Development of Data Acquisition Model for Daily Light Integral Measurement

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ABSTRACT

Daily Light Integral or DLI is the measure of the amount of Photosynthetic Photon Flux (PPF) that is received by plants throughout the day. This measurement is accounted for because there exists a relationship between the maximum yield and the amount of light the crops received. Knowing that the available sunlight is not enough, augmentation through the use of artificial lighting can be done. The aim of this study is to design a data acquisition model and implement it in an ATMega 5260 to measure the everyday DLI. Transducers were characterized to give accurate conversion of the solar irradiance incident to the sensors to variations on resistance. This characterization was done by comparing the actual measurements of solar illumination to characteristics described in the datasheet of the transducer. The Daily Light Integral was then calculated using the Planck's distributions as well as the photon energy content of the Photo-synthetically Active Radiation (PAR). The developed instrument successfully logged a 24-hr measurement of the PPF and DLI on 2 different days. The results were verified using the method for estimating DLI as suggested in a study of Dr. Morgan (2013). A low-cost transducer can be accurately used to provide reliable measurements of Daily Light Integral provided that the model used for calculating the parameters are correct.

Introduction

Plants respond to the part of solar radiation that is used in photosynthesis. This spectrum is called as Photo-synthetically Active Radiation or PAR which contains wavelength between 400nm to 700nm. PAR is within the range that human eye can perceive or the co-called visible spectrum 380nm to 770nm (Torres & Lopez, n.d., Both, 2014). Between 400 and 700 nanometers (nm) are the ones useful for photosynthesis, photo morphogenesis (light mediated development) and phototropism (directional growth) (Hjort & Sandberg, 2013). Interestingly, plants' response to energy content in PAR is more than variance of its content. That is why PAR is measured in terms of photosynthetic photon-flux density (PPFD) or the instantaneous light incident upon a surface which has a unit of micromoles of photons per sq. meter per second ($\frac{\mu mole}{m^2 s}$) (Mattson).

The accumulation of photon energy received by plants throughout the day is measured by the sum of all the PAR. This is called the Daily Light Integral in the units of micromoles per square meter per day $mol.m^{-2}.s^{-1}$. On the average, a sunny day can give as much as approximately $65\ \mu mol.m^{-2}.s^{-1}$ (Mattson, n.d). Daily light integral (DLI) can be defined as the quality of light received each day as a function of PPF and duration (day) (Hjort & Sandberg, 2013).

Daily light integral is a measure of the amount of light received by plants during the day, is also a function of the light quantity (in terms of PPF) and photoperiod (Hjort & Sandberg, 2013).

Between the total amount of light received and the growth of plants, a proportional (linear) relationship exist, that is, increasing light can enhance the growth rate. However, too much irradiance is not actually beneficial to plants (Hjort & Sandberg, 2013). As the solar irradiance contains heat energy, too much sunlight can dry up the leaves. What the plant needs is the energy in the PAR region. The optimum plant growth can be attained by giving the same light integral every day of the year independent of the amount of solar radiation received. (Both, 2014) The concept of DLI is not that complex. Within 24-hour period, the total amount of light received by plants is the Daily Light Integral (Morgan, 2013).

Farmers can measure DLI by the use of light meters that measure in foot candles or lux to estimate DLI (Morgan, 2013). On hourly basis, illumination measurements are recorded. Thus, summed up and divided to 24 hours which is multiplied by a factor of 0.20 (for sunlight). The result is in micromoles per sq. meter per second which is then multiplied to 0.0864 in order to convert this to DLI.

The problem with this estimation is its high quantization error because the measurement is sampled per hour. The proposed data acquisition model measures the amount of sunlight every second of the day.

The aim of this study is to design a data acquisition model and implement it in ATMega 5260 for measurement of the DLI.

Framework of the Study

Light is electromagnetic radiation that the human eyes can see. There are two types of measurements to determine the amount of

Table 1

Radiometric and Photometric commonly used for quantifying light

Radiometric Quantities			Photometric Quantities		
Quantity	Sym	SI Unit	Quantity	Sym	SI Unit
Radiant energy	Q	Joule [J]	Luminous energy	Q_L	[lm.s-1]
Radiant flux	Φ	Watt [W]	Luminous flux	Φ_L	Lumen [lm]
Radiant intensity	I	[W.sr-1]	Luminous intensity	I_L	[cd]
Radiance	R	[W.sr-1.m-2]	Luminance	R_v	[cd.m_2]
Irradiance	E	[W.m-2]	Illumination	E_L	Lux [lx]
Scalar Irradiance	E_0	[W.m-2]	Scalar Illumination	E_{0L}	Lux [lx]
Spectral Irradiance	$E(\lambda)$	[W.m-2.nm-1]	Spectral Illumination	$E_L(\lambda)$	[lx.nm-1]

light: radiometric quantities and photometric units. The use of different units for measurement of light depends on the object of which the effects of light are measured as it has different effects to living and non-living things. Radiometric quantities are commonly described by photons or quanta that light carries. Apparently, photometric units measure the strength of light in terms of how it is perceived by human eye. Table 1 (Biggs, n.d.) shows the overview of the radiometric and photometric units that are discussed and used in this study.

When quantifying light in terms of the energy of radiation it carries, radiometric units are used. Radiance (R) quantifies the brightness on a source or object which is a function of radiant flux (Φ) striking a surface area (A) at a solid angle(Ω) with SI unit of $Wm^{-2}sr^{-1}$.

$$R = \frac{\Phi}{A\Omega} \qquad (2.1)$$

- Irradiance (E) – quantifies radiant flux (Φ)striking at a unit area $(A)$of flat surface. The SI unit for irradiance is $W.m^{-2}$.

$$E = \frac{\Phi}{A} \qquad (2.2)$$

- Scalar Irradiance (E_o) – the radiant flux absorbed by a small sphere in all directions divided by the surface area of that sphere. The quantity of radiant flux striking the surface of the sphere is different at every point. The unit is also Wm^{-2}.

Irradiance can be derived directly from radiance R by integrating over the solid angle by the hemisphere above the surface,

$$E = \int L(\theta, \Psi) \cos\theta d\Omega \qquad (2.3)$$

Where θ is the zenith angle and Ψ is the azimuth angle. This relationship suggests that irradiance depends on the orientation of the receiving object with the incident light or the light source. On the other hand, scalar irradiance does not depend on direction such as effects of lighting in particles suspended in water or air. Scalar irradiance can be calculated from radiance R by integrating radiance over the surface area of the sphere.

$$E_o = \int_{4\pi} L(\theta, \Psi) d\Omega \qquad (2.4)$$

Other terms for scalar irradiance are "actinic flux" and "spheradiance". All of this terms that were discussed above quantify the entire spectrum range. But for spectral characterization, units that are functions of wavelengths must be used. One of these units is the spectral irradiance $R(\lambda)$ which is defined as

$$R(\lambda) = \frac{dR}{d\lambda} \qquad (2.5)$$

Where dR is the radiance produced by photons within light ray with infinitesimally small wavelength interval $d\lambda$. The SI unit for spectral irradiance is $Wm^{-2}nm^{-1}$. And with this description, irradiance R can be written as

$$R = \int R(\lambda) d\lambda \qquad (2.6)$$

Quantum units

If radiation is considered as discrete parcels of energy, conversion of radiometric units to quantum units called photons is necessary. Quantum unit is dependent on wavelength and can be described by the energy of the photon:

$$Q_p = \frac{hc}{\lambda} Q_p = \frac{hc}{\lambda} \qquad (2.7)$$

Where h is the Planck's constant valued $h = 6.626\ x\ 10^{-34}\ Js$ and c is the speed of light having the value of $c = 2.997x\,10^{8}\ Js = ms^{-1}$, and λ is the wavelength of the light ray containing the photon.

Interestingly, in photosynthesis light quantity in terms of quantum units is more appropriate because photosynthesis is a process driven by the amount of photon absorbed by light receptors of plants rather than the total amount of energy contained by these photons. Photons in wavelengths from 400-700nm can be used for photosynthesis. This part of the electromagnetic spectrum which contains photons of wavelengths 400-700nm is known as the Photo-synthetically Active Radiation or PAR region. The sensitivity of PAR sensor increases proportionally as the wavelength because the photons at 400nm wavelength have higher energy content than that of 700nm.

At 400nm any PAR sensor must have lower sensitivity at 400nm than 700nm. To get the same quantum response, the radiation has to be more energetic at shorter wavelength or spectral irradiance needs to be larger by a factor of 700/400 = 1.75 at 400nm than for 700nm. Photosynthetic Photon Flux Density (PPFD) can be calculated from spectral irradiance as

$$PPFD = \int_{\lambda=400}^{700} E(\lambda)\,\frac{\lambda}{hc}\,d\lambda \qquad (2.8)$$

Photometric quantities

Photometric quantities are measures of radiation in terms of how it is perceived by human eye. Given spectral radiometric quantities $X(\lambda)$, any associated photometric unit X_v can be calculated using the relationship:

$$X_v = K_m \int_{\lambda=0}^{\infty} X(\lambda)V(\lambda)\,d\lambda \qquad (2.9)$$

Where K_m is the maximum spectral luminous efficacy equal to $683\ lm.W^{-1}$. From these equations, (2.1) to (2.9), Daily Light Integral (DLI) can be derived as:

$$DLI = \int_{1}^{86400}\int_{\lambda=400}^{700} E(\lambda)\,\frac{\lambda}{hc}\,d\lambda\,dt\ ,$$

where 86400 is the number of seconds in a day.

The proper amount of DLI is required to maximize the process of photosynthesis for the optimal growth of crops.

Methodology

The development of the data acquisition model started with the selection of the appropriate light transducer. This is followed by sensor characterization and light calculations. The next stage is calibration of the data acquisition logger and the development of the Simulink model for Daily Light Integral measurements. The implementation of the model is verified through simulations and actual measurements using LX 1010B lux meter.

Light transducer selection

Evaluation of spectral responses of photodiode, phototransistor and light dependent resistor was made in order to select the most appropriate transducer which must be sensitive to Photosynthetically Active Radiation (PAR) region of the solar spectrum.

Sensor characterization

The sensor used is characterized by mapping its response to actual readings of LX-1010B lux meter.

Light Calculations

The light measurement (in lux) made using LX 1010B were converted to Photosynthetic Photon Flux (PPF) for the derivation of the Daily Light Integral.

Data acquisition calibrations

The actual readings of the DAQ which represent the voltage measurements of the light sensor were scaled. Adjustment or scaling of the DAQ readings was based on the placement of the sensor relative to the *lux* meter and light source.

Development of Simulink model for the translation of sensor values to Daily Light Integral

The translation of the DAQ readings to DLI measurements was done using Simulink. The model starts data acquisition in the beginning of the photoperiod. The sum of accumulated PPF measurements throughout the day is converted to DLI Measurements.

Verification of Results through Simulations and Testing

Verification was done by comparing the results of the Simulink model with the actual measured illumination using LX 1010B.

Results and Discussion

The PAR spectrum starts with 400nm to 700nm which is within the spectrum of visible light. (Argus Control System Ltd., 2010). The transducer used is light dependent resistor due to its spectral response. Fig. 1 shows the solar spectrum and Fig. 2 shows the LDR spectral response. The red dash lines in Fig. 1 marks the PAR spectrum (Scofield, 2009).

The response of the sensor to illumination received is derived using the specifications of the transducer used in the light sensor. To calculate for the resistance of the transducer, three points are needed to be identified in the characteristic curve, and conduct interpolation of the resistance based on illumination value.

The characteristic equation of the transducer is identified using interpolation as follows:

$$\frac{2-(-0.3979)}{0-3} = \frac{Y-(-0.3979)}{X-3}$$

$$\boxed{Y = -0.7993X + 2}$$

$$Y = \log(R_{kOhm})$$

$$X = \log(I_{Lux})$$

$$\log(R_{kOhm}) = -0.7993\log(I_{Lux}) + 2$$

$$\boxed{R_{kOhm} = 10^{-0.7993\log(I_{Lux})+2}}$$

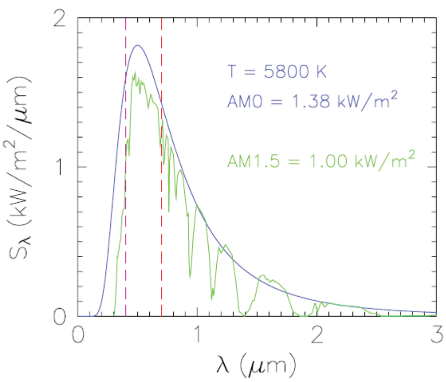

Figure 1. Solar spectrum showing the region of PAR

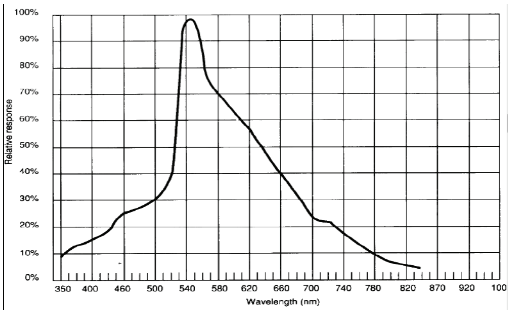

Figure 2. Light transducer's spectral response

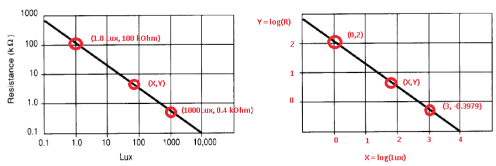

Figure 3. Interpolation of Resistance

Actual reading of illumination from lux meter is scaled with respect to the position of the sensor relative to the position of the lux meter during calibration.

The scale factor is described by the equation:

$$Ilux = Ilux_{sensor}\left(\frac{D_{sensor}}{D_{luxmeter}}\right)^2$$

The *lux* readings are translated to Photosynthetic Photon Flux, PPF by converting it first to solar irradiance measured in $\frac{W}{m^2}$.

Solar irradiance as a function of illumination can be described by the equation:

$$\emptyset\left(\frac{W}{m^2}\right) = \frac{\delta\left(\frac{lm}{m^2}\right)}{\eta\left(\frac{lm}{W}\right)};$$

$where\ \phi = solar\ irradiance; \delta = illumination;$

$\eta = efficacy\ of\ sunlight = 683\ lm/W$

Then, the PPF can be derived by using the relationship suggested by Skye Instruments as follows: (Skye Instruments Ltd., n.d.).

$$PPF = \phi * \frac{\lambda}{119.708}$$

$where\ \lambda = wavelength\ in\ nm$

Accumulation of PPF throughout the day is the measurement of Daily light integral. PPF is measured every second. Expressing DLI as a function of PPF yields,

$$DLI = \sum_{i=1}^{86400} PPF_i$$

Implementation of light calculation to a Simulink™ model requires that the analog measurements of illumination be converted to discrete-time signal. Fig. 4 shows the model for data acquisition of daily light measurements. In detail, Fig. 5 shows the implementation of characteristic equation of

Figure 4. Simulink model for acquisition of light measurements

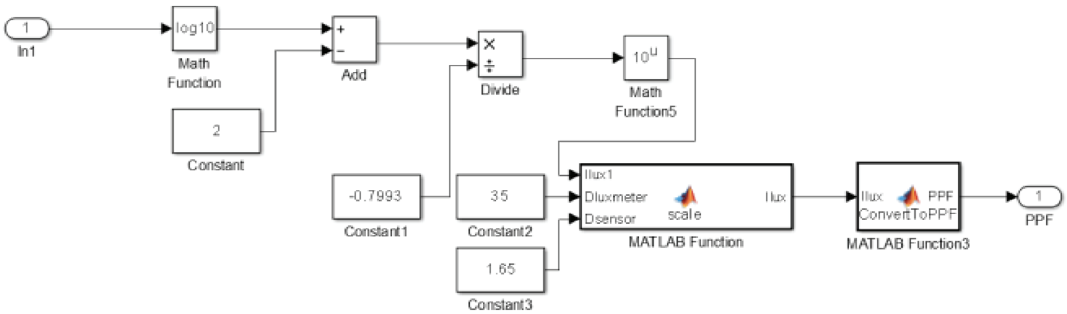

Figure 5. Simulink model for translation of sensor readings to Photosynthetic Photon Flux

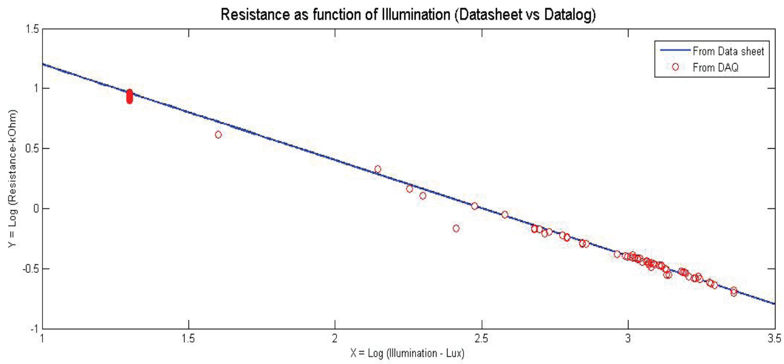

Figure 6. Resistance of the transducer as function of illumination

the sensor as well as the illumination-to-PPF conversions to the Simulink™ model.

The ADC (Analog-to-Digital Converter) used in model development is based on ATmega 2560 processor.

To test the accuracy of the developed model for DLI measurements, actual solar illumination was measured using LX1010B lux meter and was compared to measurements acquired using the model developed. Fig. 6 shows the logarithmic relationship of illumination with the resistance of the transducer used. The solid line is characterization based on the data sheet of the transducer while the red circle markers represents the actual resistance on corresponding illumination measurements.

The figure below shows the mapping of the actual illumination measurements

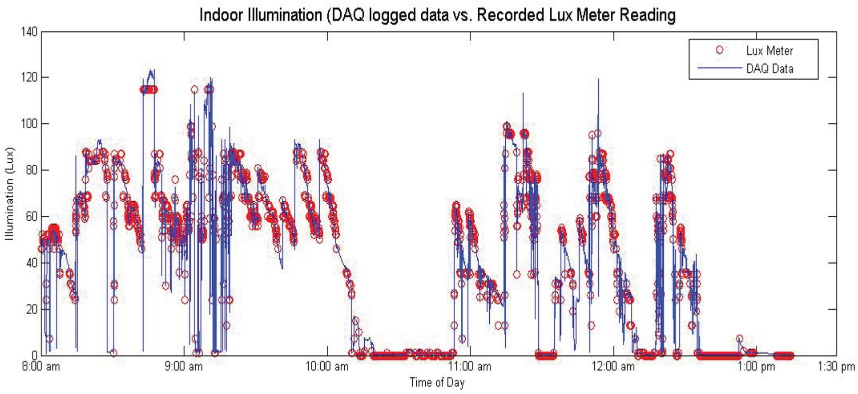

Figure 7. Resistance of the transducer as function of illumination

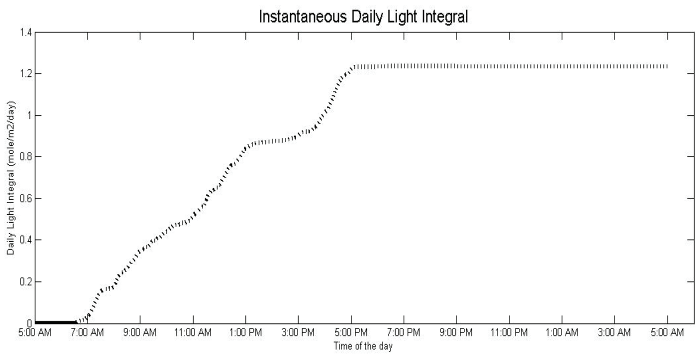

Figure 8. Resistance of the transducer as function of illumination

acquired using the Data Acquisition Model and LX1010B lux meter.

The mean relative error between the measurements of DAQ and lux meter is 1.78%, and the total DLI measured is 1.25 mole/m2/sec.

Conclusion and Recommendations

The goal of this study is to design a data acquisition model and implement it in an embedded system that can measure the everyday DLI, is achieved through the development of a data acquisition model that records the Photosynthetic Photon Flux every second of the day. The result of this research is a Simulink model which is implemented onto a microcontroller for the purpose of recording the amount of sunlight.

The study proved that a DLI meter can be developed from a DAQ system using a general purpose light transducer and ATMega 5260. The data acquisition model developed in this study can be further developed as an application-specific IC (ASIC) for Smart Farming processes focused on remote monitoring of the environment.

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