Low Cost Colour Sensors for Monitoring Plant Growth in a Laboratory

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Abstract— **An automated system for measuring plant leaf colour, as an indicator of plant health status, has been developed for plantlets growing in a modified micropropagation system. Using a custom built robotic arm, sensors located on a pan and tilt system at the end of the arm monitor plant growth and the ambient growing environment. Sensors include a compact colour zoom camera, RGB (red, green and blue) colour sensors, and environmental sensors. Leaf colour sensors provide information, in a non-destructive manner, on the health status of tissue by comparing the sensor outputs to pre-determined optimum values. These low cost colour sensors can be incorporated into a continuous automated system for monitoring leaf colour of growing plants. Subtle colour changes can be an early indication of stress from less than optimum nutrient concentrations. When combined with automated image sensing for growth analysis, and environmental sensing (RH, CO_2 and temperature) in a controlled environment, optimised rapid growth with minimal human input can be achieved using a modified micropropagation system. In this paper we detail the calibration technique for a RGB sensor and compare it with a high end spectrophotometer.**

Keywords - plant growth monitoring, colour sensor calibration, RGB colour sensor

I. INTRODUCTION

Robotic and automated systems are becoming increasingly common in all economic sectors. In the past decade there has been a push towards more automation in the horticulture industry, and it is only now, as robots become more sophisticated and reliable, that we are beginning to see them used to undertake routine, often repetitive tasks, which are expensive to do using a highly paid labour force. With rapid strides in technological advancement, more and more applications have become possible. These include the development of a robotic system for weed control [1], a system for automatic harvesting of numerous agri-science products such as cutting flowers grown in greenhouses [2] and automating cucumber harvesting in greenhouses [3]. Advances in electronics have empowered engineers to build robots that are capable of operating in unstructured environments [4]. Camera-in-hand robotic systems are becoming increasingly popular, wherein a camera is mounted on the robot, usually at the hand, to provide an image of the objects located in the robot's workspace [5]. Increasingly, robots are being used to sort, grade, pack and even pick fruits. Fruits can be identified and classified on a continuously moving conveyer belt [6]. An autonomous wheeled robot has been developed to pick kiwifruit from orchard growing vines [7]. Robotic techniques for production of seedlings have been developed, identifying a need to add a machine vision system to detect irregularities in seed trays and to provide supplementary sowing using a 5-arm robot [8].

Automation of micropropagation for the rapid multiplication of plants has been described for the micropropagation of a grass species that replaces the costly and tedious manual process [9]. A system has also been developed that combines plant recognition and chemical micro-dosing using autonomous robotics [10].

Colour as a means of assessing quality is also gaining popularity amongst researchers. These include evaluating bakery products using colour-based machine vision [11], monitoring tea during fermentation [12], grading specific fruits and vegetables [13, 14, 15] and in the health sector to determine blood glucose concentrations [16]. Near infrared (NIR) sensors are also gaining popularity as non-destructive means of assessing fruit and plant material, including use as a measure of plant nutrient status [17] as well as testing of fruit quality [18, 19, 20].

Investigation into non-destructive methods to measure the health status of plants is a relatively new area of research. Subtle leaf colour changes can be used as a measure of plant health. Although limited work has been carried out in real time, a recent micropropagation-based system used potato tissue images captured via a digital camera then scanned to identify the colour of selected pixels [21]. Spectral reflectance, using a range of spectral bands, has been used as a non-destructive measure of leaf chlorophyll content in a range of species [22]. Alternative methods make use of spectroscopic systems using a fixed light source to record colour reflectance of multiple samples [23].

This paper focuses on the use of low cost colour sensors for monitoring leaf colour of plant tissues growing in a modified micropropagation system. The calibration method of these sensors is described and its accuracy evaluated.

II. OVERVIEW OF SYSTEM HARDWARE

The reported system uses an autonomous robotic arm containing RGB (red, green and blue) colour, environmental and proximity sensors as well as a compact colour camera.

Custom software created in Microsoft® Visual Studio (VB.net) allows for a completely automated operation that requires minimal human input.

A. Robotic Arm

The robotic arm, shown in Figure 1, uses five stepper motors that are controlled through a motor controller and micro-step driver [24]. To allow the robotic arm to move vertically, a ball screw and shaft assembly is incorporated, converting rotational motion into vertical movement. The arm contains a pan and tilt system at its distal end, which houses a camera [25], colour and proximity sensors [26]. The operation of the arm is completely automated, continually gathering information from the sensors and capturing images for assessment and analysis.

The arm uses bipolar, high torque stepper motors, which provide a maximum torque of 12.3 kg/cm. and have a step angle of 1.8°. The use of a micro step driver allows the user to select an even finer resolution (i.e. more steps per revolution). The motors are controlled through a motor driver board that allows commands to be sent from the PC via a USB port to the controller to control the movement.

Figure 1. SolidWorks rendered photo of the robotic Arm.

B. Colour Sensors

Currently there are a number of colour sensors on the market, with prices ranging from low cost light-to-frequency chips to sophisticated and very expensive spectrophotometers.

Parallax (Parallax Inc, CA, USA) has two colour sensors that integrate seamlessly with their Basic Stamp microcontroller. Both the ColorPAL and TCS 3200 colour sensors are provided with some source code, making them amenable to integrating into our customised system.

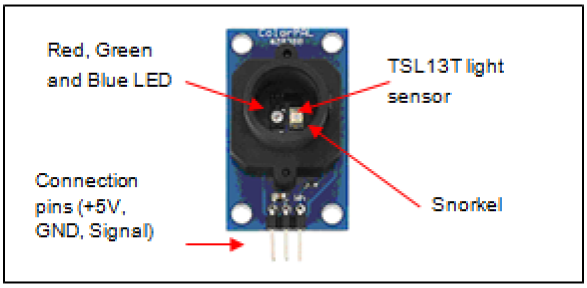

Figure 2. Parallax ColorPAL colour sensor.

The ColorPAL sensor (Figure 2) illuminates a sample using in-built red, green and blue LED light sources (one colour at a time) and records the quantity of light reflected back from the object. The ColorPAL makes use of a TAOS (Texas Advanced Optoelectronic Solutions) light-to-voltage chip. When light is reflected, the voltage, which is proportional to the light reflected, is used to determine the sample's R, G and B colour contents. The ColorPAL requires the sample to be illuminated using each of the red, green and blue LEDs, with a 'snorkel' to shield possible interference from external light sources. This requires the ColorPAL to be in direct contact with the object for an optimum reading without interference.

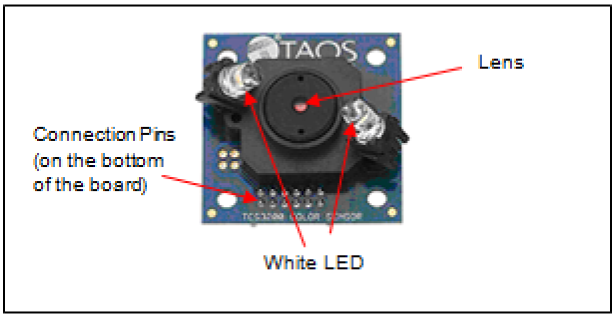

Figure 3. Parallax TCS3200 colour sensor.

The TCS3200 Colour sensor (Figure 3) makes use of a TAOS TCS3200 RGB light-to-frequency chip. The TCS3200 colour sensor operates by illuminating the object with two white LEDs, while an array of photo detectors (each with a red, green, blue and clear filter) interpret the colour being reflected by means of a square wave output whose frequency is proportional to the light reflected. The TSC3200 Colour sensor has a 5.6-mm lens, which is positioned to allow an area of 3.5 mm^2 to be viewed.

A USB4000 spectrometer (Ocean Optics Inc., FL, USA) was used to find the height at which the greatest intensity of light occurred when the RGB sensor was placed above a sample. As the two white LEDs are directed down at an angle, there is a point where the light intensity is the greatest. This position was 20 mm above the surface of the sample, as shown in Figure 4.

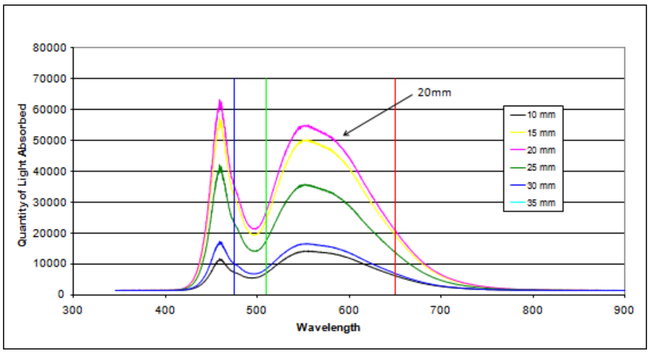

Figure 4. Light absorbed from TCS3200 across the white LED light spectrum when the sensor is positioned at 6 different heights.

Since the TCS3200 is mounted 20 mm above the sample, and therefore not in direct contact with the sample, it was more suited for our application than the full contact required by the ColorPAL sensor.

An alternate method of determining plant leaf colour is to use an image captured by a camera and through software determine the colour of the pixels. However, because plant leaves can overlap (see Figure 5), shadows are created, leading to false colour readings from the image. Since the TCS3200 colour sensor uses its own light source to illuminate the sample surface, it eliminates any potential shadowing.

Figure 5. Captured image showing areas of ”darkness” caused by overlapping which would lead to false colour readings

A Konica Minolta CM-700D Spectrophotometer (Konica Minolta Sensing Americas, Inc., NJ, USA) was used to validate and calibrate the RGB sensors. For accurate measurements, the CM-700D was calibrated by taking both white and black readings by sampling a supplied white and black object respectively.

The CM-700D gives colour in the XYZ colour space, as well as L*a*b*, L*C*h, Hunter Lab, Yxy and Munsell. A linear transformation matrix was required to transform data from the XYZ colour space to the RGB colour space to enable comparisons and calibrations to the Parallax sensor. The linear transformation equation to be solved [27] is:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M \times \begin{pmatrix} R \\ G \\ B \end{pmatrix} \tag{1}$$

$$x = \frac{X}{X+Y+Z} \tag{2}$$

$$y = \frac{Y}{X+Y+Z} \tag{3}$$

$$z = \frac{Z}{X+Y+Z} \tag{4}$$

Equations (2 – 4) combined with the standard 1931 xy chromaticity diagram provided the foundation for the linear transformation (Eq. 1). This transformation converted the *XYZ* data to an sRGB colour space, with the chromaticity values of *x*, *y* and *z* shown in Table I being standard [28].

TABLE I. X, Y, AND Z CHROMATICITY VALUES OF RED, GREEN AND BLUE CONVERTING XYZ TO SRGB

Colour	*x*	*y*	*z*
Red	0.64	0.33	0.212656
Green	0.30	0.60	0.715158
Blue	0.15	0.06	0.072186

From the *x, y* and *z* chromaticity values, the transformation matrix, *M*, is calculated (Eq. 5)

$$M \approx \begin{pmatrix} 0.721144 & 0.063298 & 0.166008 \\ 0.303556 & 0.643443 & 0.052999 \\ 0.000076 & 0.064689 & 1.024294 \end{pmatrix} \tag{5}$$

To calculate the *R*, *G* and *B* values the inverse is taken (Eq. 6 - 7).

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M^{-1} \times \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{6}$$

$$M^{-1} \approx \begin{pmatrix} 1.436603 & -0.118534 & -0.226698 \\ -0.681279 & 1.618476 & 0.026671 \\ 0.042919 & -0.102206 & 0.974614 \end{pmatrix} \tag{7}$$

III. EXPERIMENTAL RESULTS AND DISCUSSION

In order to validate the TCS3200 colour sensor, it was necessary to calibrate and test it using the CM-700D.

This involved taking 200 RGB readings with the TCS3200 using different coloured samples and averaging them. The same samples were measured, each 20 times, with the CM-700D and again averaged. These tests were all completed in a constant temperature dark room. As the CM-700D uses the XYZ colour space, a linear transformation matrix was required to convert the XYZ values to an RGB colour space (Eq. 6).

The TCS3200 was firstly calibrated through software by modifying the integration time, to allow the white object (used to calibrate the CMD-700) to have a RGB value as close as possible to 255,255,255 followed by scaling each of the RGB values, to ensure the white reading was that of the CMD-700.

In order to calculate a *calibration factor* the following equation was used:

$$R_N^{'} = R_N^{\gamma} \tag{8}$$

Where: $R_N^{'}$ = CM-700D (desired RGB value)

R_N = TCS3200 RGB (Un-calibrated sensor data)

γ = Gamma (required *calibration factor*)

First the TCS3200 sensor data were scaled to ensure all values are offset, thus ensureing that the white reading is that of the CMD-700 for each of *R*, *G* and *B* (Eq. 9)

$$R_N = R \times \frac{R'_N}{R_{max}}, G_N = G \times \frac{G'_N}{G_{max}}, B_N = B \times \frac{B'_N}{B_{max}} \quad (9)$$

where $R_{max}, G_{max}, B_{max}$ represent the maximum *R*, *G* and *B* value of a white object from the TCS3200.

The *calibration factors* (γ) for each colour were calculated using normalized data. (Eq. 10)

$$\gamma_R = \frac{\log(R'_N/255)}{\log(R_N/255)}, \gamma_G = \frac{\log(G'_N/255)}{\log(G_N/255)}, \gamma_B = \frac{\log(B'_N/255)}{\log(B_N/255)} \quad (10)$$

For each colour sample measured, the *calibration factor* was calculated and averaged using a geometric mean (as opposed to the more general arithmetic mean function [29]), thus providing the γ factor for *R*, *G* and *B* individually. The (desired) calibrated values were then obtained using equation 11.

$$R'_{N(calibrated)} = (R_N/255)^{\gamma} \times 255 \quad (11)$$

For a range of seven colours, measurements were taken using the TCS3200 RGB sensor and the CM-700D Spectrophotometer (Table II). The gamma *calibration factors* calculated were:

(Red) $\gamma_R = 0.88$, (Green) $\gamma_G = 0.46$, (Blue) $\gamma_B = 0.68$

Table III summarises the average error, error percentage and the standard deviation for un-calibrated and calibrated RGB sensor data compared with CM-700D spectrophotometer outputs.

TABLE II. RESULTS OBTAINED COMPARING THE TCS3200 COLOUR SENSOR (CALIBRATED AND UN CALIBRATED) WITH THE CM-700D OVER A RANGE OF 7 DIVERSE COLOURS

Colour	TSC3200 (un calibrated)			TCS3200 (Calibrated)			CM-700D Spectrophotometer		
	R_N	G_N	B_N	R_N'	G_N'	B_N'	*R*	*G*	*B*
Red	160	45	39	170	114	71	232	91	77
Green	94	127	59	106	184	94	14	197	76
Light Blue	128	179	200	139	216	216	156	217	214
Light Green	168	196	153	177	225	181	195	231	171
Dark Blue	39	106	160	49	170	186	1	168	200
White	248	250	246	249	253	249	248	250	246
Black	19	19	21	26	77	48	59	58	55

TABLE III. AVERAGE ERROR (0-255), PERCENTAGE ERROR AND STANDARD DEVIATION FOR RED, GREEN AND BLUE MEASUREMENTS OF THE TCS3200 COLOUR SENSOR, CALIBRATED AND UN CALIBRATED, COMPARED WITH CM-700D RESULTS ACROSS A RANGE OF COLOURS

	TCS3200 (uncalibrated)			TCS3200 (calibrated)		
Colour	*R*	*G*	*B*	*R*	*G*	*B*
Ave Error	40.339	40.304	21.128	38.951	8.663	10.571
Error %	15.819	15.805	8.286	15.275	3.397	4.145
σ	26.285	20.329	13.055	29.668	8.081	2.852

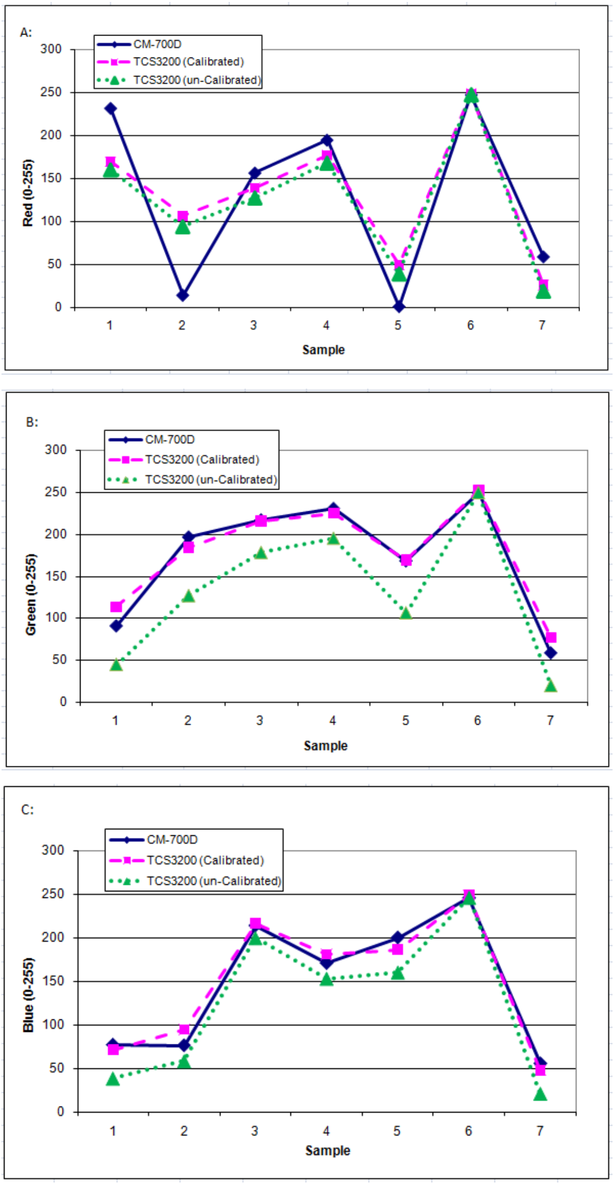

Figure 6. TCS3200 sensor *RGB* readings, calibrated and un-calibrated, compared with the CM-700D readings of: Red (A); Green (B); Blue (C). (Colour samples are as given in Table II)

TABLE IV. AN EXAMPLE OF A GREEN COLOUR INTERPRETED BY THE CM-700D AND TCS3200 COLOUR SENSOR BEFORE AND AFTER A CALIBRATION FACTOR

TCS3200 (uncalibrated)	TCS3200 (calibrated)	CM-700D Spectrophotometer
RGB = 94,127,59	*RGB* = 106,184,94	*RGB* = 14,197,76
		

As the colour sensor is intended to measure the colour of plant leaves, there is no requirement to calibrate it across the full range of colours. The sensor was therefore calibrated for a range of green - yellow colours only. Fifteen RHS (Royal Horticulture Society, London, UK) colour charts, designed for growers to classify colours, were used, with the measured data shown in Table V. Two hundred colour readings were again taken (and averaged) by the TCS3200 colour sensor, followed by 20 readings (averaged) by the CM-700D for each colour chart.

The gamma calibration factors calculated are-

(Red) $\gamma_R = 0.50$, (Green) $\gamma_G = 0.38$, (Blue) $\gamma_B = 0.59$

Table VI summarises the average error, error percentage and the standard deviation for un-calibrated and calibrated RGB sensor data compared with CM-700D spectrophotometer outputs for the 15 colours. There was a vast improvement across the 3-colour components (RGB), with the average red error improving to 5.69%, green 3.19% and blue 3.92%.

TABLE V. RESULTS OBTAINED COMPARING THE TCS3200 COLOUR SENSOR (CALIBRATED AND UN CALIBRATED) WITH THE CM-700D OVER A RANGE OF 15 COLOURS

Colour		TCS3200 (uncalibrated)			TCS3200 (Calibrated)			CM-700D		
RHS Colour Group	ID	R_N	G_N	R_N	R_N'	G_N'	B_N'	R	G	B
Blue-Green	123A	99	150	148	159	206	188	138	208	194
Green	127C	38	80	66	99	160	120	55	166	134
Green	129C	99	154	121	159	208	168	143	217	173
Green	131C	25	42	31	80	123	78	45	120	84
Green	133C	62	89	75	126	167	128	122	166	144
Green	135C	42	52	31	104	134	78	102	156	97
Green	137C	42	52	31	104	134	78	115	130	85
Green	139C	68	83	51	132	162	104	141	162	108
Green	141C	57	81	40	121	161	90	129	164	87
Green	143C	71	89	42	135	167	93	149	166	81
Yellow-Green	145C	171	171	108	209	217	157	224	224	151
Yellow-Green	147C	84	87	55	147	166	107	170	154	112
Yellow-Green	149C	174	186	101	211	224	151	221	237	134
White	155D	255	253	228	255	254	239	255	253	228
Black	202A	17	17	18	66	86	57	62	62	61

TABLE VI. AVERAGE ERROR (0-255), PERCENTAGE ERROR AND STANDARD DEVIATION FOR RED, GREEN AND BLUE MEASUREMENTS OF THE TCS3200 COLOUR SENSOR, CALIBRATED AND UN CALIBRATED, COMPARED WITH CM-700D RESULTS ACROSS A RANGE OF COLOURS

	TCS3200 (uncalibrated)			TCS3200 (calibrated)		
Colour	R	G	B	R	G	B
Ave Error	51.133	66.459	48.513	14.509	7.179	9.114
Error %	20.052	26.063	19.025	5.690	2.815	3.574
σ	24.628	24.030	16.998	12.303	7.473	5.374

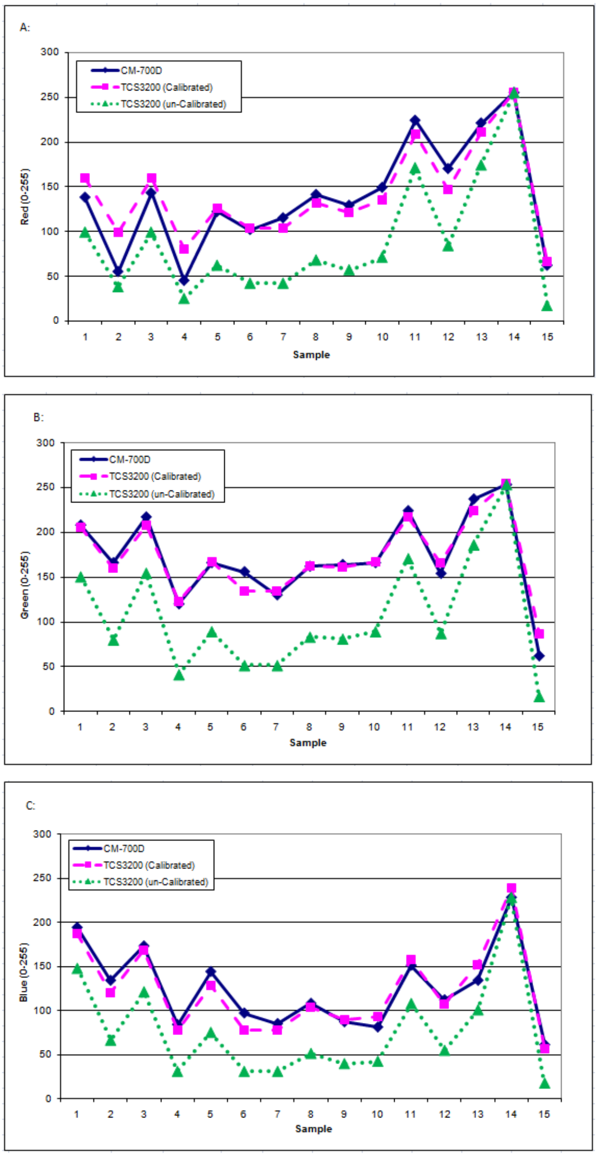

Figure 7. TCS3200 sensor RGB readings , calibrated and un calibrated, compared with the CM-700D readings of: Red (A); Green (B); Blue (C) for a range of RHS green colours. (Colour samples are as given in Table V)

TABLE VII. VISUAL RESULTS SHOWING THE RGB COLOUR INTERPRETED BY THE CM-700D AND TCS3200 COLOUR SENSOR, BEFORE AND AFTER CALIBRATION (RHS 141C)

TCS3200 (uncalibrated)	TCS3200 (calibrated)	CM-700D Spectrophotometer
RGB = 57,81,40	RGB = 121,161,90	RGB = 129,164,87
		

With the calibration factor determined, the TCS3200 was able to identify the colour of selected plant material. The sensor has been integrated with a proximity sensor to ensure all readings are taken at a fixed height above the plant leaves. As the colour sensor is attached to a robotic arm, the sensor is able to return autonomously to the same position to record the colour, making it possible over time to identify subtle changes in the colour of the plant leaves. These changes in plant material will allow plant nutrient concentrations to be adjusted in order to achieve optimum growth.

IV. Conclusion and Future Work

Experimental results show that the Parallax TCS3200 is a useful low cost colour sensor, which following calibration can provide accurate RGB readings. It is therefore a useful component for integrating into an automated monitoring system such as a robotic arm, with various other sensors, for the monitoring and control of plants growing in a modified plant micropropagation system. Future work involves completing the entire robotic system with fully integrated sensors. This will allow investigations to be carried out to optimise plant growth based on the information obtained from the colour sensors, by relating colour information to plant quality. This will be further enhanced by additional growth data obtained from captured plant images. The use of NIR sensors offers further potential for non-destructive assessments of plant tissue structure.

Further test results will be presented in an extended version of this paper. It will also include investigations into a CIE RGB transformation (instead of a sRGB transformation) and the use of a least squares regressions approach as an alternative method to calculating the gamma calibration factor.

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