Multi-Disciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: 10543

GONIO SPECTROPHOTOMETRIC DEVICE UPGRADE

Dale Turley, ME Student, RIT

Jason Herrling, ME Student, RIT

Dave Wagner, EE Student, RIT

Sam Seibert, ME Student, RIT

May 19, 2010

ABSTRACT

The primary goal of the Goniospectrophotometric Device Upgrade project is to retrofit an existing spectrophotometric device giving it increased functionally, precision, and autonomous control. Dr. David Wyble, an color scientist at the Rochester Institute of Technology, facilitated the project and envisions the device as a future research tool. Dr. Wyble provided the design team with specific requirements for the system. The sample holder would need an additional degree of rotation in a pitching motion, the system must be able to run completely autonomous, the device needs to be able to measure both a sample and a reference for measurement comparison, and that the user interface needs to be easy to use.

The final product is an aluminum sample holder that has been integrated into the original system and is capable of achieving three degrees of freedom: sample yaw, detector yaw, and sample pitch. Additionally, it is capable of holding both a sample and a reference tile for testing and interchanging between the two. Testing shows that the motors are capable of achieving the accuracy needed but the sample pitch and leaf motors fail for repeatability due to “drift” in the encoders. It is recommended that the system be integrated with absolute encoders to eliminate this “drift” in the future. In this paper, the design, fabrication, control, and testing processes with results will be described in detail.

NOMENCLATURE

autonomous – functions without the need of outside control
CAD - computer aided design; use of computer technology to aid in the design and production of a product. Typical CAD packages are 3D solid surface modelers.
CNC – computer numerical control; computer “controller” that reads G-code instructions to drive a machine-powered cutting tool to selectively remove material
PCB - Printed circuit board, used to electrically connect electronic components using conductive pathways, tracks or traces etched from copper sheets laminated onto a non-conductive substrate
prototype – An original, full-scale, and usually working model of a new product or new version of an existing product
reference – a rectangular shaped tile that is used as a comparison to the test sample measurements
microcontroller - a small computer on a single integrated circuit consisting internally of a relatively simple CPU, clock, timers, I/O ports, and memory
sample – a rectangular shaped tile which surface is measured for color data
spectral data – refers to different wavelengths of light which coordinate to colors on the visible spectrum
spectrophotometry [1] – the quantitative measurement of the reflection or transmission properties of a material as a function of wavelength
worm gear – A gear consisting of a spirally threaded shaft and a wheel with marginal teeth that mesh into it

yaw axis – the vertical axis about which the detector and sample holder is allowed to rotate around
pitch axis – the horizontal axis about which the sample is allowed to rotated around

INTRODUCTION

Webster's defines [2] color as "a phenomenon of light (as red, brown, pink, or gray) or visual perception that enables one to differentiate otherwise identical objects" Color is in fact how one perceives light that is reflected off of or though objects. It is also known that perceived color changes with the observation angle and the angle at which incident light reflects off of the surface. In the strict sense, we cannot directly measure perceived color; however we can measure and subsequently calculate certain factors which are responsible for producing this sensation of color. Figure (1) [3] below shows the basic phenomena of how light is reflected off a surface and observed as color by the eye.

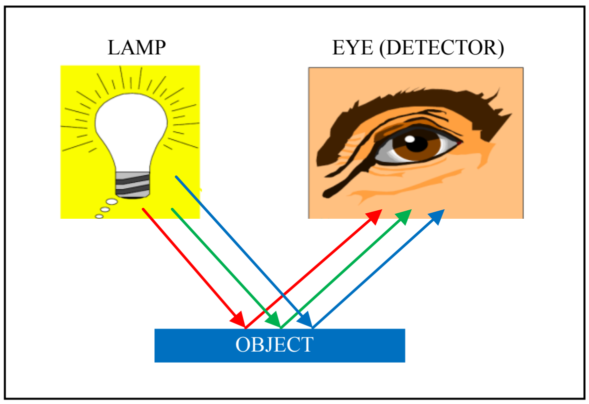

Figure (1) - Visual color process requires light source, object, and a receptor

It is not enough to only measure color in the two-dimensional realm but to describe the color of an object in a three dimensional hemisphere. To allow this the object is enabled to rotate about the horizontal axis as shown below in Figure (2) [3].

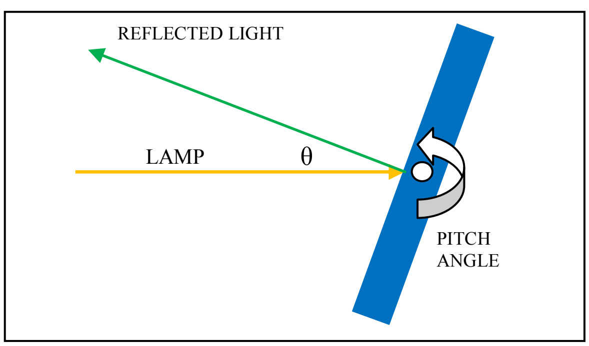

Figure (2) – Light reflects off object at a given pitch angle

Measuring spectral data with a detector at known angles of object yaw, object pitch, and detector yaw is only relatively useful if there is no basis or point of reference to go off of. To remedy this, a reference sample with known spectral data is used and compared to the test sample in order to achieve true color measurements. This concept is depicted in Figure (3) [3] where the detector measures the sample and reference at identical angles.

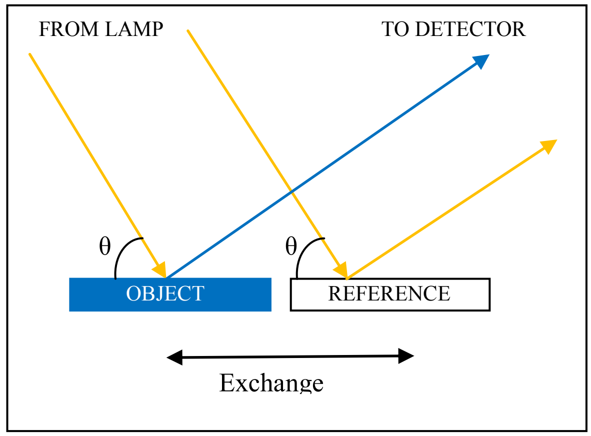

Figure (3) - Visual color process requires light source, object, and a receptor

To cater to the growing needs of the color science industry team P10543 is charged with the tasked of retrofitting a spectrophotometric device with the capabilities of pitching the sample around a horizontal axis, comparing the sample with measurement of a reference, and being able to program the device with a PC so that it can be run without the need for a manual operator. The objective of the project is to redesign the device with added functionality and to build a working prototype that professors and students in the Center for Imaging Science at RIT can use as a research tool. The working prototype will include a sample and reference holder, microcontrollers to control the operation of motors and encoders, and a software program to interface with the system.

PROCESS

Overview

In order to meet the requirements and desired outcome of the project the design team was split into four distinct groups. The groups had the following functions: Structural, Electrical, Controls, and Software. The structural group was responsible for the design and manufacture of a sample holder. The group delivered a CAD model of the holder as well as a working prototype. Tasks performed by the electrical group provided a power supply and power distribution to the platform. The group also delivered a working relay board to the controls group for motor control. The controls group was in charge of motor feedback, motor homing, as well as working with the electrical group for a safety circuit. The software group supplied a LabView interface for the user as well as subroutine code for the Arduino microcontrollers to run the motors, receive feedback from the encoders, and run the homing routine.

Holder Design Conception

One of the primary objectives of the project was to design a new sample holder that will allow for sample pitching and interchangeability between a sample and a reference. This design was subject to many constraints which were directly or indirectly provided by the customer. These constraints include:

- Dimensional constraints
- Torque and size constraints of motors
- Constraints on sample sizes to be used
- Budget constraints
- High accuracy of angular movements
- Repeatability of angular movements
- Safe to leave unattended

Figure (4) displays the CAD model conceived as a solution to the problem subject to the constraints listed above.

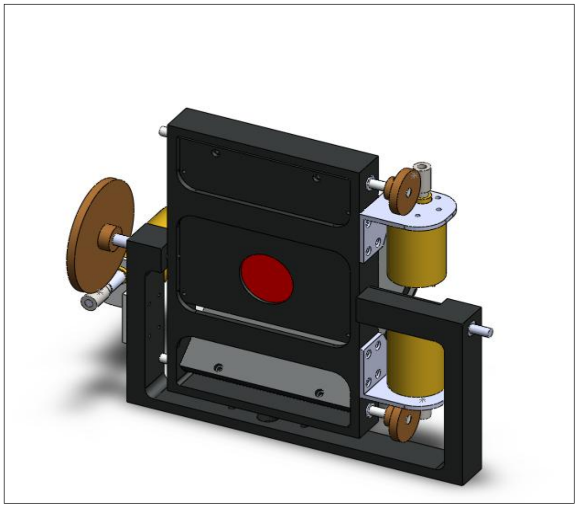

Figure (4) – CAD representation of holder design

This design has two notable features. First the holder frame is suspended on a rotational axis. The shaft is connected to a DC gear motor through a worm gear to control pitch angle of the assembly. Second, the holder frame houses both a sample and a reference. Each is attached to the frame though separate rotational shafts also connected to DC motors though worm gears. When either surface is brought flush against the frame it is in the test position. Whichever surface is not in the test position is rotated away from the frame and clear of the other sample, this is referred to as the standby position. Figure (5) shows how the sample and reference are inserted into the frame. Note that in Figure (4) the red sample is rotated into the "test" position and the white reference is rotated away into the "standby" position.

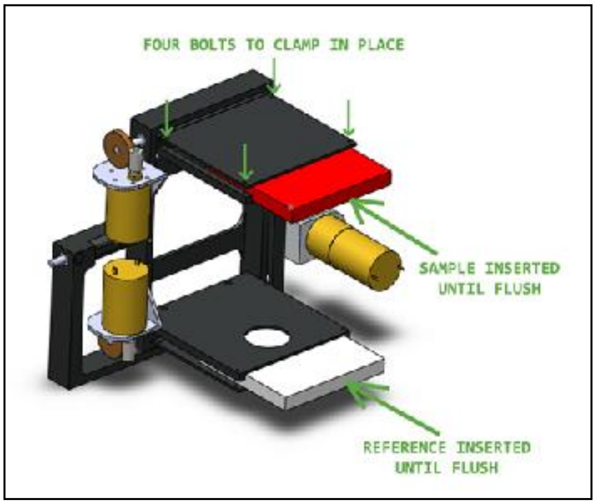

Figure (5) – Shows sample and reference being inserted into holder frame

Holder Prototyping:

CNC Machining

Due high dimensional tolerances of the shaft hole locations the team optioned to have the vertical support, the holder frame and the two leafs to be CNC machined by RIT's Brinkman Lab. Design clearances were verified using SolidWorks. Stock material (Aluminum 6061), technical drawings and CAD files were provided to the Brinkman Lab for CNC machining on an Okuma ACE Center MB-46VAE.

Manual Machining

The RIT machine shop band saw and 3-axis Bridgeport mill were used to cut and machine the stock aluminum to size for the motor brackets and back clamps. The lathe was used to machine all the drive shafts.

Tolerances

Geometric tolerance was used to ensure that the critical dimensions between the shaft holes and testing surface did not exceed the maximum allowable error of 1mm between where the light beam hits the sample and the point where both rotational axes meet on the sample holder. Interference or force fits were used between all ball bearings. Gears were attached to shafts using spring pins with interference fits.

Control System Conception

Another primary objective of the project is to automate the current device. Each of the motors uses a closed feedback loop to control precise location of the motors. Relative encoders are mounted to the drive shafts of each motor. The encoders tell the angular position of the shafts in real time so that the motors can be stopped when they reach the desired test location. The entire system is controlled by three Arduino microcontroller boards. The boards have digital input/output pins which control the motors with PWM. Each board has an internal counter which is used for the encoders. The boards have USB connection to interface with a PC and the software program. The system architecture flowchart in Figure (6) shows the flow of information throughout the system. The input to the system is a list of coordinates into the LabView program. The coordinates go to the microcontroller which tells the motors to move. When the motors have reached position based on feedback from the encoders they will stop for a detector reading. Spectral data from the detector goes back into the LabView program and is exported to a spreadsheet.

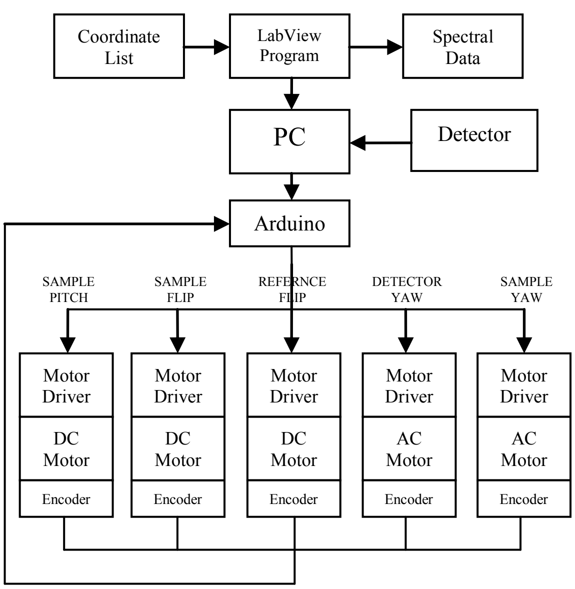

Figure (6) – System architecture flowchart

Because the encoders are relative a homing device is needed to initialize the motor locations. Upon system startup the program cannot tell where the motors are because there is no reference to measure off of. The team decided to use a Hall Effect sensor to "zero" the location of the motors. The Hall Effect sensor is a transducer that varies its output voltage in response to changes in magnetic field. The senor is attached to the rotating parts connected to the shafts and a stationary magnet is embedded into the frame, when the sensor and the magnet align an electrical switch is tripped that tells the system that the motor is currently at the "zero" position. Figure (7) below shows the Hall Effect.

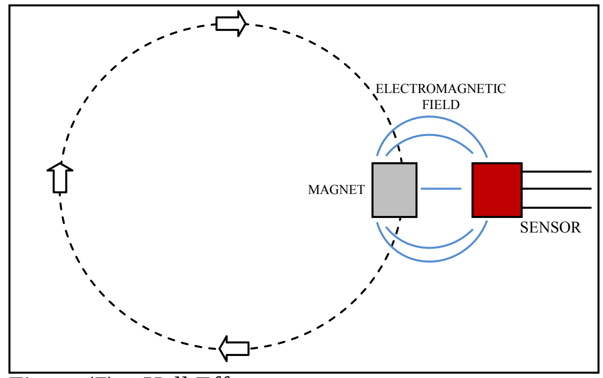

Figure (7) – Hall Effect

Controls Prototyping

To mimic the manual controls of motor speed and direction a PCB Relay was designed to replace the manual switches and potentiometers. The relay board takes the input signals from the Arduino microcontroller and enables different speed voltages to the motors and also switches the directional polarity of the motors.

Figure (8) shows a high-level schematic for the relay driver system. In order to control motor polarity, a single-pole double-throw electromechanical relay was used. The default direction is clockwise, and if the relay is energized, motor turns counterclockwise. In order to control motor speed, a variable resistance (trimmer potentiometer) was used in series with a normally closed single-pole single-throw relay. The speed is proportional to the resistance between pins 8 and 9 of the control pack. Power to the motor may be enabled or disabled by energizing a shunt normally closed single-pole single-throw relay. In order to drive these 12V relays, from Arduino we input 5V TTL levels to a transistor array chip.

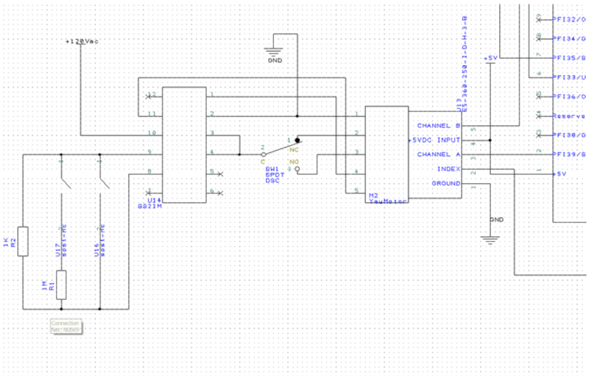

Figure (8) – Yaw motor control circuit

In order to implement the relay driving circuitry, we designed a circuit board. The PCB includes two single-pole relays, one double-pole relay, a Darlington transistor array, input for 12V power and GND, and header interfaces to the motor, control pack, and Arduino. Figure (9) shows the designed circuit and Figure (10) shows the PCB layout.

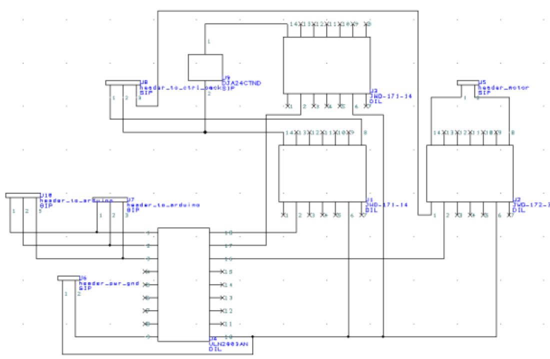

Figure (9) – Circuit for PCB

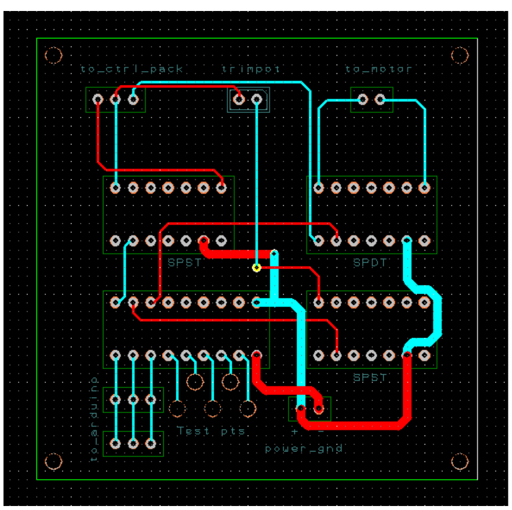

Figure (10) – PCB layout for control of each yaw motor

Software:

The software used for the automation of the system is completely customized using LabView and an abbreviated subset of C++ to program each of the Arduino microcontrollers.

LabView is implemented as an abstraction layer between the end user and the microcontrollers. This allows the user to easily work with a GUI interface while communicating via a serial interface to issue commands to each of the three microcontrollers. In addition to automating the testing procedure LabView also allows us to provide an interface to the user such that they may manually control each motor to aid in set-up of the tests and provide error recovery.

Below the LabView control layer is the C++ based code that is complied and stored on each of the three microcontrollers. The serial communication protocol in the system revolves around the use of a 6 character command string. Using these 6 characters the LabView interface is able to relay what function each of the microcontrollers must accomplish.

Due to the microcontroller's single threaded nature and the use of relative encoders on each of the monitored axis of rotation, it was determined that it was too risky to have any microcontroller move more than one motor at a time. This is primarily due to the heightened risk of interrupt collisions, which over time can add significant positional error with missed encoder ticks. By only moving one motor at a time the controller only has to monitor one encoder at a time eliminating the possibility of missing an interrupt.

The two Arduino Duemilanove controllers are responsible for positioning the sensor arm and rotating the entire fixture into appropriate angles. Each microcontroller is responsible for tracking each electronic pulse from the encoders and interpreting it into location. In addition the microcontroller must then be able to determine which direction it must rotate to position the device at the appropriate angle and then perform the move. Once this is completed the microcontroller sends a confirmation message to the LabView interface.

The final Arduino Mega controller performs much the same function as the two smaller controllers, in that it must track and position the tilt axis. However, it is also responsible for moving the test and reference samples into appropriate positions. Due to the nature of the design significant control logic is implemented to prevent the collision of the two sample holders.

Testing Procedures

The customer specified that the finished system must be accurate to within at least 1degree on every motor rotation compared to the input angle from either the program or manual controls. To test the accuracy and repeatability of the pitch and flip motors a digital camera is setup on a tripod viewing the side of the holder so that changes in angle can be observed. The sample and reference leafs will be moved to a position of 90° past the test position and then back to 55° past the test position. The test position is considered the 0° point for both leafs and positive rotation is away from the holder. The position at 55° rotation is the standby position of the leafs and the 90° position is the wide open position. After this movement an image is captured and used to determine motor accuracy. The image is uploaded into Photoshop where the angle can be measured from the image. The same process of moving the leafs back to 0° degrees, then forward to 90° and finally back to 55° is repeated 5 times without re-establishing a new "zero" in the software. An image is captured after every movement to 55°. Each image is uploaded to Photoshop where the absolute angles are measured and compared to each other for variations.

A similar test is performed to determine the accuracy and reliability of the pitch motor. Using the same camera setup the pitch motor is "zeroed" and then moved to a position of +90°. An image capture is taken in this position and used to measure the movement accuracy. The motor is then moved in the negative direction in increments of 15° until it reaches -90°, taking image captures after each 15° movement. It is then moved back in the positive direction for 15° increments until it is back at +90°. The image captures are uploaded into Photoshop and the actual angles are measured. The results will yield repeatability data of which an average loss of accuracy per degree of movement can be established.

The accuracy and repeatability of the two yaw motors can be measured using the tick marks already existing on the gears of these motors. The position of the motor will be read out by the visually inspecting the angular ticks, this will be considered the "zero" position for the test. Movements of +180°, back to 0°, and then to -180° will be made and measured by the tick marks to determine motor accuracy. The motor will then be re-zeroed and moved in the positive direction in increments of 15° input to the program. The actual angle moved will be recorded for the tick marks after each movement. Incrementing will go to +90°, back to -90°, and then forward again to +90°. The recorded data can then be used to establish an average loss of accuracy per degree of movement.

A tolerance test will be performed on the holder to verify that the machining and assembly of parts was made within specified tolerances. A dial indicator will be mounted so that the point of the indicator is hitting the test surface, exactly at the point where the light beam hits the sample. The pitch motor and sample yaw motor is then moved to ±70° and the travel distance of the dial indicator is observed. The zero position is the position so that the test surface is normal to the light source. Maximum offset of the dial indicator is recorded and compared to the specification for assembly tolerance.

Other tests are performed to ensure that the system works and are always performing as expected. The safety system is tested for functionality by purposely blowing fuses, manually running the system into limit switches and testing the emergency switch.

RESULTS AND DISCUSSION

Reliability and Accuracy Test Results:

Pitch Axis:

Accuracy: PASS
Reliability: FAIL

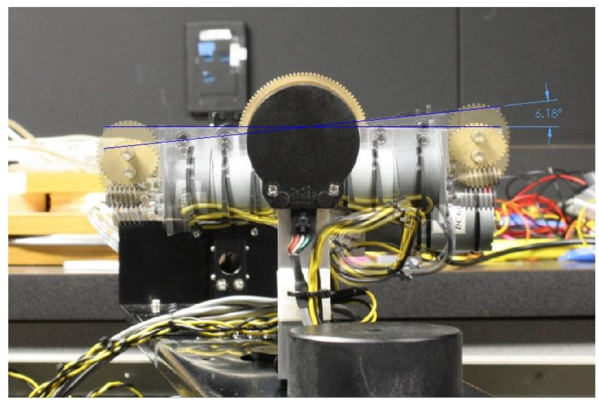

Figure (11) – Result of pitch axis reliability test

The tilt axis failed to perform within tolerance values due to encoder "drift". Initial accuracy after establishing a fresh zero point was acceptable when moved 90˚. However after running 2 cycles of a test that involved stopping every 15˚ for 5 seconds through a 180˚ hemisphere rotation the tilt axis shifted 6.18˚ from the previous baseline as seen in Figure(11). Yielding an average loss of 1˚ of accuracy for every 116˚ of movement of the axis.

Sample Holder Movement: Fail

Initial testing of the bottom leaf of the holder was successful repeatedly stopping at 55˚ 4 out of the 5 times in the test. The test involved establishing a fresh zero point, moving the sample to 90˚ and retracting back to 55˚. Then repeating this test by moving the leaf back to 0˚ and then repeat the movement, without establishing a new zero point in the software.

Testing on the top segment however was a noticeable failure. Between the initial 55˚ specified and the final 55˚ location the controller thought it was varied in excess of 40˚ by the time the last of the 5 cycles was completed.

Fixture Rotation: Pass

Rotating the fixture through 180˚ arcs demonstrated better than ±1˚ accuracy and repeatability at each of the stopping points, which were separated by 15˚. Accuracy could be improved further by enabling the slow speed of the motors and fine-tuning position at a slower speed. As of now the assembly over runs the desired position by 1 to 2 ticks of the encoder when stopping from full speed, yielding the slight variability in accuracy.

CONCLUSIONS AND RECOMMENDATIONS

In a project such as this, customer satisfaction is of utmost importance. Repeatability is paramount for a color measurement system. Therefore, the following changes should be made to the system in the future in order to get the system to a useable state for the customer. It is recommended that the relative encoders on the tilt assembly should be replaced with the originally specified (or equivalent) absolute encoders. The relative encoders are vulnerable to jitter, whereas the absolute encoders are not affected. Also, the absolute encoders prevent the need for additional homing routines. The only drawback to absolute encoders is increased cost.

The addition of springs to tension the various panels could also significantly improve results in accuracy and repeatability. The springs would mitigate the backlash caused by excess room in the gears. This would tighten the tolerances, thus decreasing the effects of vibration and gravity.

Since the Labview interface was left incomplete due to time constraints, it is suggested that the customer that use Matlab to automate the system through pre-defined serial commands from the Arduino code.

In retrospect, all of the shafts would better be made of stainless steel instead of aluminum. The stainless steel would be more robust and would achieve closer tolerances due to less deflection while turning in the lathe. However, stainless steel would take more time to machine.

REFERENCES

[1] "**spectrophotometer**." Encyclopedia Britannica. 2010. Encyclopedia Britannica Online. 13 May. 2010 <http://www.britannica.com/EBchecked/topic/558879/spectrophotometer>.

[2] Patterson, R. F. "Color." *New Webster's Dictionary*. Miami, Fla.: Paradise, 2001. Print.

[3] Guttman, Jeffray L. Real-time Goniospectrophotometer. Photon, Inc, assignee. Patent 7321423. 22 Jan. 2008. Print.

ACKNOWLEDGMENTS

The P10543 MSD team would like the express its gratitude to those that made an invaluable contribution to the project.

Many thanks to the team guide, Edward Hanzlik for his guidance and support. Additionally, the team would like to express gratitude to Dr. David Wyble and the Center for Imaging Science for his guidance, support, use of the lab and equipment, and conception of the project itself. Furthermore, we would like to recognize those whose assistance in the project was invaluable. Mr. John Wellin, Dr. Mark Kempski, Dr. Mark Hopkins, Mr. Robert Kraynik, Mr. Steven Kosciol, Mr. John Bonzo, Val Hemink and Mr. John Quenin.