An automated imaging BRDF polarimeter for fruit quality inspection

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ABSTRACT

The purpose of this project was to test and implement recent research of polarization and scatter properties that suggest using a cross polarization imaging system to reduce glare artifacts. In particular, the use of this research is to improve the machine vision of apple quality detection in the food industry. The automated measurement system was implemented by acquiring pictures at different angles and different polarization states of apples. The opto-mechanics, system integration, synchronization and data collection are controlled with LabVIEW.

Keywords: BRDF, polarization, imaging, quality inspection, opto-mechanics, illumination

1. INTRODUCTION

Over 80 million tons of apples are produced worldwide every year with the average apples weighing 1/3 of a pound. Combined with a product and yield growth of 3.1% and 2.31% respectively, there is a clear increasing global demand¹. Apples must go through a quality inspection in order to prevent consumer non-satisfaction. The most common failure during inspection is caused by bruising². In order to sort such large amounts of apples there is a demand for automated machine vision technology. This has resulted in a majority of the larger apple companies using machine vision in order to keep up with the growing industry^{3,4}. Those machine vision systems are faster than human visual inspection, however they are lacking in their overall effectiveness with as low as 63% detection accuracies for some types of apples⁵. The reasons for this low effectiveness has been found to be from the aspherical shape of the apple along with the wax that is used to protect the apples from rotting and other types of defects. This creates a glare that can hide the bruise.

Recent research has suggested that the cross polarization is able solve glare problems for a specific cultivar, which gives the apple a Lambertian bidirectional reflectance distribution function (BRDF) but this claim still needs to be further investigated⁶. To investigate this claim you would need to combine BRDF and polarization which has been reported, however the system was manual, time consuming, cumbersome, and only measured one point for the BRDF⁶. Therefore, an automated system is proposed in this work which can answer these claims for multiple points of BRDF. A novel automated system is proposed that would make measuring the BRDF and linear polarization effects on an apple or any other object you put into the system. In this experiment only the linear polarizations were measured.

2. MATERIALS AND METHODS

2.1 Samples

The orchards from the company Yakima Fresh located in Yakima, Washington, USA provided the cultivars of apples including Crisp Pink, Red Delicious, Granny Smith, and Braeburn apples. These apples were picked October 5th 2014. These apples were stored in a controlled atmosphere in California. The atmosphere conditions were 1°C and 5% oxygen until they were sent to the University of Arizona June 2015. At the University of Arizona, they were held in 1°C refrigerator until the day before they were supposed to be tested. There are apples that were cleaned in hot water multiple times in order to get rid of the wax. They will be referred to as un-waxed apples.

2.2 Polarimeter Setup

Figure 1. The System in its entirety. In this figure the more important elements are the stand(S) that holds the apple, the motorized rotation plate (RPL), the camera(C), the cable holder (CH), Motorized Rotating Polarizer (RP), the Halogen Light source with diffuser (H), and the Fixed Linear Polarizer (LP).

A 16mm focal length lens model 59-870 (Edmund Optics, Barrington, New Jersey, USA) was attached to a camera model GRAS-03K2M-C (Point Grey, Richmond Canada) that was mounted on the main arm of the setup. In front of that, also attached on the arm, is the motorized rotation mount NR360S/M (ThorLabs, Newton, New Jersey, USA) with a high precision linear polarizer DPM-050-VIS (Meadow Lark, Frederick, Colorado, USA) inserted in it. The motorized rotation mount is powered by the controller BSC201 (ThorLabs, Newton, New Jersey, USA). On the other side of the arm is mounted a black background and two weights to counter balance the imager. This arm is attached to the rotation stage with a hole. The following is passed by a stand connected directly to the optical table beneath. This ensures that the object does not rotate with the system. In order to prevent torque within the cables all the cables were attached above the rotation center. The wires are connected to the devices to the computer and the USB DAQ USB-6501 (National Instruments, Austin, Texas, USA) using USB and RS232 connections. The specific devices controlled by the USB DAQ is the halogen light source and the rotation table. A Halogen light source DECOSTAR 51 ALU (Osram, Munich, Germany) is attached roughly 500 mm away with a diffuser (model TSG-LEGB, Knight Optical, Kent, UK) attached to it. In between the light source and the setup is another linear polarizer DPM-050-VIS (Meadow Lark, Frederick, Colorado, USA).

2.3 System Calibration

In order to calibrate the system, the noise created by the sensor's dark current was reduced from the system prior to measurement by taking a dark image and subtracting it from the other intensity images. Another part of the system calibration was to use a non-polarizing mirror in order to ensure that the crossed polarization was indeed crossed. The linear polarizer was set up that would remain stationary and then used the non-polarizing mirror and rotated the other polarizer until there was the minimum amount of light. This was how it was known to be cross polarized. For further reduction of the residual noise in the degree of polarization images, the images were post processed.

2.4 Automated Measurement steps

The different phases of the automated measurement system are summarized in Figure 2. The hardware initialization consists of the camera, the motorized rotational mount controller, and the USB DAQ being turned on. The USB DAQ is connected to the motorized rotation table and it sends communications one way while the other two devices will send and receive data from the computer. The illumination was turned on and allowed to warm up for 15 minutes. All of the instruments initialize communication with the computer. Then the rotation table and the linear polarizer are rotated to its start position. The rotate rail loop rotates the rail 18° added from its current position. The rotate polarizer loop rotates

the polarizer 45° from its current position. The image acquisition phase acquires an image of the object and saves the image into a predetermined folder with the position of the arm and polarizer embedded in the name. The hardware initialization phase took 45 seconds to initialize communications between the computer and the other instruments. This was due to a deduction in the arm speed, which was necessary to avoid oscillations. It was damped with internal feedback. The polarizer then turns to its first position. Once the polarizer is in place the image is acquired and saved. Following the picture being taken the polarizer will go through all of its position taking pictures after each rotation until it returns to its starting position and then the arm will move to the next position. This will continue until all of the images are acquired at different polarization states and reflectance angles.

Figure 2. Automation flowchart describing the different measurement steps.

2.5 Stokes Vector Calculations and Degree of Polarization

The data that was acquired was further interpreted using Stokes Polarimetry. Stokes Vector polarimetry enables to see further polarization properties than the using only irradiance images that were received from the setup. Stokes uses the knowledge of the linear polarization in the X and Y along with the circular polarization. The equation that can be used to find the Stoke components is:

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I_H + I_V \\ I_H - I_V \\ I_{45} - I_{135} \\ I_R - I_L \end{pmatrix} \quad (1)$$

In this system, the circular polarization is assumed negligible because of the circular polarization contribution is one order of magnitude lower than the linear contribution⁶. I_H , I_V , I_{45} and I_{135} stand for a horizontal, vertical, 45 degrees, 135-degree linear polarized image. The intensity images that we took with the camera represent these images.

The degree of polarization is based on the Stoke Vector components. It allows us to know how much of the light that is hitting the object is polarized versus non-polarized⁷. The equation is

$$DoP = \sqrt{\frac{S_1^2 + S_2^2 + S_3^2}{S_0}} \quad (2)$$

All of the calculations that were done for the system calibration were done in MatLab (Mathworks, Natick, Massachusetts, USA) and with the elements of the functions corresponding to matrices of pixels from the image acquired.

3. RESULTS AND DISCUSSION

3.1 Linear polarized vs cross-polarized imaging

The system was able to test the effectiveness of the Cross polarization for the removal of glare which like it had been theorized⁸. Multiple cultivars and angles of the apples are shown below. The use of different cultivars and angles was to ensure that the conclusions were independent of these variables. In Figure 3., the nonpolarized crisp pink apple has a glare that is at 100% brightness which is reduced to the brightness of the apple at roughly 75% when cross polarization is used.. The overall brightness of the apple is increased by about 10%. In figure 7. the same pattern is shown with the 100% brightness in the glare reducing to the 75% of the rest of the Granny Smith apple and the overall color increasing by 10% again. However it is worth mentioning that the there is a much smaller area of about 85% brightness which is not reduced to the 75% brightness like the other apples did. In figure 8. The same patterns as the crisp pink apple appear on this Red Delicious apple. These tests show that the major reduction of the glare is independent of the angle and the cultivar. The system was tested by emitting linearly polarized light towards a fruit and testing whether the light reflected maintained polarization. It also observed scatter evolution for different angles. Thus, the cross polarized illumination gives Lambertian reflectance properties of the apple which is independent of the angle or cultivar. This quantifies the majority reduction of the glare through the use of cross polarization. This glare reduction is significant because of the potential it has of hindering an automated system using machine vision to see bruises behind said glare.

Figure 3. (Left) Arm at 144°, aligned linear polarizers, bruised Cripps Pink apples, (Right) Arm at 144°, crossed linear polarizers, bruised Cripps Pink apples

Figure 4. (Left) Arm at 108° , aligned linear polarizers, bruised Granny Smith apples, (Right) Arm at 108° , crossed linear polarizers, bruised Granny Smith apples

Figure 5. (Left) Arm at 54° , aligned linear polarizers, bruised Red Delicious apples, (Right) Arm at 54° , crossed linear polarizers, bruised Red delicious apples

3.2 Stokes Image Polarimetry

Figure 6. Figure 7. S0, S1, S2, and degree of linear polarization in image form of Crisp Pink Apples at 108°

Figure 7. S0, S1, S2, and degree of linear polarization in image form of Crisp Pink Apples at 144°

Figure 8. S0, S1, S2, and degree of linear polarization in image form of Crisp Pink Apples at 54°

By applying the equations 1 and 2, we can see that Stokes Polarimetry and the Degree of polarization applied to different angles will take the same pattern. In S0 or the irradiance image, there will be a value of 100% where the glare is supposed to be and steadily lower as you move away. In S1 there will be a value of around 60% in the shape of the glare and the rest of the image will be 0. Lastly in the S2 there will be no significant value except for a possible outline of the glare with a value of 40%. This trend of 40% outline happens in both the 144° and 54° but not the 108° but is not significant. For the degree of polarization, all three angles show the lowest degree of depolarization at the glare spot with values of 60% and the rest of the image is mostly depolarized or under 20%. The background of this set up is what caused the higher percentages outside of the apple and this is due to it depolarizing light worse than the apple.

4. CONCLUSION

A fully automated imaging BRDF polarimeter was demonstrated in this work and was used to prove that cross polarizations could be used to effectively remove glare for multiple apple cultivars independently of the angle. This system does not compete with the speed of the current industry systems. This system could also measure the polarization properties automatically with angle information. However, if you were to apply the concepts of using cross polarization to the systems already in place it would greatly increase its ability to detect bruises. Thus the concepts that were developed by this machine could increase the efficiency and effectiveness of the industry. With the use of Stoke and Degree of polarization that this system provided this work could be used in medicine. Another way this set up could be used with the proper measurements would be to quantify glossiness which can be used in biomedicine or a number of other fields. By simply changing the configuration of the system by adding 90 degrees to the rotation arm location, transmittance measurements are also possible. The calculation of the Stokes vector and the degree of polarization will provide information about the decrease in intensity of the glare. It shows in both the intensity images and the Stokes images that the glare has been reduced by from 100% to the standard value of 75% in the surrounding area. The Stokes Vector and degree of polarization are also examples of information that could be used to help in the other industries to tell them information about the objects interaction with light.

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