Greenhouse lighting control by chlorophyll fluorescence

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***Abstract*— It is possible to use the measurement of chlorophyll fluorescence emitted by plants to detect the plants stress. One factor causing stress is too high or too low light intensity. This paper discusses how fluorescence signal is measured and phase estimated from the measured signal. Two different methods are explored for phase estimation, one uses DFT and another one uses Hilbert transform. The results are similar, which adds certainty to their correctness. However, it is decided that DFT method is better, since the resulting phase estimation signal oscillates less. Continuing with DFT only, the phase shift compared to an excitation signal is estimated for different light intensities. It is seen that the specific plants used have phase shift zero when light intensity is around 100 µmol photons m^{-2} s^{-1}. This indicates that the plants are acclimated to this intensity. A PID controller is implemented that should keep the phase shift at zero by changing light intensity.**

I. Introduction

The key to the rise of the sedentary human civilization was agriculture, to cultivate land and breed plants and animals for food and other necessities. Nowadays agriculture is essential to feed the growing population and food production needs to be increased by 60 % by 2050 to satisfy the rising demand [6]. Thus farming industries will increase and effectiveness in the cultivation will be essential for the future.

It is beneficial for plant growing industry to maximize the growth of the plants and minimize the energy usage. One factor that influences the growth is light. The light can come from natural sources or by the use of artificial light. If a plant receives too little light, the plant growth is diminished. On the other hand, if the light intensity is too high, the plants become stressed, which will again reduce the growth, and energy used for the lights is wasted.

When plants absorb light energy, part of this energy is used for photosynthesis or heat dissipation, but small part is re-emitted as light. This emitted light is called chlorophyll fluorescence. It is possible to estimate the stress level of plants by measuring a fluorescence signal emitted by plants. It has been noticed during earlier research that the signal differs depending on the stress level of the plant[1]. The idea is to use these measurements to design a feedback control of the lighting in order to use the optimal level of lighting.

Some work has already been carried out in this field. Thorough studies have been done to confirm that remote measuring of plant stress level is possible and methods are being developed to analyze it through chlorophyll fluorescence response signal [1]. Research has been done to find the optimal spectrum of the light [2]. The frequency response of the fluorescence signal has been thoroughly analyzed, mostly how the magnitude changes with the light intensities applied [4].

If the light could be autonomously adjusted according to the plants stress level, plant growth and efficiency could be maximized. This paper discusses one possible way to implement such autonomous system. It has been shown before that phase shift can be used to estimate light induced stress [1]

and that's what is done in this project also. The first step is signal processing of the plants emitted chlorophyll fluorescence, in order to estimate phase shift from the fluorescence signal. Secondly, a controller is used to lock the phase shift to a desired value by changing the lamp intensity. Controller implementation has not been done before in a system like this.

II. Method

A. Set-up

The set-up for the experiment consists of basil plants, a spectrometer sensor and two LED lamps.

The basil plants were bought fully grown and therefore their growing conditions are not known.

The spectrometer (Maya2000 pro ocean optics) with 600 µm optical fibre is used to measure the chlorophyll fluorescence from the plants and the light from the LED lamps. The fibre has 25° field of view.

The LED lamps are the RX30 and LX602G from Heliospectra. The wavelength channels used in the RX30 are 420 nm (blue) while the channels used in the LX602G are the 450 (blue) and the 660 (red).

The system from power to emitted light is non-linear so a mapping between input to lamp and output from lamp was made using the measurement of lamp output. The spectrometer with a 50 µm optical fibre was used for that, equipped with a cosine corrector, which gives it 180° field of view. The following result was generated:

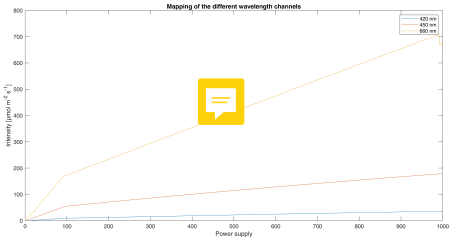

Figure 1: Mapping conversion between power input to emitted light

B. General description of experiment

With the intention to create a fully autonomous lighting system which can keep the stress level in plants steady by locking a specific phase shift, numerous steps are preformed continuously:

- Generate background light with a satisfying spectrum
- Generate a sinusoidal light to induce sinusoidal fluorescence signal
- Measure the chlorophyll fluorescence emitted by the plants
- Filter the measured signal
- Estimate the phase shift between the generated sinusoidal signal and the measured fluorescence signal
- Use a controller to achieve a predefined phase shift
- Change the background light according to the controller output

C. Generating lights

The fluorescence signal emitted by plants should be sinusoidal for a phase analysis. To induce a sinusoidal fluorescence signal, a sinusoidal excitation signal is used, i.e. intensity of lamps should change in a sinusoidal fashion, that causes fluorescence signal to also be sinusoidal. The wavelength spectrum of the sinusoidal lamp signal needs to be outside the spectrum of the chlorophyll fluorescence (740 nm). This is to be able to measure the fluorescence from the plant without interference of the lamp signal. The LED lamp used for that is the RX30 and the wavelength used is 420 nm. The data presented in figure 1 in chapter II-A suggests that maximum intensity the LED can produce in 420 nm is 35 µmol photons m^{-2} s^{-1}. To have a sinusoidal with noticeable change in amplitude, i.e. large signal to noise ratio, the wave was defined to have as big amplitude as possible without risking reaching the maximum value and getting saturated. The lamp generated sinusoidal was therefore defined to have a mean value of 17 µmol photons m^{-2} s^{-1} and an amplitude of 15 µmol photons m^{-2} s^{-1}. A period time of 60s was chosen. The same period has been used before for phase estimation which enables to compare the results to previous work[1].

To evaluate phase shift, both the excitation signal from lamps and the emitted fluorescence signal should be measured. Even though the excitation sig-

nal is generated from the LEDs, disparity between the expected LED output and real LED output is presumed due to imperfection of the mapping between lamp input and lamp output. Comparison between the measured and the pre-defined fluorescence signal is given in the figure 2.

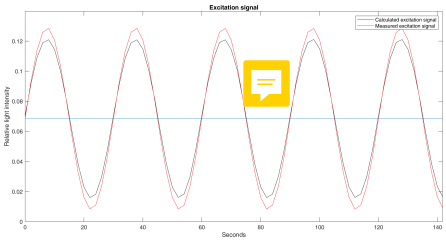

Figure 2: The calculated and measured excitation sinusoidal signal

The data suggests that the phase of the two sinusoids are equal. The difference between the signals are the intensity and the amplitude. This is reasonable due to one being a reflection of the other and does not matter in the context, since magnitude information is not used. From this test it is concluded that the excitation signal doesn't need to be measured.

To grow well, the plants need light in the correct growth spectrum i.e. the color spectrum that is optimal for plant growth. This is provided with a background light complementing the sinusoidal signal. A previously used combination of wavelengths in a similar experiment is 70% red, 20% blue and 10% green light [3]. However, the LED used to generate such light is the LX60 and only has wavelength channels in red, blue and white light. Therefore the spectrum was adjusted to 70% red (450nm) and 30% blue (660nm). While, the sinusoidal excitation light will be the same throughout the experiment, the intensity of the background light will be regulated by PID to accomplish the correct phase shift.

D. Measuring fluorescence

The plants emit chlorophyll fluorescence in the spectrum from 660-800 nm with two peeks around 690 nm and 740 nm, this is illustrated in the figure 3 [5].

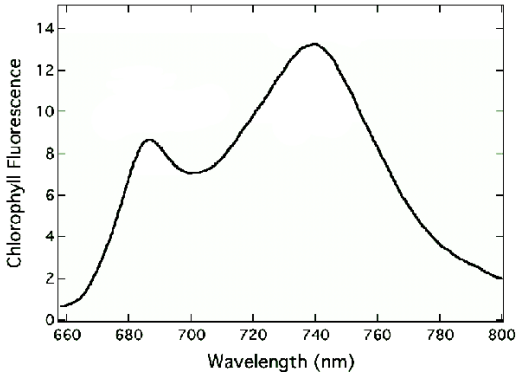

Figure 3: chlorophyll fluorescence emission spectrum

The peak in 690 nm is hard to measure properly because 660 nm background light is used and it will interfere with 690 nm signal. Instead the 740 nm peak is measured.

Measurements are obtained every 2 seconds, i.e the sample rate is 0.5. Filtering, phase estimation and control is done with the same sample rate.

E. Filter

The fluorescence signal is not perfect, there are aspects that will impact the signal. The measured fluorescence signal is approximately linear with respect to excitation signal, though some nonlinearity will be present. This means that change of the input does not result in a proportional change of the output. This will result in noisy fluorescence signal. Measurement of a signal also adds noise. To decrease the impact of the noise to the phase estimation, the signal can be processed by adding a noise reducing filter.

It is no problem if the filter changes the amplitude, as only phase is important for this experiment. Since there is only one frequency that contains important information and it is known, it is natural to filter out all other frequencies.

The idea is to use a notch filter. Notch filter passes most frequencies except a narrow region, which is strongly attenuated. By filtering the noisy

signal with notch filter, the result is signal containing only noise. This result is then subtracted from the original signal, which eliminates the noise.

F. Phase estimator

Now, when satisfying signals are achieved, phase shift between the excitation signal and the fluorescence signal can be estimated.

There are several possible ways to estimate phase shift. Two different methods were chosen to be tested and evaluated. The method chosen should achieve a robust estimation despite possible noise present. Another thing to consider is that phase should be tracked continuously i.e. as frequently as possible, to be able to control it.

First method chosen was to convert the signals into frequency domain by using discrete Fourier transform (DFT). This gives a new signal with the same number of samples as the original signal. Every sample is a complex-valued function of frequency. The samples are evenly spaced and lie between frequencies $[0, F_s]$, where F_s is the sample rate. The samples after the Nyquist frequency $\frac{F_S}{2}$ are mirrored repeats of the first half of data and thus don't give any useful information. Therefore, it is essential that the sample rate chosen is larger than twice the sinusoid signal frequency of the transformed signal.

Both the excitation signal and the fluorescence signal are converted into frequency domain by DFT. Last 150 samples are used for that. As DFT is a complex signal, it contains information about both magnitude and phase. Phase is evaluated for both signals for the sample that corresponds to the sinusoid frequency and the difference is found between them. Denoting Fourier transform of fluorescence signal at frequency k as $y(k)$ and Fourier transform of excitation signal at k as $x(k)$, the phase shift is defined in equation 1 as

$$\Delta\theta(k) = \arg(y(k)) - \arg(x(k)) = \arg(\frac{y(k)}{x(k)})\,. \tag{1}$$

The advantage of this method is that by evaluating phase only for the sinusoid frequency, any noise is rejected. The problem is that there may not be any sample that corresponds exactly to the sinusoid frequency, thus the nearest sample is used. The precision of phase estimation is dependent on the closeness of this sample to the desired frequency. Thus the precision of the estimation can be improved by increasing the length of the Fourier transformed signal.

Second method explored was to turn the signals into analytic signal by using Hilbert transform. If the transformed signal is $x(t)$, then its analytic signal is defined in equation 2 as

$$z(t) = x(t) + iHT(x(t))\,, \tag{2}$$

where $HT(x(t))$ denotes Hilbert transform of $x(t)$. $z(t)$ is thus a complex signal with real part $z_r(t) = x(t)$ and imaginary part $z_i(t) = HT(x(t))$. From complex signal it is easy to obtain phase and phase shift as in equation 3 and 4 respectively.

$$\theta(t) = \arg(z(t)) = \arctan(\frac{z_i(t)}{z_r(t)}) \tag{3}$$

$$\Delta\theta(t) = \arg(z_y(t))) - \arg(z_x(t)) = \arg(\frac{z_y(t)}{z_x(t)}) \tag{4}$$

Here z_x is analytic signal of excitation signal and z_y is analytic signal of fluorescence signal. Phase information is obtained for all time samples of the transformed signal. If a signal consisting of 150 samples is input, then it is possible to get out phase for all 150 time points. It should be noted that the result is less accurate near the edges of the signal.

In this project, phase was estimated every time step. Every time step last 150 samples of input and output signal were given in to the phase estimator. Only one estimated phase value was desired as output. To achieve this, an average over the phase signal was taken. Quarter of the signal from beginning and end was discarded first, knowing that these might be inaccurate.

Hilbert transform requires transformed signal to have mean value zero. However, the lamp signal and fluorescence signal have mean value above zero. Because of this, the mean value was subtracted first from both signals, before estimating phase. This operation introduces an undesired trend to the

signal, unless a multiple of number of samples in one period is used for signal length. Since there are 30 samples in one period, 150 is an acceptable length.

G. Controller

The system is controlled by a PI-controller. More complex model-based controllers are excluded, because it is difficult to derive a model for this system. In the future, model-based control can be explored after finding the model by system identification. A PI-controller consists of two components, a proportional and an integral part which can be seen in equation 5.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{5}$$

The proportional part multiplies the error with a factor, this reduces the gross error in the system. The integral part uses past errors and integrates them over time. This part is used to remove the residual offset error that is left. The PI-controller only has two design parameters, K_p and K_i, which makes it very easy to tune and is the main reason it is used in the project [7]. If the design parameters are large the controller will react to changes faster, while at smaller values changes will take longer time. There's predicted to be much noise and distortion in the measured fluorescence signal, therefore small values for the design parameters are favorable in this project.

A famous controller is the PID-controller. It is very similar to the PI-controller but has one extra element, a derivative part. This part uses the rate of change which is seen in equation 6. The derivative part is used to calculate future trends of the error.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{6}$$

That type of controller is not used in this project for two reasons. One is mentioned above, that it is one more parameter to tune. The other one is that the derivative part can induce more oscillatory instability and therefore needs more accurate tuning than a PI-controller.

The system is discrete therefore the PI-controller must also be discrete, meaning that the control input is calculated at every time sample. The discretized PI equation is seen in equation 7.

$$u(k) = K_p e(k) + \Delta t K_i \sum_{i=1}^{k} e(k) \tag{7}$$

III. Result and Discussion

The filter used for the fluorescence signal is a notch filter, previously discussed in the chapter II-E. The result of the filter can be seen below in figure 4.

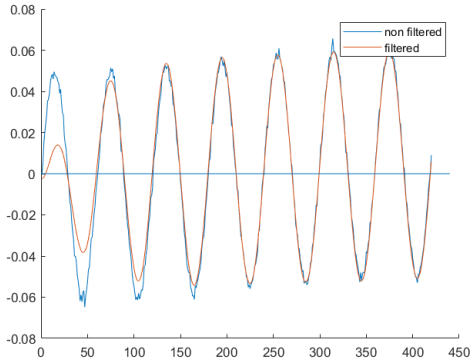

Figure 4: Plot with the original and the filtered fluorescence signal

The amplitude is not correct in the beginning of the signal but the phase is correct throughout the signal. The only information we use is the phase of the signal therefore it does not matter that the magnitude is modified.

When the experiment was run without the controller, the hypothesis was that the phase shift would be rather constant over time because the light intensity is not changing. The figure 5 shows this experiment with the use of two different methods to estimate the phase shift, discrete Fourier transform and Hilbert. ~~These methods can be read more about in the chapter II-F.~~

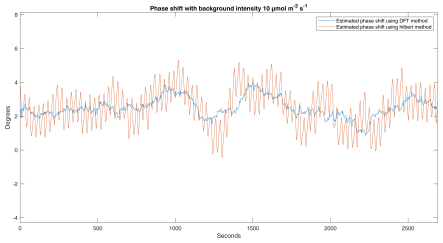

Figure 5: Phase shift estimated with the discrete Fourier transform and the Hilbert method during background intensity 10 µmol photons m^{-2} s^{-1}

	Intensities			
	10	**75**	**100**	**125**
Mean intensity	0.53	2.24	0.31	1.14
	Intensities			
	160	**200**	**300**	
Mean intensity	5.16	7.25	9.00	

Table I: The mean values of the phase shift with different intensities

The data suggests that the phase shift is relatively constant for the discrete Fourier transform method varying between 1.5 to 4 degrees. For the Hilbert method the phase shift fluctuates much more and in larger range between the values -0.5 to 5 degrees. Although they both follow the same pattern which could indicate that the estimation is fairly correct. By the conclusion that the discrete Fourier transform method fluctuates less, this method is selected as the method to be used further in the following experiments.

More experiments were done without a controller, comparing how the phase shift behaves depending on the level of intensity from the background light. With each intensity, the experiment was run for 1 hour. The result of these experiments is displayed in figure 6 and the mean value of the signals is displayed in table I.

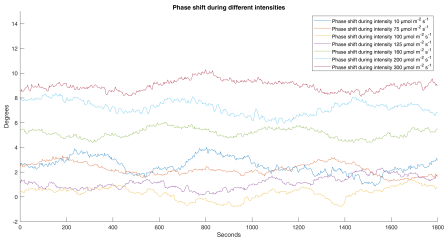

Figure 6: Estimated phase shift during background intensity 10, 75, 100, 125, 160, 200, 300 µmol photons m^{-2} s^{-1}

While the intensity is increased from low values, the phase shift gradually decreases. At intensity 100 µmol photons m^{-2} s^{-1} the phase shift is around zero degrees. When continuing to increase intensity, the trend turns and phase shift starts to increase instead. This data indicates that the phase shift at zero degrees is the one that should be aimed for.

The results indicate that it is possible to estimate phase shift with given methods and find optimal light intensity based on the estimations. However, more experiments should be done to be certain about which intensity is optimal for the plant.

Over time some other intensity may become more optimal for the plant due to changing circumstances. Zero degrees phase shift can then happen at a different intensity than 100 µmol photons m^{-2} s^{-1}. The controller therefore needs to regulate the light intensity so that the phase shift always stays at approximately zero degrees.

A short test of the PI-controller with the design parameters $K_p = 0.05$ and $K_i = 0.05$ was made testing if the controller could keep the phase shift steady when the intensity was initially specified to 130 µmol photons m^{-2} s^{-1}. Unfortunately, the experiment did not go as planned. As seen in figure 7. the phase shift began to be steady itself around zero after initially being slightly off. However, after 120 seconds oscillations began which got worse over time.

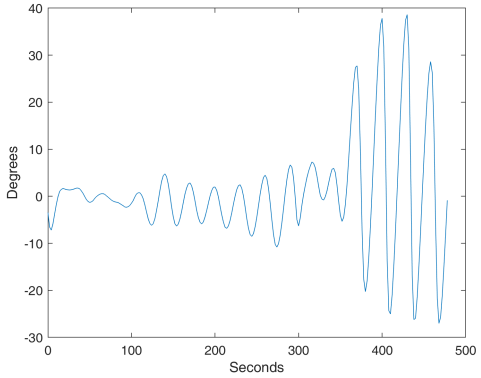

Figure 7: Phase shift behaviour with PI-controller

To solve this the controller needs further development and more testing needs to be done, ideally over several days, which unfortunately is not possible within this project.

Overall, a system was built up, a notch filter was designed, the phase shift estimated and evaluated using two different methods and a PI-controller implemented. What could be further done is to adjust the PI-controller and run more, longer experiments.

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