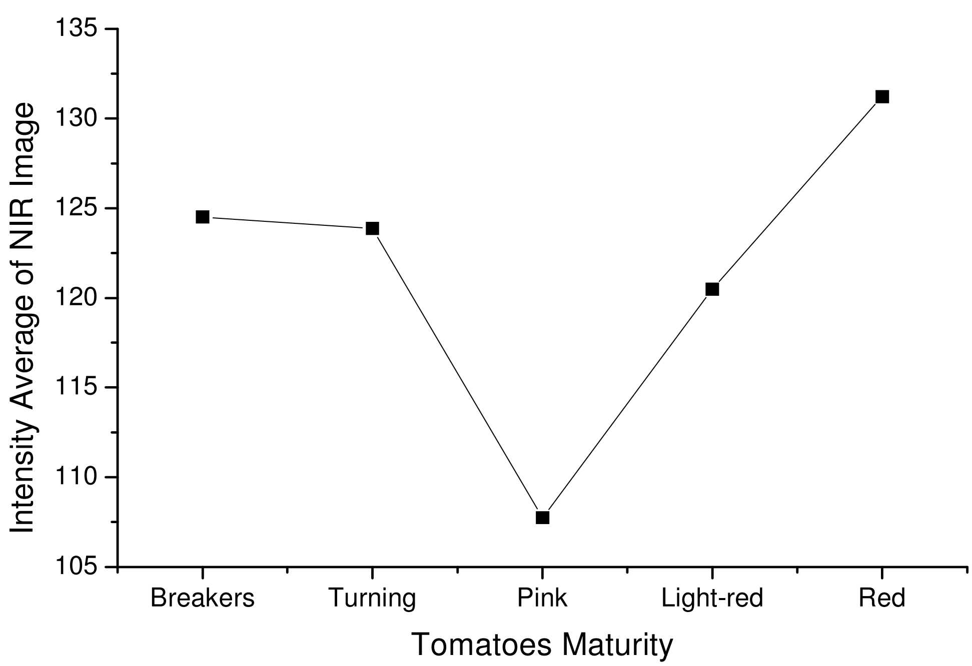

Figure 6. Average value of tomato near-infrared images for five maturity stages (at 810 nm).

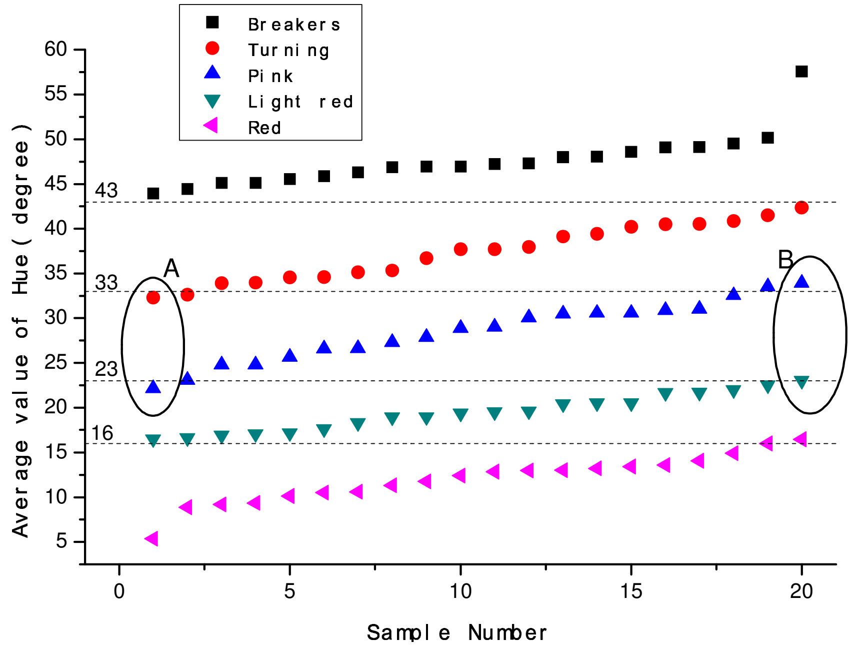

Figure 7. Distribution of hue average for fresh tomatoes.

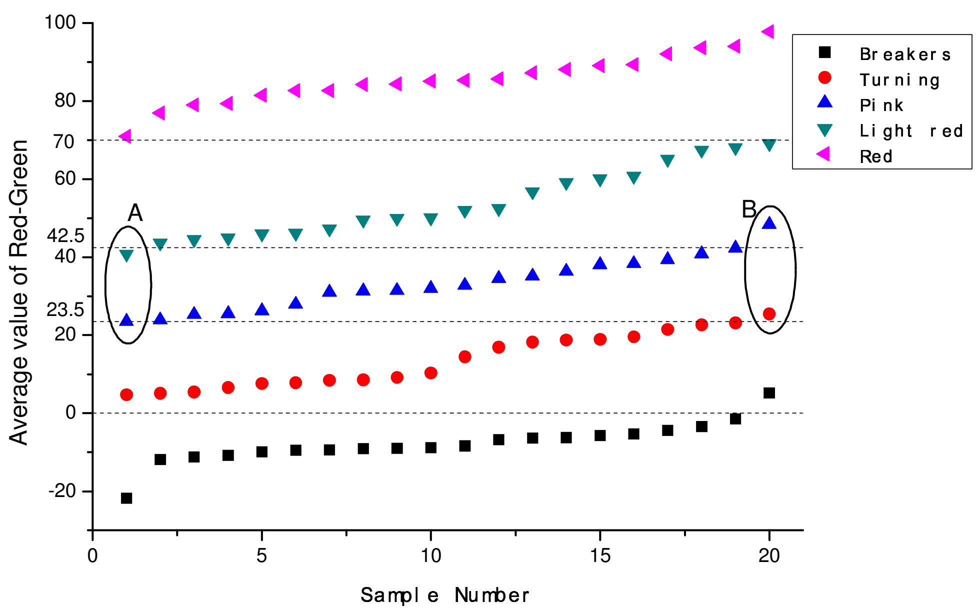

Figure 8. Distribution of red-green color difference average of fresh tomatoes.

When the average value of the red-green is 70, the light red and red stages can be recognized. Accuracy rates of tomato judgment for each stage are: 95% for breakers, turning, pink and light red stages, respectively, 100% for red stage and 96% for the average accuracy rate. This method works better than the method of hue component average. However, the judgment error is produced by samples at the pink stage and adjacent stages, amongst pink, turning and light red stages. Thus, the key point is to advance the judgment accuracy rate of tomato in the pink stage. Samples causing errors mostly focus on tomatoes whose maturities, by further research, are below the pink stage (such as samples A and B in Figures 7 and 8). These kinds of samples, influenced for a long-time by sunlight during their ripening, are more often marked with different colors on their surfaces and they greatly change their coloring degree. Subjective judging errors and visual judging errors of the computer are made due to different angles of observation.

Conclusions

To sum up, the judgment of maturity for the fresh tomatoes on growth state was studied by using color image-processing technique. The image analyses were carried out with RGB and HIS color models. It can thus be concluded that:

1. With the change of maturity stage, the hue average of tomato images tends to decrease progressively, and the average of the red-green color difference component tends to increase progressively. The hue average and red-green color difference average of tomato images also has the maximum standard deviations at the pink stage.
2. The minimum intensity average of the tomato near-infrared images is at the pink stage as compared with the maturity stages of all samples.
3. The hue and red-green color difference averages can work as standards to judge maturity stages of fresh tomatoes. With a judgment accuracy of 96%, the red-green color difference average method works better than that of the hue. The judging errors of the two methods are mainly caused by recognizing tomatoes at the pink stage.
4. When the hue average value is 43 or the red-green color difference average value is 0, fresh tomatoes can be distinguished between the breakers stage and turning stage or the above stages. Equal value of the red and green component averages of the tomato's image should be regarded as the judgment reference at the beginning of the harvest in the turning stage of tomatoes.

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