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MICRO-GONIOPHOTOMETER

(MICRO-GLOSS MEASUREMENT DEVICE)

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ABSTRACT

A micro-goniophotometer is a device used to measure the gloss of a paper sample. There are currently commercially available gloss meters, however, they are quite expensive (~$20,000-$100,000 US dollars) and complex in design. Dr. Jon Arney, a recently retired professor at the RIT Center for Imaging Science, has developed a simplified and more economical gloss meter. However, the new device is mounted to a desktop, cannot be easily transported, and is difficult for an inexperienced operator to use properly. The objective of this project was to develop a more user-friendly, portable version of Dr. Arney's original micro-goniophotometer gloss measurement device. The result is a micro-goniophotometer that can fit on a desktop and be moved by a single person. This device also is self-contained and does not need to be completely broken-down into multiple components if it must be moved. The device was designed and documented with intention that it could be recreated by most anyone with access to a machine shop, necessary tools, and background information regarding gloss measurement fundamentals.

NOMENCLATURE

Class – A programming concept which models a real thing or idea.
GUI – Graphical User Interface – Handles inputs and outputs for the plugin.
Plugin – A computer program written to run as part of another program.
ImageJ – An image processing program written in Java with an easy to use plugin interface. [2] [3]
MathCAD – A math modeling tool used by Dr. Arney to program the original algorithm for the image analysis done by the micro-goniophotometer.

INTRODUCTION

The word "gloss" is intuitively easy to understand, but making an optical measurement that correlates well with the human perception of gloss remains a challenge. The hypothesis behind this project is that both spatial resolution (micro-) and angular resolution (gonio-) are required of an instrument in order to correlate meaningfully with the human visual perception of gloss and also with the underlying cause of gloss. Typical hand-held gloss or reflectance meters are capable of measuring the amount of light shining off of a surface, and can correlate a number to the surface reflectance. However, there is more than one component of light the causes "glossiness". There both a spectral and a diffused component to reflected light. Diffused light also has two types; angularly diffused and spatially diffused light. Typical measurement devices cannot differentiate between these two light components. The measuring of the human perception as it relates to gloss requires the separate measurement of the different types of light. A device utilizing a bidirectional reflectance distribution function (BRDF) is capable of differentiating between the specularly reflected light from the bulk light. Thus, a micro-goniophotometric bench-top instrument has been developed and demonstrated. This instrument collects polarized and un-polarized light reflected from a paper sample that has been wrapped around a cylinder to extract the specular and diffuse components of light.

BACKGROUND

While the original version of Dr. Arney's micro-goniophotometer has been successful in collecting more information than a traditional gloss meter, there are two issues that prevent its mass adoption: the original instrument is a table-mounted experimental device that is not user-friendly and requires extensive training and operating experience to produce accurate and reproducible results. Also, the device components are rigidly mounted on a steel tabletop and not easily relocated. If the device had to be moved to another location, all of the components would need to be removed from the magnetic table and then reconstructed at the new location. This is a time consuming and tedious process, and requires precise alignment of the components. The objective of this multidisciplinary project was to design a transportable device that can be used by an inexperienced operator and still capable of generating reproducible and accurate results as demonstrated with the original device. A previous MSD (P08541) team had made an attempt at building such a device, but the end result was that it did not provide the expected improvements compared to the original design. There were also coding errors in the software generated by the past group causing inaccurate data results. The decision was made to rewrite a new code entirely for the new device by using a different programming language,. This would reduce the likelihood of coding errors.

DESIGN PROCESS

Preliminary Design

The preliminary design process of the project initially involved researching the theory behind gloss measurement, as well as meeting with Dr. Arney to ensure the team had a basic knowledge of gloss. This would help prevent the design of a device incapable of generating correct data results. The customer needs were recorded and reviewed by the team based on the expectations provided by Dr. Arney. The needs were then used to develop engineering specifications with measurable units and tolerances. The design, development, and construction of the device were based on these specifications. Dr. Arney also requested that the previous team's data analysis program be rewritten using an alternate coding language and made more user-friendly by reducing the number of input parameters. The new hardware and software would then be combined and tested to ensure proper operation. Data produced using the new device would then be compared to data produced using the original device. The project would be determined successful if the device was built within the engineering specs provided, while still generating data results equal to or better than the original device results.

Specifications

Based on Dr. Arney's provided customer needs, the team was able to generate a data table of specifications with measurable units, dimensions, and tolerances where possible. The focus of the device was to make operation easier for an inexperienced user. Ideally, the device was to be "single-button" operable. This means that the user could mount the gloss sample, and then capture images, analyze data, and produce results without the need to click more than one button on the user interface. This would require automation of the physical hardware, and would have added complexity to the new design. Because the device was to be portable, Dr. Arney asked that it be able to fit in an airline over-head compartment, and weigh no more than approximately 30 lbs. Other dimensions were developed based on the theory of gloss measurement, and the working range of the optical (camera and lens) assembly.

Original Device Hardware

The new device hardware would serve the same purpose as the hardware in the original device, but would allow for a more portable and robust design. Hardware consisted of the following components: sample mount, polarizing filter, video camera, lens, frame grabber, LED light source, fiber optic line light, power source, and device enclosure.

Sample mount - The sample mounting fixtures consisted of three different diameter PVC cylinders standing vertically upright in view of the camera. Depending on the gloss level of the sample, the cylinder with the appropriate diameter would be selected and positioned at a fixed distance from the camera. Each tube had to be placed precisely at its own corresponding distance from the camera. The sample would then be taped to the pipe such that it appeared in the viewing area of the camera. The taping procedure was also tedious and required the sample be tight against the pipe cylinder.
Polarizer – A 360-degree rotating polarizing lens would need to be adjusted to a position at which the most light could pass through. The user would then take a picture, and rotate the polarizer 90 degrees to prevent polarized light from passing through to the camera, and a dark image would then be captured. It was possible for the user to set the polarizer at the incorrect setting initially, or possibly not rotate the lens the correct 90 degrees. This would have a negative impact on data analysis.

Camera – The original camera worked well for its purpose, but was large and expensive to purchase. A smaller, less expensive camera could be used in its place.

Lens – The lens was mounted to the camera, and was both bulky and expensive. It also did not need to be adjusted to control the amount of light getting to the camera photo sensor. Instead, the light intensity of the image was controlled using the frame grabber adjustments on the computer interface.

Frame grabber – This is the computer hardware (internal component) that captured the images in view of the camera. The original frame grabber was too large to fit in most desktop computers, and was impractical to use with the new device.

LED light source – A small aluminum block housed red, green, and blue LED bulbs. They were the source for the light that would reflect off of a sample The contacts on the LEDs, wiring connections, and power switch were exposed and posed a potential electrical hazard. Electrical tape was used to hold most of the parts together, but the heat from the LEDs caused the tape adhesive to fail and fall off.

Fiber optic line light – This light has a fiber optic cable that plugs-in to the LED light source. The bar on the other end emits a 10" line of light across the sample. The light emitted must use this style of line light in order to simulate an infinitely long light source. Any other light source would cause uneven reflected light across the sample and result in inaccurate data.

Ambient light cover – A black felt cloth covered the device during operation to prevent exposure to outside ambient light. However, some light still was able to pass through around the bottom edges of the felt where it met the table surface.

Power source – A universal power supply used typically in research laboratories was used to power the LEDs. It was large, heavy and expensive to purchase.

Original Device Software

The primary customer needs for the programming portion of the micro-goniophotometer were as follows: one-button operation; accuracy, speed, and precision equal to or better than the previous program; fewer inputs than the previous program; and running as a plugin for ImageJ. Time and design constraints took the one-button operation requirement out of scope.

The main portion of the programming for the micro-goniophotometer is translated from a MathCAD program written by Dr. Jon Arney. The previous group had also tried to translate this program into Java for use in their own plugin, but it was decided that it was overly complex and disorganized. A portion of that code was considered for reuse, but it was discovered to be incorrect after testing.

Concept Development and Selection

Hardware – The main issues regarding the original hardware were that the components were too heavy, too large, and too expensive to meet the engineering specifications of the new device. Nearly all of the hardware could be substituted using components that would be smaller in size and weigh less, which would allow for a more portable device. Other components were too costly or could be redesigned to make operation simpler. This was the basic criterion for hardware design and selection process. The values for the design criteria are explained in more detail in the engineering specifications document.

Software – The original interface worked as intended, but required a number of inputs from the user. Also, users would have to rely on their own judgment of what numerical values to input. Both these issues could lead to inaccurate data due to user error or inexperience. The new software would require fewer numerical inputs from the user and would be easier to operate. This would reduce the time needed ao produce a data result and also reduce the likelihood of an error.

Feasibility Assessment

Because Dr. Arney's original device had already been proven successful in producing data results, the team was able to develop the new device knowing that the new project would be based on a working design. By carefully modeling the new geometry and working closely with Dr. Arney while selecting new hardware, the chances of success would increase.

A number of hardware concepts were generated for each of the main components. Using a number based selection system; the concepts that most closely fit the design criteria and were most likely to succeed were selected as the designs. The greatest limiting factor was the expense required to obtain or build the components. A set budget of $1500 had been specified, and the project could not be built if the new components were to exceed this financial limit. The software design was limited only to the desired appearance of the user interface. The code itself did not have alternatives since Dr. Arney provided a detailed algorithm and had specified the language in which code would be written. A number of potential risks were identified throughout the design, and were taken into consideration during the design development and selection.

Hardware Design

Many of the components were redesign to improve original device operation while some parts from the old device were reused. The sample mount would no longer require 3 different cylinders at three different mounting positions from the camera, but instead the mount would be fixed and a zoom lens would be used. The zoom feature allows the cylinder size to appear larger or smaller while simultaneously changing the perceived distance. This was designed to have the same effect as using different cylinder diameters at different distances from the camera lens.

The new polarizer would not longer need to be rotated, but would instead use two fixed lenses orientated 90 degrees from one another. This would include mounting the two lenses sided-by side in a sliding frame. By only having to slide the frame from one lens to the other, the chances of setting the lens at the wrong angle was eliminated, as could have happened with the original rotating lens during operation.

A smaller, more affordable camera was used as opposed to the large and expensive camera, which was not needed to capture the images used for data analysis. The old camera was a high-resolution research camera, where the new camera was a black and white gamma-1 camera and was about four times smaller. The black and white camera could be used since the program is measuring pixel values and color does not have any significance. The new camera was a component that was given to the team by Dr. Arney, and so it did not have to be purchased.

A new lens was sourced for the device. Working with an optics component provider and their technicians, a lens was selected and purchased based on the working distance and features required. This meant that the lens have an F-stop to control incoming light, have a zoom feature, and have a focal adjust to ensure sharp images could be taken, despite whether the lens was zoomed in or out. The working range from lens to sample was 12" based on the math in the coded algorithm. Only one available lens fit the design criteria, so it was selected for use.

The original LED lights and mounting block were reused. Setscrews were incorporated to hold the parts together, while the lights and switches were rewired to reduce the likelihood of an electrical short or shock hazard. The fiber optic line light the the old device was also reused.

The enclosure was no longer a felt blanket, but now an aluminum box. The box allowed for all the components to be mounted within it, and provided a rigid base for component mounting. A lid on top allows for easy adjustment and sample changing when open, and prevents ambient light from entering when closed. Because the components are completely enclosed in the box, the device can be transported as a single unit with disassembling the hardware.

One of the major new additions to the design of the device is the addition of a micrometer controlled aperture. Any aperture is an adjustable light restrictor in the lens. It can be open to allow the maximum available light to pass to the camera; it can be closed to eliminate the pass of light, or can be set anywhere in between. The original device used an adjustment in the software for the old frame grabber to control the light exposure, and so it did not use this new aperture feature. The new frame grabber did not have this adjustment, and is the reason why the aperture adjustment was included in the new design. The F-stop must be adjusted while the enclosure is shut to prevent outside light from affecting the image. This was solved by attaching a control rod to the F-stop on the lens, and having it exit through a small hole in the side of the enclosure. This eliminated the need to have the enclosure lid open during adjustment. However, the team needed a way to correlate the position of the control rod to the amount of light passing through the aperture. The solution was to attach the rod to a modified micrometer mounted to the side of the enclosure. A table was generated to correlate the aperture position to the reading on the micrometer. This allowed for the fine adjustability needed for the aperture adjustment. The reading on the micrometer tells the user what aperture value should be input on the user interface.

Electrical Design

One of the essential components of the micro-goniophotometer is the camera. The camera used was a Hitachi KP-M2RN analog Monochrome CCD Camera. The camera was selected after performing a test of camera Tone Transfer Function (TTF). A Kodak 20 step reflection gray scale was used to measure the TTF of the camera. The camera was focused onto the step wedge with a field of view covering only about 3 steps. With step 0 (the most reflective step) in the field of view, the f/stop of the camera was adjusted so that the image of step 0 was just saturated (all pixel values = 255). A single image of each step from 0 through 13 was captured using that f/stop setting, and the mean pixel value, P, of each step was measured. The reflection density values, D, of the steps were 0.05, 0.15, 0.25, ...1.35 for steps 0 through 13. The reflection factor, R, for each step is given by equation (1), and a plot of pixel values "P" versus R is shown in Fig. 1.

$$R=10^{-D} \qquad (1)$$

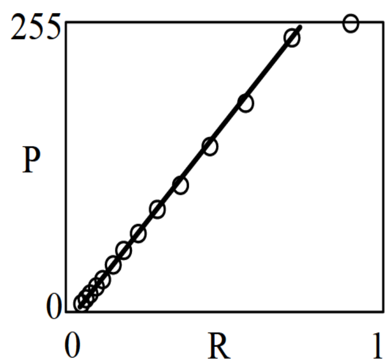

Figure 1: P versus R for the camera

The camera was saturated at step 0, as shown by the 255 value in the upper right of Fig. 1. The other steps had pixel values below 255 and were used to determine the TTF of the camera. The data was well described by equation (2)

$$a \cdot R^{\gamma} + b \quad \text{with } a = 347.6,\ b = -9.007,\ \gamma \equiv 1. \tag{2}$$

The correlation coefficient for this line is $r^2 = 0.9994$. Thus, the camera is well described as a $\gamma = 1$ camera, which was the required feature.

The camera needed a frame grabber board (Analog to digital converter) that is installed in the computer to allow capturing and displaying images. The frame grabber selected was a PIXCI SV5 by EPIX Inc.

The device used three different color light source (red, green and blue). The micro-goniophotometer requires a bright light source to generate a reflection from the sample. By trial and error, and based on availability, 100 lumen LEDs rated at 700 mA (red, green and blue) were selected. The LEDs were manufactured by "Luxeon Inc." Although these high lumen LEDs worked as intended for most of the samples, they were not bright enough for very low gloss samples. Higher lumen LEDs should be used for better results. Also, a 700mA current driver was used to stabilize the current and protect the LEDs.

The device uses a single small and efficient power source. The new power organization minimized the number of wires and the needed power adapters compared to the old device. A CFM4OD-01 Cincon 5V/12VDC linear and switching power supply was used to power the device components. This power supply provides 25 W, 5V / 5A output 1 and 12V / 2.5A output 2. It is 80% efficient, and generates about 0.0284 BTU/min.

A fan was initially included in the design for cooling. This concept was eliminated because it would allow external light to enter the device and yield incorrect data. Device vibration and dust were also issues associated with the cooling fan. Due to these disadvantages, and the fact that power supply LEDs dissipated a relatively small amount of heat, the fan was eliminated.

The electrical system layout and architecture is shown in Figure 2.

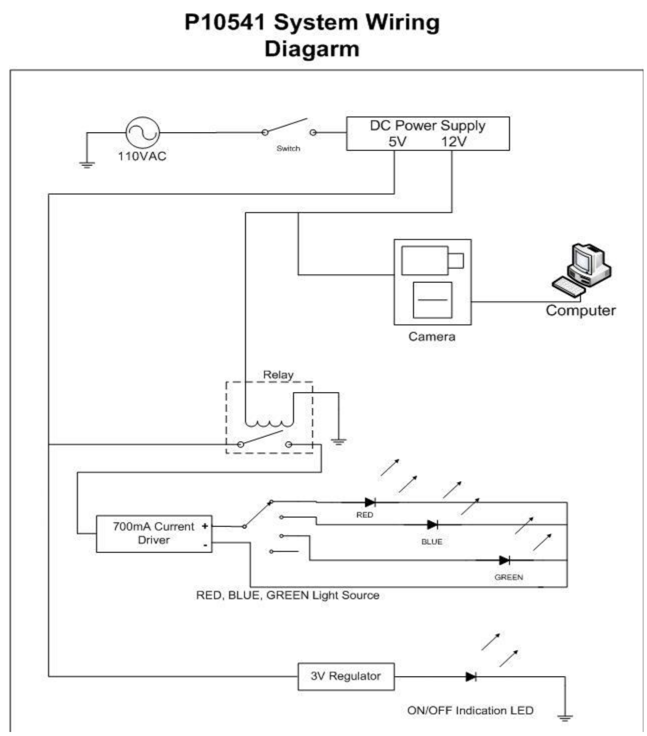

Figure 2: Diagram of the device wiring

Software Design

Since the previous code was considered unusable, programming for this version started from scratch. After discussions with Jeff Robble (a CS grad student at RIT), it was decided that the MathCAD algorithm programmed by Dr. Arney was fairly procedural (step-by-step) and could be programmed as one operation. The new program would was simplified thanks to optimizations and standardizations stemming from good device design. Certain variable parameters in the last device were fixed in this device (working distance, instrumentation angle, camera gain, and cylinder diameter). The remaining inputs (bright and dark images, reference reflectance, field of view, reference area, and baseline angles) would still need to be input by the user.

The MathCAD code was essentially copied line for line to program the algorithm. Some small changes and optimizations were made (some calculated values were never used and some things were MathCAD-specific). The other parts that were programmed were some classes to hold results and the classes that would show the GUI. The previous GUI showed ten inputs (besides the images). The new GUI shows six inputs (Figure 3).

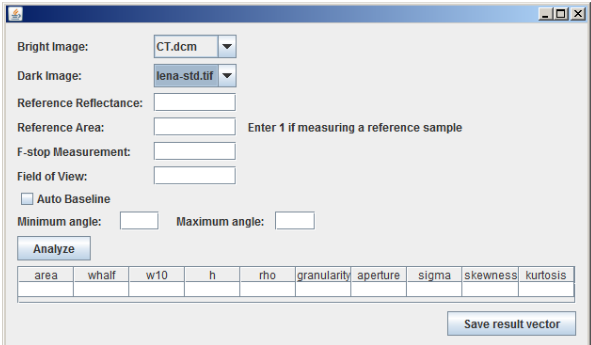

Figure 3: A screen shot of the plugin window

One input from the old plugin (exposure time) had to be changed due to the fact that it was not controllable on the new camera. It has been substituted by "aperture Measurement", which is read from the device and interpolated to a percentage using a table generated for each specific device.

Testing for the plugin was done by comparing its calculations to those of the MathCAD program. Assistance from Dr. Arney was required to verify results that were similar, but not numerically equivalent to those from the MathCAD program. Once the program was verified for correctness, it was then tested for statistical control.

EXPERIMENTAL SETUP AND TESTING

The preliminary testing of the hardware included testing the new device adjustable camera lens to determine if it could operate as intended. Since this was a new addition to the operation of the hardware, it was an area of concern. The lens, camera, and mounting platform were assembled and mounted to the base of the optics hardware mounting platform. The sample mount and optics package were then placed on a flat surface using spacing and dimensions that were the same as the new device design. The main concern was to determine if the lens would stay in focus when the zoom was adjusted from the wide view to the close view. Once the camera was connected to the computer's frame grabber, it was determined that the lens would operate as intended, and the team was able to continue with the construction of the device. It was possible that the majority of the hardware would need to be redesigned had the lens not worked as intended.

Once the device had been fully constructed, the team needed to perform three different testing procedures associated with the actual hardware. The first test was to determine if there was ambient light entering the case through the small openings along where the lid edges meet the main enclosure box. It was important to seal the enclosure from incoming light as best as possible since ambient light could have a negative effect on the data results. To determine if there was external light coming into the case, and study the effect on the performance, the light source was turned off. Images were captured with the lid closed and room light on. The test was repeated with the room light off. The images were analyzed using ImageJ software by reading the pixel values. The results are shown in Figure 3.

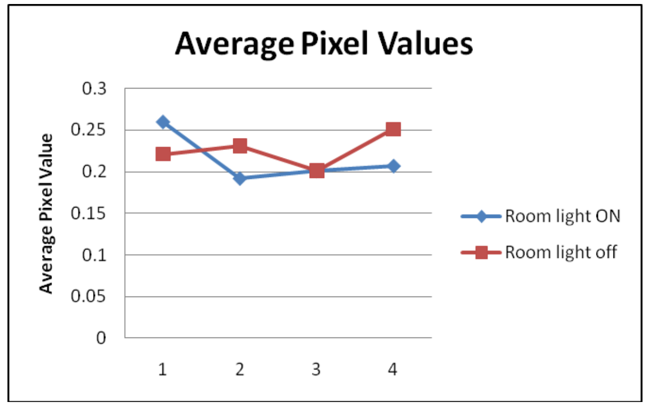

Figure 4: Results from light interference test

This test showed that almost no external light was entering the device. This meant that the results should not be affected.

The second test was to determine the effect of vibration on image capture and data results. If the device were to be bumped, moved, or jostled; how would this effect the results and to what extent? A test was performed by vibrating the device while taking data. A 10" box fan was placed on top of the device and turned on to generate a vibration. The results with vibration were compared to the normal results. No differences were observed in the results. This demonstrated that vibrations (i.e. fan, table shaking, relocation, etc) would not be an issue for the device.

The last test was to determine the temperature of the components inside the enclosure, and if the electrical parts were generating too much heat. Although the heat would likely not affect data results, it could cause damage to heat sensitive parts, such as the camera, or cause an operator to burn their hand if they are not careful. To test the temperature of the components, the device was left ON for 21 hours. The component temperatures were measured using a thermocouple and the test result is shown below:

Ambient room temperature: 75°F
Device enclosure temperature: 76 °F
LED block: 75 °F
LED back surface: 173 °F
Power supply: 90 °F
Camera: 92 °F

This test showed that temperature of the device after being left on for an extended period of time would not increase the overall interior device temperature to dangerous levels. The LEDs generate the most heat at the rear heat sink surface. This temperature will not damage the device, nor will it affect the other components.

Although the device will probably never be operated for such a long period of time, this test represents a worst-case scenario should someone accidentally leave the power on overnight.

The most important test was to use the completed device to collect data and determine if it was capable of producing accurate and repeatable results. Data was taken using samples with known gloss measurement values as a comparison. If the new device could reproduce the measurements and generate the same result multiple times, then the data result portion would be considered successful. The results would also be compared to data produced by Dr. Arney's original device in order to determine if the new device could produce equal or improved results.

RESULTS AND DISCUSSION

Achieved goals:

-Device consistency goal (+/- 5% when measuring exact same sample) met when sample is not moved and camera settings are not changed
-Program outputs match MathCAD program outputs for same input
-Samples are much easier to load and measure
-No strings needed
-No tape needed
-Device is self-contained as one unit
-Smaller than last team's device

Goals not achieved:

-Device is inconsistent when rotating sample around drum
-Cylinder not precisely aligned
-Specific size requirement not met

Test 1:

Repeating captures of the same sample without re-mounting the sample, zooming, or changing the f-stop. FOV = 11.509375mm, F-stop value = 232. Results are shown in Figure 5 and Figure 6.

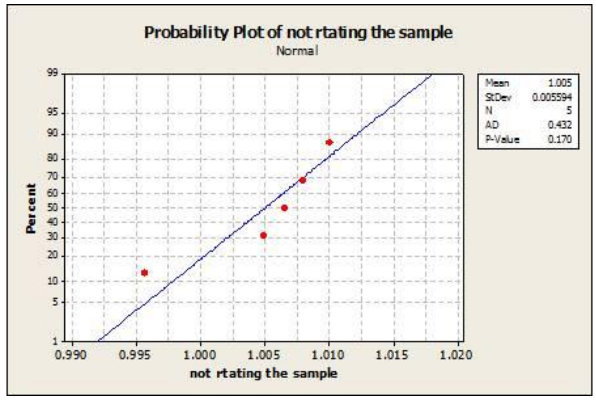

Figure 5: Probability plot of test 1

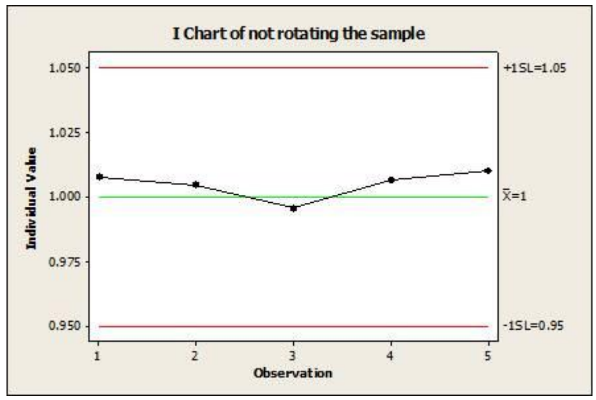

Figure 6: Control chart of test 1

-Consistently within error range (+/-5% of desired value of 1)

Test 2:

Repeating captures of the same sample without zooming or changing the f-stop, but re-mounting the sample.
-FOV = 11.509375mm, F-stop value = 232. Results are shown in Figure 7 and Figure 8.

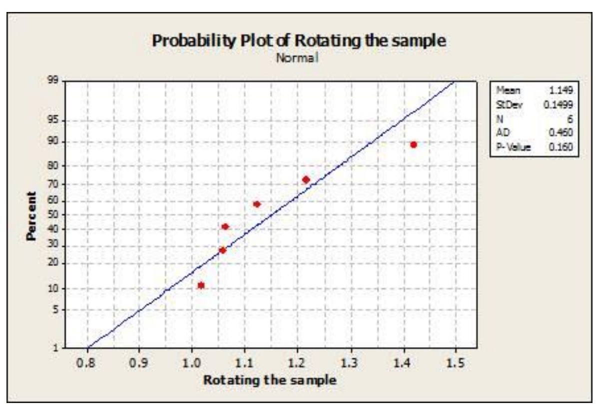

Figure 7: Probability plot of test 2

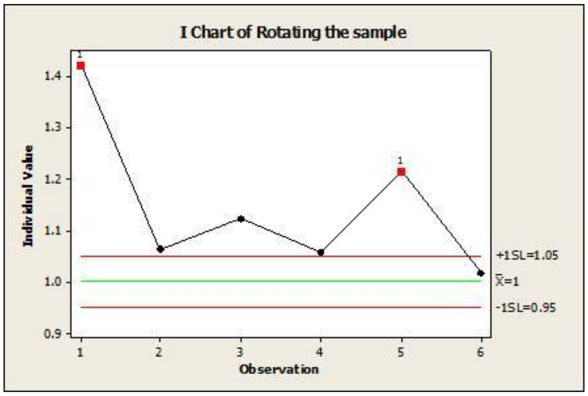

Figure 8: Control chart of test 2

-Well outside error range (+/-5%), mean value of 1.149 which is 15% higher than desired value of 1

Test 3:

Repeating captures of the same sample without changing the f-stop, or re-mounting the sample, but zoomed in
-FOV = 5.85390625mm, F-stop value = 232. Results are shown in Figure 9 and Figure 10.

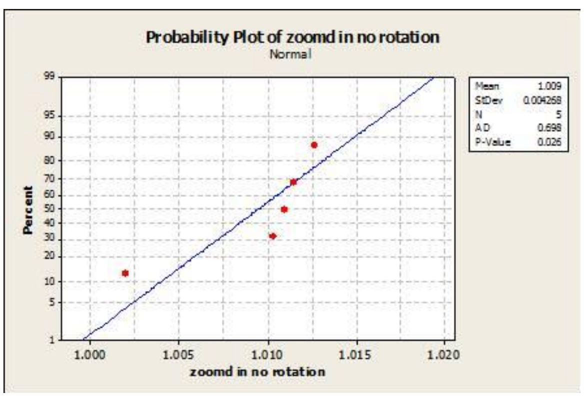

Figure 9: Probability plot of test 3

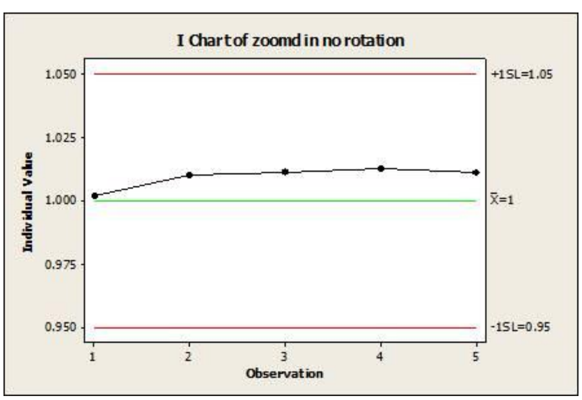

Figure 10: Control chart of test 3

-Consistently within error range (+/-5% of desired value of 1)

Problems:

- When re-mounting the same sample and running calculations, the values are running on the high side by approximately 15%.
- Reflection is also skewed (rotated) so that it is not perfectly vertical in the captured image (could be alignment problems, could also be that the sample is not held tightly to the cylinder).
- The shift causes errors in the “Auto baseline” calculation (not often used anyway).
- Re-mounting a sample also sometimes causes differences in data besides a shift.

CONCLUSIONS AND RECOMMENDATIONS

The original device was scaled down and made portable such that it could be moved as a single unit without the need to disassemble all the components. Also, the device is more user friendly than the original in terms of device setup, sample loading, software interface, and overall operation. A test subject was brought into the lab to test the device by following the video procedures developed by the team. The subject had no previous experience using the micro-goniophotometer, and did not receive any instructions aside from the provided operating procedures. It took the user approximately 30 minutes to complete the procedure from power-on to data results. The user did not have any problems or questions that would have prevented him from getting a final data result. In terms of usability and documentation, the project was successful. The customer also was pleased with the final outcome of the project despite the issues associated with obtaining an accurate data result.

Improper alignment in the physical setup of the device (as well as samples not being held tightly to the roller) caused the light bar in the captured images to be shifted to the side and rotated such that the reflection was not truly vertical. This caused errors in auto-baseline calculation (caused by the shift) and in skewness, tenth width, and half width calculations (caused by the rotation). The auto-baseline errors were correctable by using the manual baseline inputs. The statistical errors were not correctable. Errors also came from problems in the mathematical theory of the device. Using a reference area from a different zoom level would cause errors in the area and rho calculations correlated to the ratio of the reference sample's field of view to the measured sample's field of view. The calculations done by the plugin were corrected so that this problem was fixed. Further development and corrections will need to be implemented in the future to correct these problems. The device itself

FUTURE IMPROVEMENTS

-*Miniaturization*: The device can be further miniaturized by using a smaller camera, redesigning the outer casing to fit closer to the internal components, and using a different sample loading mechanism that does not translate from left to right (this may limit the versatility of the sample mount, but would allow for a smaller case.)

-*Automating the saturation adjustment*: A self sensing mechanism could be designed such that if the image is over saturated, a microcontroller will send a signal to a small DC motor to open or close the F-stop by the needed amount. The alternative would be to use a different frame grabber card which could have a function built into the software capable of adjusting the gain or sensitivity as with the original device.

-*Automating the polarizer sliding mechanism*: a microcontroller can be programmed to control a DC motor to slide the polarizer when taking a capture of a light or dark image. This should reduce the likelihood of user error, or make operation easier.

-*Integrating these processes in the program*: The saturation self-sensing mechanism, field of view adjustment and the polarizer sliding mechanism can be integrated in the Java program such that a single click button in the GUI will do the adjustments, capture the bright image, slide the polarizer, capture the dark image, and then do the analysis. Most of the microcontrollers can be programmed in C++ that can be easily integrated in/linked to any Java code. Alternatively, it would be beneficial to have the capability to discretely adjust the zoom and focal controls. This would aid in reproducing data results consistently.

REFERENCES

[1] J.S. Arney, L. YE, J. Wible and T Oswald, Analysis of Paper Gloss: March 2006

[2] ImageJ: http://rsbweb.nih.gov/ij/

[3]Java:http://java.sun.com/javase/downloads/index.jsp

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