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Color Sensor Comparison for Solvent Extraction Processes

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Changing the World's Energy Future

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Color Sensor Comparison for Monitoring Solutions in a Solvent Extraction Process

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JAY D. HIX

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Introduction

Idaho National Laboratory is building Beartooth, a testbed to advance research into nuclear material solvent extraction process. This testbed will give researchers the opportunity to develop novel solvent extraction processes and train early career scientist on known nuclear extraction processes for knowledge transfer. Beartooth extraction operations will include the use of centrifugal contactors designed for the recovery and purification of special nuclear materials from irradiated fuel. This new testbed will provide researchers with the opportunity to study innovative technologies in addition to solvent extraction techniques. As part of that initiative, this project will integrate non-traditional (atypical to a solvent extraction process) measurement sensors into a system of contactors to determine the state-of-health. These non-traditional sensors have the potential to enhance nuclear safeguarding efforts and other process activities. The non-traditional sensors include accelerometers, acoustic microphones, colorimetric, pH, conductivity, viscosity, density, infrared cameras, and ultra-sonic tank level sensors. This report documents the testing and evaluation of two different colorimetric sensors that measure the light in the red (R), green (G), and blue (B) color spectrum. Color sensors of this type have not be studied as a monitoring tool for solvent extraction and may provide operators additional information to optimize an extraction process.

Sensors

The first stage of this report is focused on identifying color sensors that are inexpensive and widely available. This was done by performing a literature review and identifying commercial off-the-shelf options in the market. Two sensors were identified for testing and evaluation. The first sensor identified was, the Atlas Scientific RGB sensor. The second was the Texas Advanced Optoelectronic Solutions (TAOS) TCS34725 color sensor. The first sensor from Atlas Scientific was chosen due to the weather-resistant housing, low cost, and wide availability. At the time of this writing, the cost of this sensor retailed for $56.99 USD. The second sensor from TAOS was chosen because of its low cost, small geometry package and widespread availability. The TAOS sensor retailed for $7.99.

The Atlas Scientific RGB sensor, Figure 1, has a RGB data output of 24 bits. Each of the R, G, and B values has a bit depth of 8for a total of 24 bits. The sensor also has onboard LEDs for optimal illumination of the test subject. The sensor can read a data set every 400 milliseconds and operates at a voltage of 3.3-5V. The small photo-eye located in the center of the senor has a sensing area of 15-degrees. This sensor also is IP67 water-resistant and dustproof up to 1 meter. The data format for the Atlas sensor is ASCII and deploys a data protocol of UART and I^2C. This sensor is least sensitive to blue and most sensitive to red. The sensor is most effective at distances less than 5cm. At larger distances (> 20cm) the color will have a darker shade. The greater the distance (>45cm), the color will vary and become different shades of grey [1]. Sensor programming includes 18 different ASCII commands for input and output. The most common commands used in this project are listed in Table 1.

Figure 1. Atlas Scientific Colorimetric RGB Sensor

Table 1. ASCII Command list

ASCII Command	Function
C <cr>	Enable/disable continuous read mode
C, 1<cr>	Enables continuous reading once per 400ms
C, n	Continuous reading every n*400ms (n…99)
Cal <cr>	Performs Calibration
L <cr>	Enable/disable target led
L, % <cr>	Sets target LEB brightness percentage

The TASO TCS34725 RGB sensor, Figure 2, returns a digital 8-bit number for each of the R, G and B values. This device also employs an on-chip integrated IR blocking filter. The sensor also has a wide dynamic range of 3,800,000:1 and a sensing area of 30 degrees. In contrast to the Atlas Scientific RGB sensor, the TASO senor is not IP67 waterproof or dustproof. The TASO sensor communicates over a 2-wire I^2C serial bus, at speeds up to 400 kHz. [2] The sensor chip is designed to be coupled to an Arduino or raspberry pi and operates ideally at 3.3-5V. The TASO RGB sensor is most sensitive to light in the red spectrum and least sensitive to light in the blue spectrum. The sensor is more reliable the closer it is to the source, within 10cm. At distances greater than 10cm, the sensor will have a difficult time deciding what color the subject is. The most common commands used in the program the TASO are listed in Table 2.

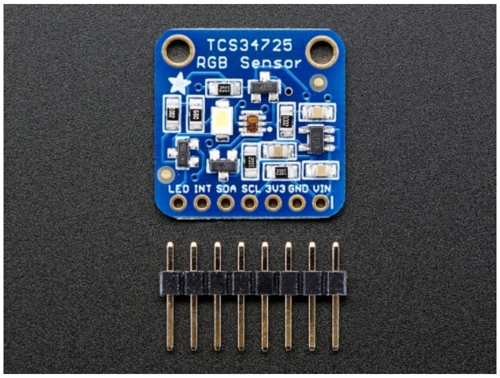

Figure 2. TASO Colorimetric Sensor

Table 2. TASO command list

Command	Function
DigitalWrite(pinLED, High)// Low	Enables or disables LED function
Tcs.getRawData(&r, &g, &b);	Gets color data for red, green, and blue
Serial.print(r,g,b,DEC)	Prints the data to the serial port

Communication

The Atlas Scientific RGB sensor data was streamed through the serial port and read using LabVIEW. The TASO senor was programmed in the C/C++ language via example code, using an Arduino for the micro controller and power source to the sensor. LabVIEW was also used to read the data stream from the Arduino.

The Atlas Scientific RGB senor needed a basic USB to serial converter between the sensor and computer, pictured in Figure 3. This was required to stream the data from the sensor to the computer's serial port. Using LabVIEW, a serial driver was programmed to communicate with a COM port at a baud rate of 9600. The LabVIEW program, pictured in Figure 4, reads the data in the buffer and if the bytes per frame match

Figure 3. USB to serial converter

what's expected, a conditioned loop executes. Once the conditional loop executes, it will parse out the red, green, and blue data values. Once it handles the RGB values it sends it through a RGB to Color function. This then displays the color to the Graphical User Interface (GUI) in the LabVIEW front panel. As seen in Figure 7.

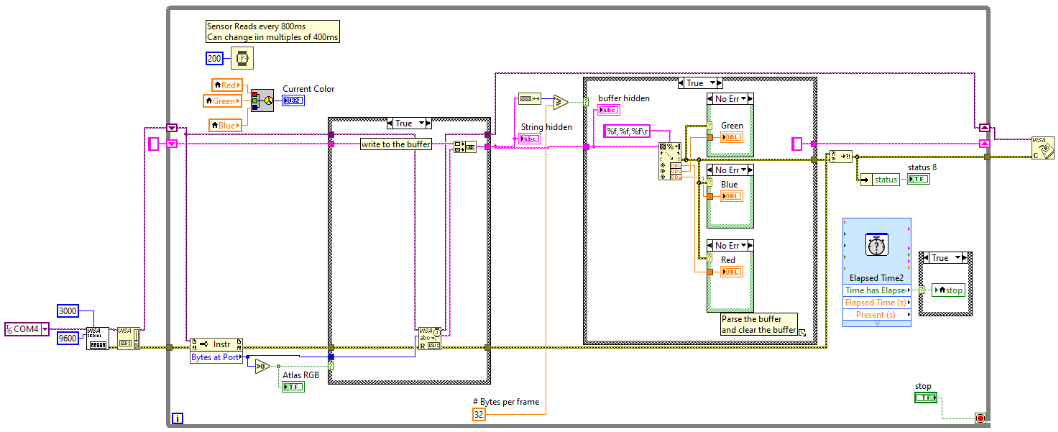

Figure 4. Atlas Scientific RGB sensor read serial port program

The TASO sensor was programmed using an open-source code from Adafruit [3]. Some aspects of this code were modified to output the data in a specific format. This code was downloaded to the Arduino to run independently. When the code was imported onto the Arduino, a windows terminal was used to ensure that the data stream was properly displayed. Using LabVIEW, a serial driver was programmed at a baud rate of 9600 to read the COM port of the Arduino. Similarly to the Atlas Scientific sensor, the TASO reads the data in the buffer and if the bytes per per frame matches what's expected a conditional loop executes. When the loop executes, it will parse out the red, green, and blue data values and send them to a RGB-to-Color function that will display the color on the GUI. Figure 5, shows the code that reads the serial port.

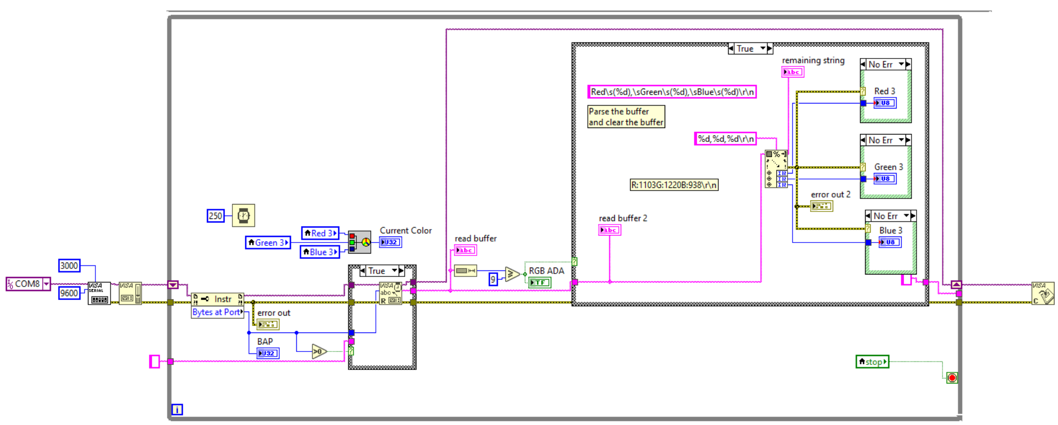

Figure 5. TASO RGB sensor read serial port program

A small loop was written to open and save data to a text file. The following operations are run in parallel: A file path is chosen at the start of collection, and a file name is given by using this format year, month, day, hour, and minute. Inside the file, a header is used to concatenate the data below its respective header. Local variables, for each of the RGB values, for the Atlas and TASO sensors are used to write the respective data to the file under its corresponding header. The data is collected every 10 seconds. Figure 6, shows the file save loop.

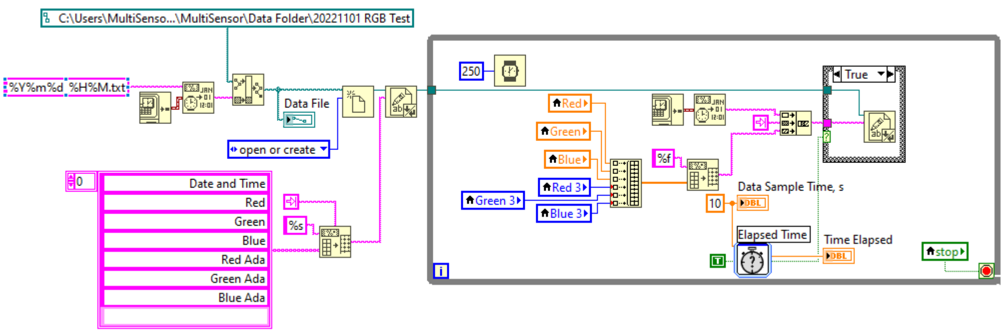

Figure 6. Save data to file loop.

The file path, sample time, elapsed time, RGB values, and corresponding color indicators are displayed on the GUI (Figure 7). Appendices 1 & 2 show the LabVIEW program and the open-source code for the Atlas and TASO sensors. In addition, Appendix 3 shows an example of the text file that is generated during a test.

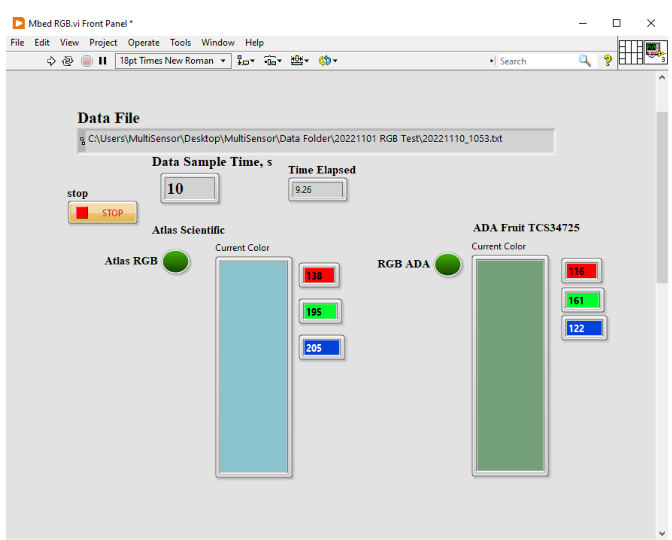

Figure 7. Graphical User Interface

A Teflon collimator was custom-built to adequately read the RGB color values in liquid. The collimator allows the fluid to flow into a cup-type apparatus to enable the sensor to accurately identify the color. The collimator has an input hole and a fill hole to allow air to escape. Without this collimation the Atlas or TASO senor could not adequately process the color.

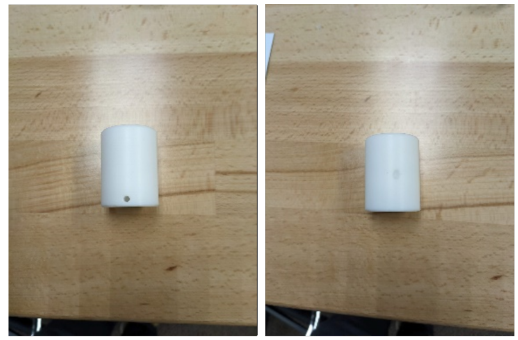

Figure 8. Pictured on the left shows the hole to allow the fluid into the collimator. Pictured on the right shows the fill hole, this allow excess air to be removed.

Testing and Evaluation

The final stage of this project tested the sensors in a laboratory environment with several solutions of different colors to demonstrate their capabilities, limitations, and benefits. The Atlas Scientific and TASO sensors were tested against several colors and color concentrations. The colors include Molybdenum $MoCl_5$, Nickel Sulfate $NiSO_4$, Ammonium Metavanadate NH_4VO_3, Erbium Nitrate $Er(NO_3)_3$, Copper Nitrate $CuNO_3$, Iron Nitrate $Fe(NO_3)_3$, Titanium Chloride $TiCl_3$, and nano pure water H_2O. These colors were diluted in H_2O.The first experiment used Copper Nitrate to test the on-sensor LEDs. The LEDs were used to illuminate the sample for color detection. Copper Nitrate is blue in color and chosen because both sensors are less sensitive to light in the blue spectrum. This test demonstrated the accuracy of each sensor in the blue color solution and how the LEDs support the measurement. Pictured in Figure 9 are the sensors under test.

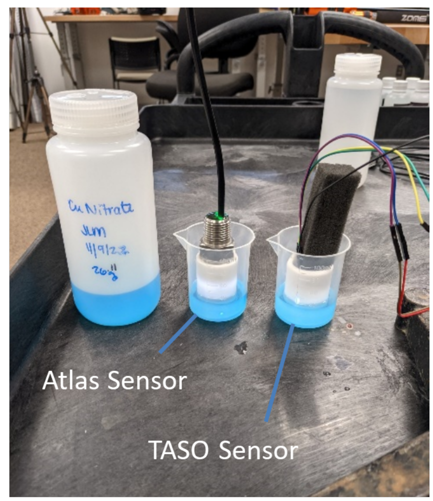

Figure 9. LED and Color experiment

Pictured in Figure 10 are the results of the of the LED and Copper Nitrate experiment. The picture on top in Figure 10, is with the Atlas Scientific sensors LEDs turned off, and the TASO LEDs turned on. The picture on the bottom in Figure 10, is with the Atlas Scientific sensors LED turned on, and the TASO LEDs turned off. The results suggest that the Atlas Scientific sensor works better with the LEDs on and the TASO sensor works better with the LED turn off. Although the TASO sensor suggested that the color is green. Though, in reality it is closer to blue than, the red color it recommended with the LED turned on. The rest of the data that has been collected is with the Atlas Scientific sensor LEDs turned on and the TASO sensor LEDs turned off.

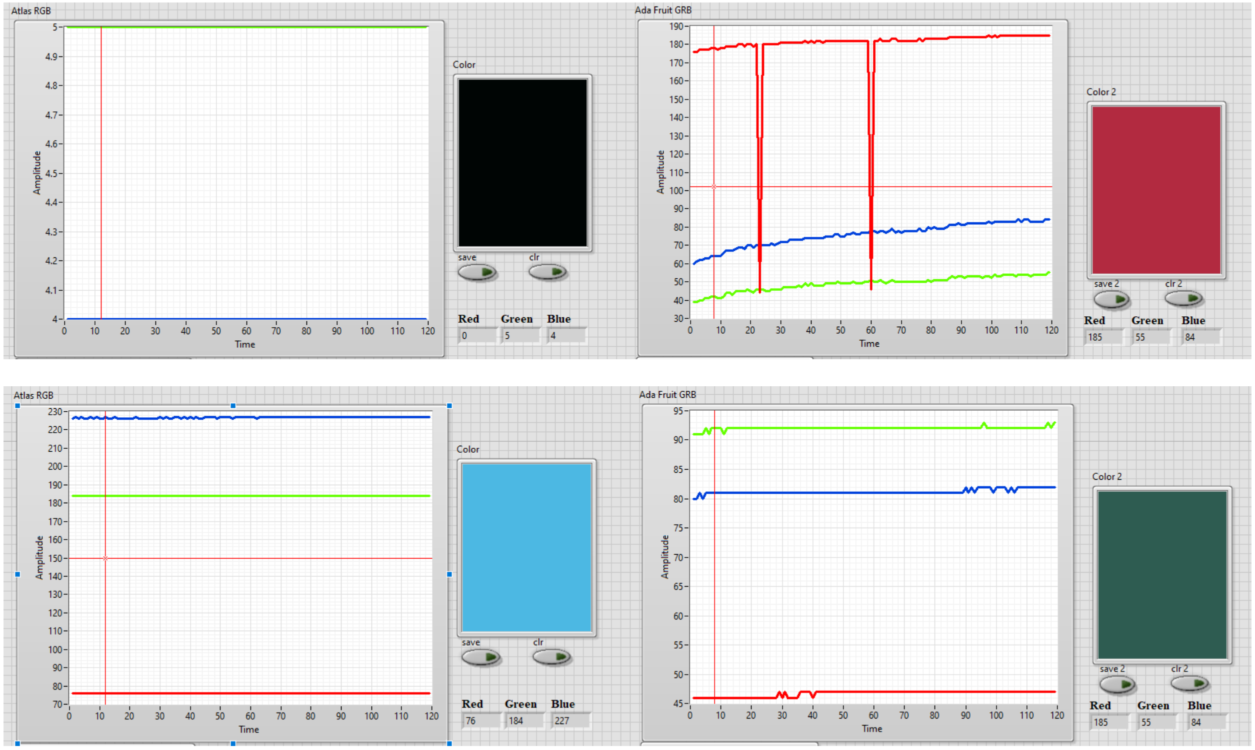

Figure 11. Atlas and TASO Sensor LED Experiment

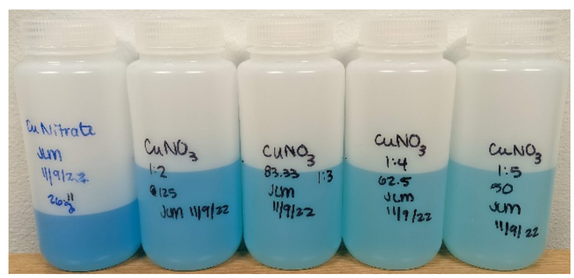

Figure 10. $CuNO_3$ Concentrations

The second experiment used Copper Nitrate, however, the solutions had different concentrations. The 1:1 concentration is 26g of $CuNO_3$ per 500ml of H_2O. The solution color concentrations are pictured in Figure 11. The weight percent of the concentration (w%) and the RGB values, averaged every 10 seconds for 20 minutes, are shown in Table 3. Pictured in Figure 12 on the left, is the Atlas Scientific sensors RGB values and color representation. Pictured on the right, is the TASO RGB values and color representation for each of the concentrations.

Table 3. Concentration and RGB values for $CuNO_3$

$CuNO_3$	w%	Atlas R	Atlas G	Atlas B	TASO R	TASO G	TASO B
1:1	5.222	76	184	226.725	46.70833	91.96667	81.175
1:2	2.700	105	196	218.875	62.46667	114.95	91.6
1:3	1.799	118.9583	192.7333	207.025	77.55	122.6667	93.55
1:4	1.350	123.1	192.0667	203.85	89.70833	136.8417	101.75
1:5	1.080	140.95	197.375	206.4167	137.35	190.5417	150.0417

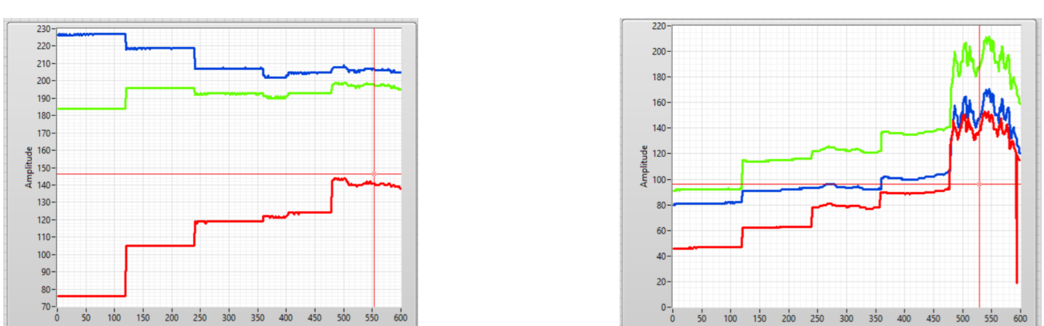

Figure 12. RGB values and color representation for $CuNO_3$ Concentrations

The next concentration experiment was with Nickel Sulfate. The 1:1 concentration was a mixture of 21.12g of $NiSO_4$ per 500ml of H_2O.The color concentrations of the Nickel Sulfate are pictured in Figure 13. The concentration weight percentage (w%) along with the RGB values are shown in Table 4. The RGB values were data averages collected every 10 seconds for 20 minutes. Pictured in Figure 14 on the left, is the Atlas Scientific sensors RGB values and color representation. Pictured on the right, is the TASO RGB values and color representation for each of the concentrations.

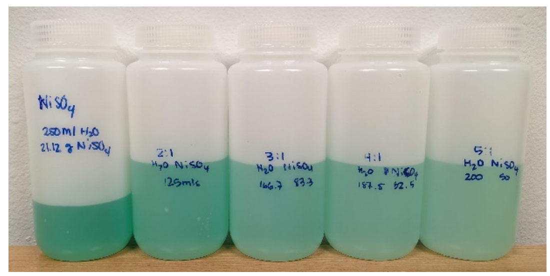

Figure 13. $NiSO_4$ Concentrations

Table 4. Concentration and RGB values for $NiSO_4$

$NiSO_4$	w%	Atlas R	Atlas G	Atlas B	TASO R	TASO G	TASO B
1:1	4.224	96	175.0167	145	58	100	53
1:2	2.112	137	205.9417	181.9583	89.59167	116	68
1:3	1.407	161	219.425	199.575	96	119.775	69.475
1:4	[illegible]	[illegible]	[illegible]6.9333	211.008[illegible]	[illegible]	[illegible]	[illegible]
1:5	[illegible]	[illegible]	[illegible].95	216.97[illegible]	[illegible]	[illegible]	[illegible]00833

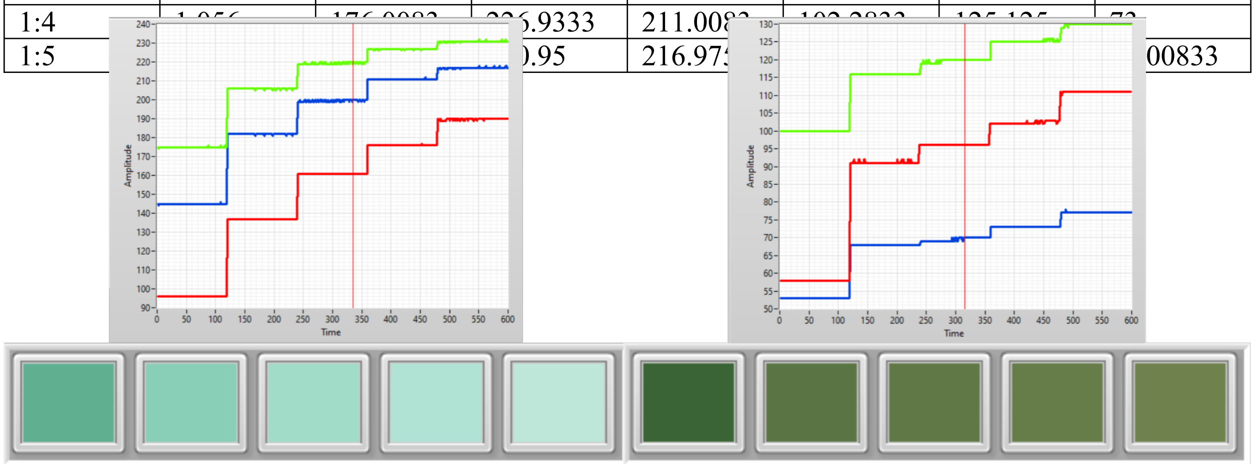

Figure 14. RGB values and color representation for $NiSO_4$ Concentrations

A series of different color solutions were also tested to understand how the RGB sensors would respond. The colors include Molybdenum $MoCl_5$, Nickel Sulfate $NiSO_4$, Ammonium Metavanadate NH_4VO_3, Erbium Nitrate $Er(NO_3)_3$, Copper Nitrate $CuNO_3$, Iron Nitrate $Fe(NO_3)_3$, Titanium Chloride $TiCl_3$, and nano pure water H_2O. These colors were diluted in H_2O. Table 5 shows the grams per milliliter of solution in H_2O and its weight %. It also shows the average RGB values. The data was collected every 10 seconds during 20-minute measurement intervals. Figure 15 shows the Atlas Scientific sensors RGB values and color representations. Figure 16 shows the TASO sensors RGB values and color representations.

Table 5. Color solutions and their corresponding weight % and RGB values

Solution g/ml(H_2O)	W%	Atlas R	Atlas G	Atlas B	TASO R	TASO G	TASO B
$MoCl_5$ 5.64g/500ml	1.128	144.075	57	44	112.3583	70.9	61.70833
$NiSO_4$ 21.12g/500ml	4.224	96	175.0167	145	58	100	53
NH_4VO_3 7.04g/250ml	2.826	252.7583	217.9833	141.6083	215.6167	170.9	77
$Er(NO_3)_3$ 36.6g/250ml	14.640	225.4833	166.9833	155.9667	152.2083	96.09167	55.29167
$CuNO_3$ 13.5g/250ml	5.400	76.94167	184.925	226.05	43.39167	92.35833	77.85
$Fe(NO_3)_3$ 27.0g/250ml	10.800	153.0333	67.01667	43.975	106.125	41.18333	19.19167
$TiCl_3$ 3.08g/250ml	0.392	222.4917	222.5167	235.8667	88.66667	62.45833	40.35833
H_2O 500ml		229	228.1	226	184.717	156.66667	107

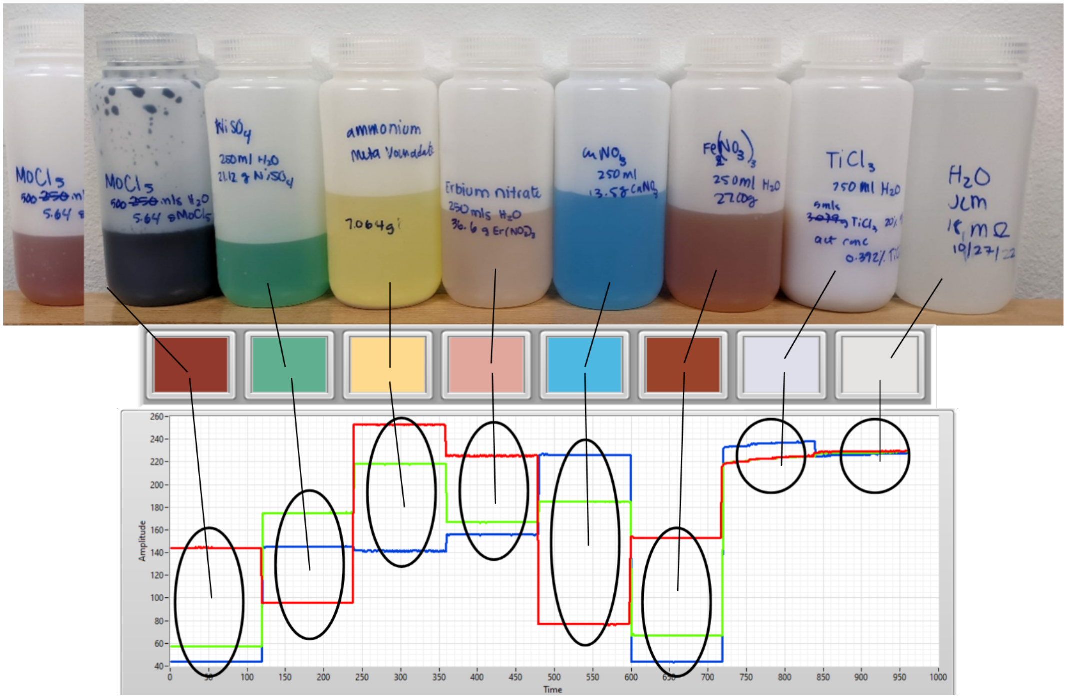

Figure 15. Atlas Scientific RGB data values and corresponding color representations

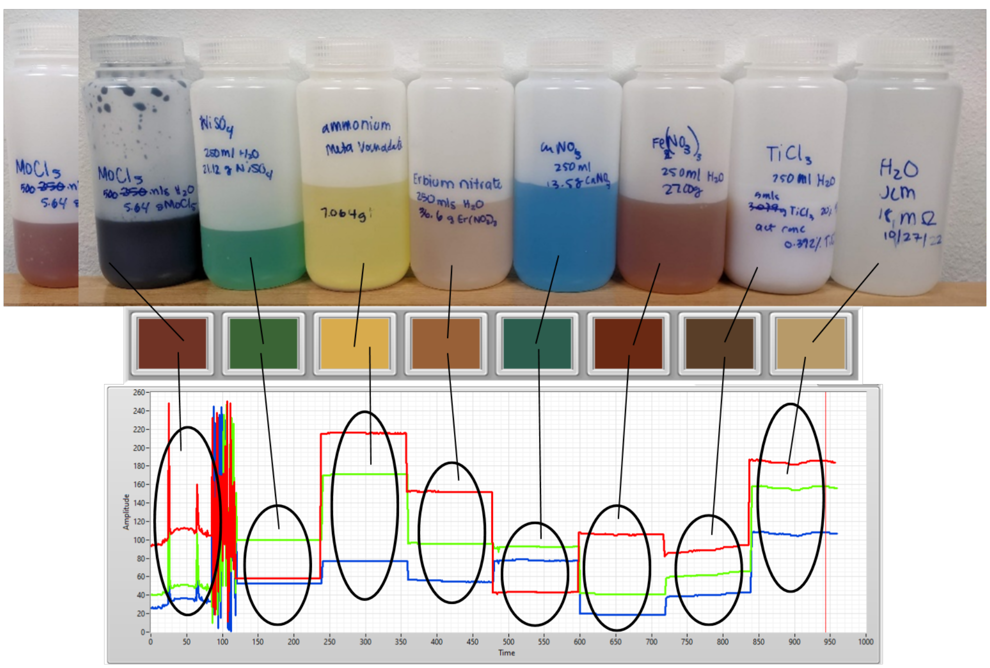

Figure 16. TASO RGB data values and corresponding color representations

The results from the first concentration experiment, using $CuNO_3$, show the TASO sensor had a difficult time stabilizing the RGB values as the color got lighter. This is observed in Figure 12 between ~475 and ~600 s and results from the TASO sensor being lease sensitive in the blue spectrum. In addition, the color measured by the TASO sensor was more green than blue.

In the $NiSO_4$ concentration experiment, the TASO sensor was more stable than the first experiment. However, the sensor measured the color closer to a forest green rather than a lighter green color, as seen in Figure 14. It was closer to determining the observed color than it was in the $CuNO_3$ color solution. In determining the different color solutions, the TASO had a difficult time with the $CuNO_3$, $TiCl_3$, and the H_2O. It was able to detect the different color solutions, yet it still it deployed a darker shade of color. But none the less it still, resolved the color.

During both color concentration experiments the Atlas Scientific senor was more stable throughout the experiment, than the TASO sensor. During the $CuNO_3$ in the 1:5 concentration the Atlas did show slight variation in the RGB values seen in Figure 12. It was more stable than the TASO sensor as they are both least sensitive to the blue light spectrum.

In comparison, the Atlas Scientific sensor outperformed the TASO sensor. In both the color concentration experiments as well as the different color series. The Atlas sensor was more stable during experiments when measuring the RBG values. The Atlas sensor also gave a closer color determination for the represented colors. The Atlas scientific RGB sensor was chosen, not only because it outperformed the TASO sensor, but also for the form factor. The Atlas sensor is already waterproof and hardened for harsh environments whereas the TASO sensor would need more work to get to a waterproof state.

References

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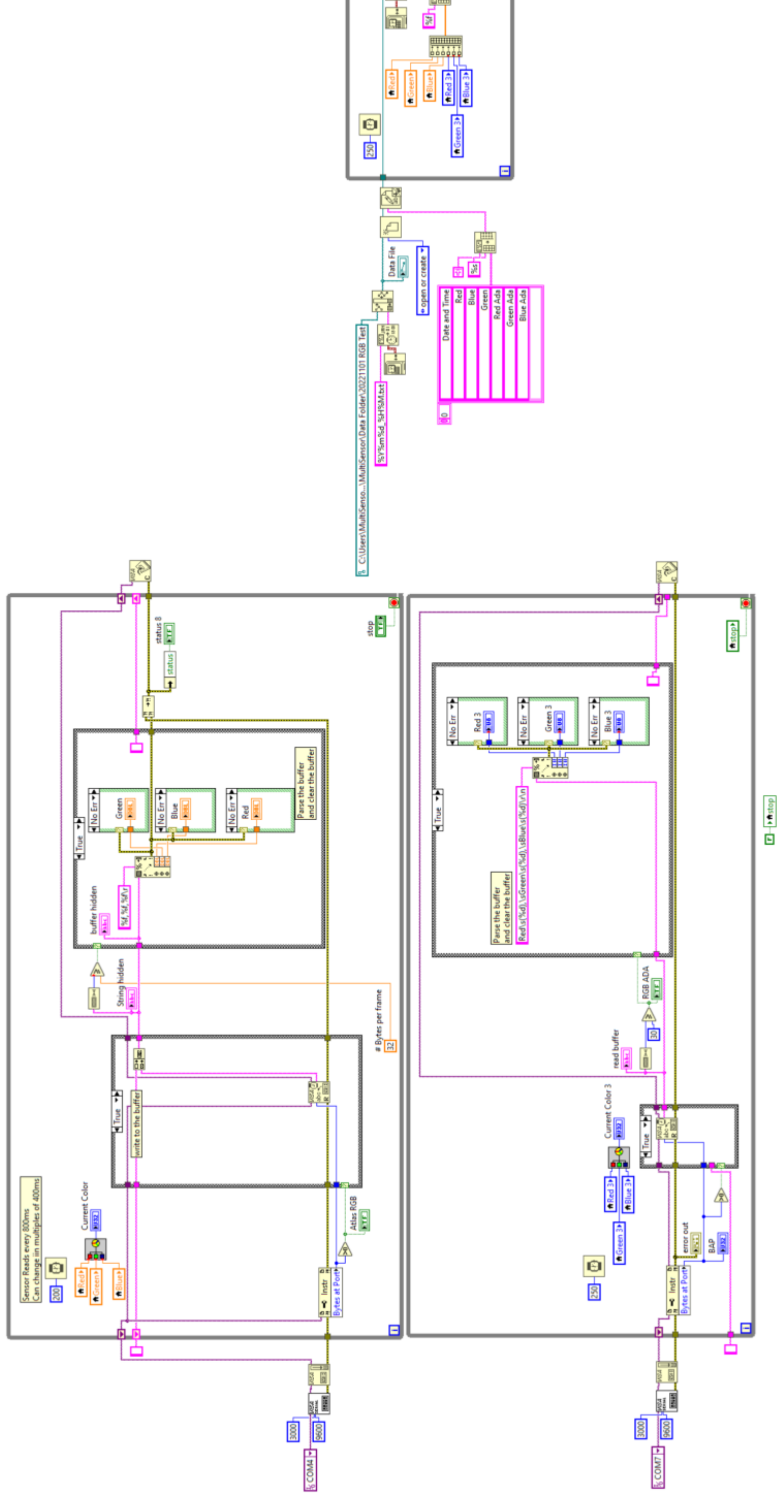
3. Earl, Bill. “Adafruit Color Sensors.” *Adafruit Learning System*, https://learn.adafruit.com/adafruit-color-sensors/arduino-code.
4. Industries, Adafruit. “RGB Color Sensor with IR Filter and White LED - TCS34725.” *Adafruit Industries Blog RSS*, https://www.adafruit.com/product/1334#description.

Appendix 1.

LabVIEW Program



Appendix 2

TASO RGB open source code.

```
#include <Wire.h>
#include "Adafruit_TCS34725.h"
/* Example code for the Adafruit TCS34725 breakout library */
/* Connect SCL    to analog 5
   Connect SDA    to analog 4
   Connect VDD    to 3.3V DC
   Connect GROUND to common ground */
/* Initialise with default values (int time = 2.4ms, gain = 1x) */
// Adafruit_TCS34725 tcs = Adafruit_TCS34725();
/* Initialise with specific int time and gain values */
Adafruit_TCS34725 tcs = Adafruit_TCS34725(TCS34725_INTEGRATIONTIME_614MS, TCS34725_GAIN_1X);
const byte pinLED = A0; // Pin on your microcontroller
void setup(void) {
  Serial.begin(9600);
pinMode (pinLED, OUTPUT);
  if (tcs.begin()) {
    Serial.println("Found sensor");
  } else {
    Serial.println("No TCS34725 found ... check your connections");
    while (1);
  }
}
void loop(void) {
  uint16_t r, g, b, c, colorTemp, lux;
digitalWrite(pinLED, HIGH); // Turn LED on, LOW turns it off
  tcs.getRawData(&r, &g, &b, &c);
  // colorTemp = tcs.calculateColorTemperature(r, g, b);
  colorTemp = tcs.calculateColorTemperature_dn40(r, g, b, c);
  lux = tcs.calculateLux(r, g, b);
Serial.print(r,DEC); Serial.print("");
  Serial.print(","); Serial.print(g,DEC); Serial.print("");
  Serial.print(","); Serial.print(b,DEC); Serial.print("");
  Serial.println("");
}
```

Appendix 3

Data file example

Date and Time	Red	Green	Blue	Red Ada	Green Ada	Blue Ada
11/10/2022 8:14	76	184	227	140	241	236
11/10/2022 8:14	76	184	227	142	244	241
11/10/2022 8:14	76	184	227	144	247	248
11/10/2022 8:15	76	184	227	148	253	1
11/10/2022 8:15	76	184	227	150	2	8
11/10/2022 8:15	76	185	227	155	9	15

11/10/2022 8:15	76	184	227	158	12	21
11/10/2022 8:15	76	184	227	160	15	25
11/10/2022 8:15	76	184	227	162	17	27
11/10/2022 8:16	76	184	227	163	18	30
11/10/2022 8:16	76	184	227	164	19	32
11/10/2022 8:16	76	184	227	166	22	35
11/10/2022 8:16	76	185	227	167	24	38
11/10/2022 8:16	76	185	227	168	26	41
11/10/2022 8:16	76	184	227	169	27	43
11/10/2022 8:17	76	184	227	169	29	44
11/10/2022 8:17	76	184	227	170	30	46
11/10/2022 8:17	76	184	227	170	30	47
11/10/2022 8:17	76	184	227	171	33	49
11/10/2022 8:17	76	184	227	172	33	50
11/10/2022 8:17	76	185	227	171	33	50
11/10/2022 8:18	76	184	227	172	35	53
11/10/2022 8:18	76	184	227	173	35	54
11/10/2022 8:18	76	184	227	173	35	54