Exploiting Chlorophyll Fluorescense for building robust low-cost Mowing Area Detectors

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***Abstract*— Detecting cost-effectively and accurately the working area for autonomous lawn mowers is key for widespread automation of garden care. Therefore, we propose an active low-cost sensor approach for detecting fluorescence response. The area to be detected is illuminated by an LED and the chlorophyll fluorescence response is observed by a phototransistor. The signal from the phototransistor is further processed by a transimpedance amplifier, an amplifier and a band pass filter and forwarded to a microprocessor. By choosing only low-cost consumer products for construction, high-volume lowest cost sensors can be built. We demonstrate the feasibility of our low-cost approach by evaluating the sensor mounted on an autonomous lawn mower in a garden environment.**

I. Introduction

Many strategies were proposed to detect the boundaries of the working area for autonomous lawn mowers, for example vision based localization and mapping strategies [1], [2] or capacity based sensor technology for detecting humidity [3]. However, since for autonomous mowers the safety impact on leaving the mowing area is high, the sensory systems have to be reliable. Vision based systems use color and texture identifiers to detect grass-containing regions using statistical methods, e.g. Bayes classifier [4], and reach accuracies of $90\,\%$, shaded grass, and $95\,\%$, illuminated grass [5]. Capacity based systems have to be calibrated and are sensitive with respect to change in air conditions, such as rain or fog. The only working electronics in consumer market use perimeter wire, electro-magnetic field measurement technology which safely detects wire crossing and in/outside area estimation. Such technique has been firstly introduced in lawn mowers in [6]. However, such sensor systems come with the drawback of the installation of a perimeter wire surrounding the lawn which results in additional time and maintenance costs. In order to overcome these problems, we introduce a cost-efficient grass detection system based on remote chlorophyll fluorescence sensing, Figure 1.

Current remote chlorophyll fluorescence sensing systems can be grouped into ground based measurement and long distance systems [8]. The ground based measurement systems can be further partitioned into active and passive ones. We do not consider long distance sensing techniques as applicable for autonomous mowers. For the ground based measurement systems, the most popular group of sensors for active chlorophyll fluorescence sensing are FLiDAR (Fluorescence Light Detection and Ranging) [9]. Here, brief periodic excitation pulses ($< 1\,\mu s$) with defined wavelength (e.g. $355\,nm$) are used for excitation. Current FLiDARs are using multiple excitation wavelength, e.g. for identifying plant species [10] or the stress level [11]. However, since by design autonomous mowers aiming for low acquisition and maintenance costs, FLiDARs in general are too expensive. Passive remote sensing in comparison relies on the fluorescence induced by the natural sunlight. Since only around $2\,\%$ of the incident light is re-emitted as chlorophyll fluorescence, it represents only a very small fraction of the recorded spectrum. Thus, Fraunhofer lines are used in order to measure the fluorescence signal, for example due Fraunhofer line discrimination [12]. Passive sensing might be a cost effective solution but requires sunlight which limits the applicability, for example when the mowing time should be over night. To address the problems of low maintenance and acquisition costs, reliable detection of the mowing area and constant operational readiness, we propose low-cost high-performance active chlorophyll sensor which

(1) stimulates the chlorophyll fluorescence by emitting blue light with a standard $432\,nm$ light emitting diode (LED).
(2) detects the chlorophyll fluorescence response using a standard infrared phototransistor.
(3) filtering the sunlight response by using high stimulation frequencies.

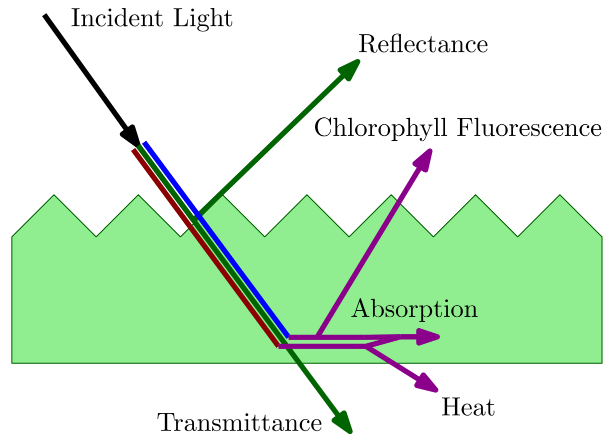

Fig. 1: Example diagram for Chlorophyll Fluorescence inspired by [7]. About $78\,\%$ of the incident radiation is absorbed, while the rest is either transmitted or reflected. About $20\,\%$ is dissipated through heat and only $2\,\%$ emitted as fluorescence.

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II. Sensor Concept

We investigated chlorophyll fluorescence as a unique feature of plants and grass. We start by introducing the main concepts of chlorophyll fluorescence required for the sensor design. For a detailed survey, we refer to [13] and [14]. Based on the specific characteristics we introduce a cost-efficient sensor design, Figure 2, using available analog consumer electronic in combination with a small microprocessor.

A. Chlorophyll Flourescence

Light energy absorbed by plants, more specifically by the chlorophyll molecules, can either drive photosynthesis reaction, it can be dissipated as heat or re-emitted as light which is called chlorophyll fluorescence, see Figure 1. These three processes are in competition to each other, thus a decrease in efficiency at one process will increase the efficiency at another. In general, the light re-emitted by the chlorophyll fluorescence is of a magnitude much lower then the absorbed light, between $1-2\,\%$. However, since it is possible to stimulate chlorophyll fluorescence given a certain wavelength, it can be exploited for a sensor system. Therefore, the excitation wavelength has to be around $430\,\mathrm{nm}$ whereas the re-emitted light is of longer wavelength at around $684\,\mathrm{nm}$, see Figure 3.

An important characteristic for the design of our sensor is the life time of chlorophyll fluorescence, thus the time after stimulation in which chlorophyll fluorescence can be measured. This characteristic time span is around one nanosecond. For example, Schmuck and Moya [17] showed for spinach leaves that at steady state conditions the mean lifetime is $0.415\,ns$ and when closing all reaction centers of the photosystem II [18], thus enhancing chlorophyll fluorescence, the mean lifetime is around $2\,ns$. Similar results have been achieved in [19] with maple and spinach leaves and in [20] with maize and spruce leaves. Thus, stimulation of chlorophyll fluorescence with a frequency of up to $1\,GHz$ is possible.

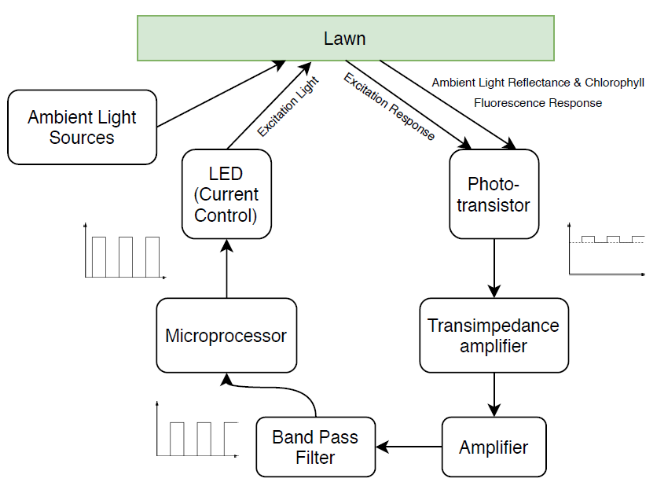


Fig. 2: The processing steps for the proposed low-cost sensor. The Microprocessor controls the LED which emits a pulsed light for stimulating the chlorophyll process. The light radiated back is then absorbed by the PT and the result further processed and sent back to the microprocessor for evaluation.

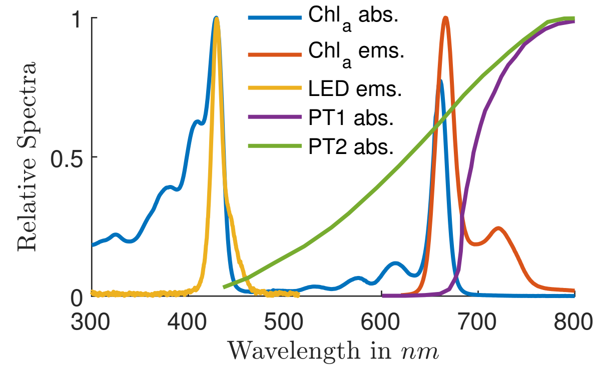


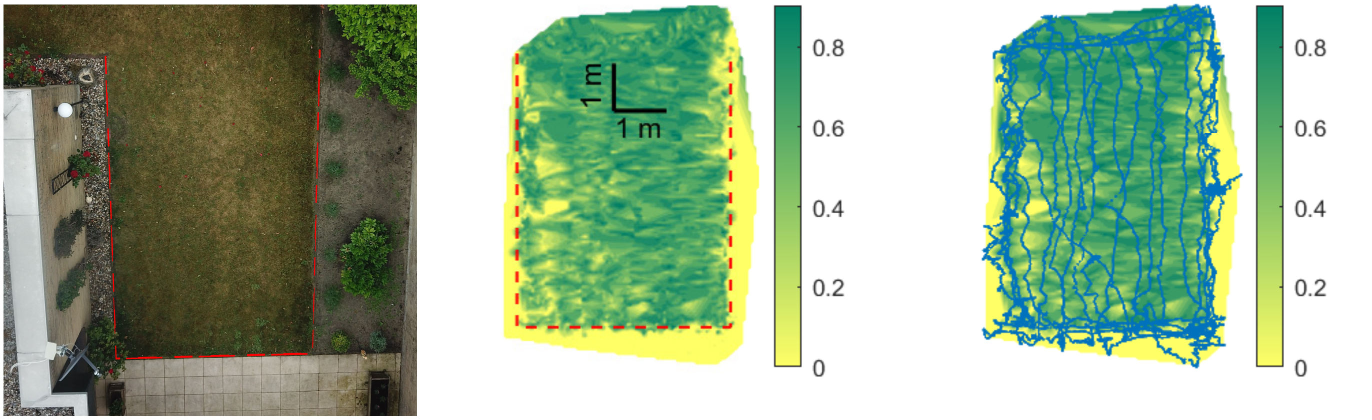
Fig. 3: Examples of different normalized absorption and emission spectra. The blue and red lines show the absorption and emission fluorescence spectra for Chlorophyll a in diethyl-ether taken from the PhotochemCAD database [15],[16]. The yellow line represents the measured emission spectrum of a consumer LED with emission peak at $432\,nm$. The purple and green lines show the spectral responses for the RPT37PB3F Phototransistor from *Rohm Semiconductor* and the PT480 from *SHARP*.

B. Sensor Design

As shown in Figure 3, the absorption spectrum of chlorophyll is particularly strong in the range around $430\,nm$, whereas the emission spectrum is located in the area of $650-750\,nm$. Thus, we require as stimulation source a consumer LED with emission peak at around $430\,nm$ and as absorption sink a standard phototransistor with a sufficient good spectral response between $650-750\,nm$. Moreover, the emission spectrum of the chosen LED and the spectral response of the phototransistor should not overlap. Otherwise we can not distinguish between the fluorescence response and the LED radiation. Consumer market phototransistors, however, either have a spectral response in the visible or in the infrared range whereas the emission response of chlorophyll lies between these ranges, as shown in Figure 3. To avoid detecting the directly reflected light of the LED, a phototransistor in the infrared range is chosen for the construction of our sensor. Specifically, we chose the RPT37PB3F since it has a sufficiently good spectral response in the desired area and does not intersect with the emission spectrum of the LED.

C. Signal Processing

In order to distinguish between the excited chlorophyll fluorescence and the ambient light (e.g. sunlight), the LED signal is modulated with a certain frequency f_{LED}. The current signal captured by the phototransistor is transformed using a current-to-voltage converter (transimpedance amplifier). The output voltage is further amplified and the resulting



(a) The section of the garden environment from the bird's eye perspective.

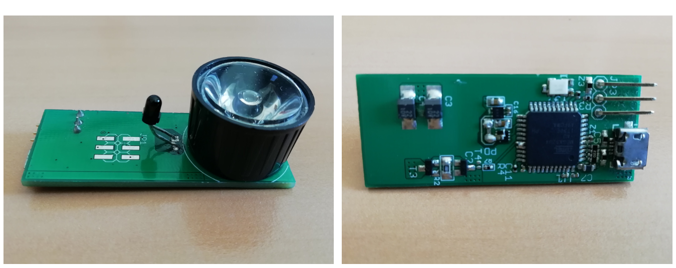
(b) The interpolated map based on the sensor measurements and the mower movements.

(c) The measurements positions recorded by the real-time locating system.

Fig. 4: Evaluation results for the chlorophyll fluorescence sensor under real garden conditions.

signal band pass filtered such that it is freed of ambient light influences.

The control unit of the sensor is a small microprocessor, the *ATMEGA32U4*, which generates the excitation signal for the LED using a pulse width modulation (PWM) signal with a predefined frequency $f_{\text{LED}} = 35\,KHz$. The amplified and filtered signal is then processed by a digital input, which indicates if a signal has been detected or not. To achieve high excitation frequencies, the in- and output signals are generated and captured by directly using interrupt routines. The pulse length, thus the time where the LED emits light, is defined as t_{pulse}. To be able to measure also the quality of the grass, thus the amount chlorophyll in the reception area of the sensor, it can be varied between $t_{\text{pulse}} = \frac{10}{457} \cdots \frac{100}{457} \frac{1}{f_{\text{LED}}}$. Multiple measurements are then taken with different pulse lengths. The lowest pulse length with which a chlorophyll fluorescence signal can be detected can then be transformed into a relative measure for the amount of chlorophyll. In addition, plastic lenses were used for emitting and receiving optics to focus the light onto and from the measurement area. The whole setting allows for high-volume lowest cost sensor. In Figure 5, a prototype of the proposed remote chlorophyll fluorescence sensor is shown.



(a) The LED and the phototransistor.

(b) The processor.

Fig. 5: The remote chlorophyll fluorescence sensor.

III. Evaluation

We tested the proposed chlorophyll fluorescence sensor in a realistic garden environment on an autonomous lawn mower. Therefore, we imitated first standard line following behavior recording the perimeter of the test field, and second, let the lawn mower drive in parallel lines over the field. For the localization of the lawn mower we used the real-time locating system (RTLS) MDEK1001 from *Decawave*. In Figure 4, the evaluation results are shown. Figure 4a shows the evaluated section of the garden environment from the bird's eye perspective, Figure 4b the interpolated sensor measurements and Figure 4c the path of the lawn mower. Here, 0 indicates no chlorophyll fluorescence and 1 optimal amount of chlorophyll in the reception area of the sensor. We recorded 13462 measurements during the run with the lawn mower, whereby 8840 measurements showed chlorophyll fluorescence and 4622 measurements showed none. The interpolated map, which is based on the recorded measurements, shows distinct boundary lines, marked in red, which can be used for navigation. Especially in the areas outside the lawn clearly no chlorophyll fluorescence was detected. However, zero chlorophyll fluorescence detection can also happen inside the lawn area, for example due to damaged grass or bald spots.

IV. Conclusion

We proposed a low-cost sensor approach using chlorophyll fluorescence for working space detection for autonomous lawn mowers. We demonstrated, that our sensor reliably detects the lawn area under real life conditions by evaluating the sensor in a realistic garden environment. It is a low-cost approach, that is robust to different illumination conditions and even works at night. In future work, we will evaluate our sensor under different environmental conditions and on different types of lawn.

References

[1] Junho Yang, Soon-Jo Chung, Seth Hutchinson, David Johnson, and Michio Kise. Vision-based localization and mapping for an autonomous mower. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3655–3662. IEEE, 2013.

[2] Tomoya Fukukawa, Kosuke Sekiyama, Yasuhisa Hasegawa, and Toshio Fukuda. Vision-based mowing boundary detection algorithm for an autonomous lawn mower. *Journal of Advanced Computational Intelligence and Intelligent Informatics*, 20(1):49–56, 2016.

[3] Fabrizio Bernini. Lawn-mower with sensor, November 3 2009. US Patent 7,613,552.

[4] Ukrit Watchareeruetai, Yoshinori Takeuchi, Tetsuya Matsumoto, Hiroaki Kudo, and Noboru Ohnishi. Computer vision based methods for detecting weeds in lawns. *Machine Vision and Applications*, 17(5):287–296, 2006.

[5] Alexander Schepelmann, Richard E Hudson, Frank L Merat, and Roger D Quinn. Visual segmentation of lawn grass for a mobile robotic lawnmower. In *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 734–739. IEEE, 2010.

[6] S Lawrence Bellinger. Self-propelled random motion lawnmower, March 16 1971. US Patent 3,570,227.

[7] Malcolm Davidson, Michael Berger, Ismael Moya, José Moreno, Tuomas Laurila, Marc-Phillipe Stoll, and John Miller. Mapping photosynthesis from space-a new vegetation-fluorescence technique. *ESA bulletin*, 116:34–37, 2003.

[8] Ismael Moya and Zoran G Cerovic. Remote sensing of chlorophyll fluorescence: instrumentation and analysis. In *Chlorophyll a Fluorescence*, pages 429–445. Springer, 2004.

[9] F Castagnoli, G Cecchi, L Pantani, I Pippi, B Radicati, and P Mazzinghi. A fluorescence lidar for land and sea remote sensing. In *Laser Radar Technology and Applications I*, volume 663, pages 212–216. International Society for Optics and Photonics, 1986.

[10] Jian Yang, Wei Gong, Shuo Shi, Lin Du, Bo Zhu, Jia Sun, and Shalei Song. Excitation wavelength analysis of laser-induced fluorescence lidar for identifying plant species. *IEEE Geoscience and Remote Sensing Letters*, 13(7):977–981, 2016.

[11] G Samson, N Tremblay, AE Dudelzak, SM Babichenko, L Dextraze, and J Wollring. Nutrient stress of corn plants: early detection and discrimination using a compact multiwavelength fluorescent lidar. In *Proceedings of the 20th EARSeL Symposium, Dresden, Germany*, pages 214–223, 2000.

[12] James A Plascyk. The mk ii fraunhofer line discriminator (fld-ii) for airborne and orbital remote sensing of solar-stimulated luminescence. *Optical Engineering*, 14(4):144339, 1975.

[13] Kate Maxwell and Giles N Johnson. Chlorophyll fluorescence—a practical guide. *Journal of experimental botany*, 51(345):659–668, 2000.

[14] Hazem M Kalaji, Gert Schansker, Marian Brestic, Filippo Bussotti, Angeles Calatayud, Lorenzo Ferroni, Vasilij Goltsev, Lucia Guidi, Anjana Jajoo, Pengmin Li, et al. Frequently asked questions about chlorophyll fluorescence, the sequel. *Photosynthesis Research*, 132(1):13–66, 2017.

[15] Masahiko Taniguchi, Hai Du, and Jonathan S Lindsey. Photochemcad 3: diverse modules for photophysical calculations with multiple spectral databases. *Photochemistry and photobiology*, 94(2):277–289, 2018.

[16] Masahiko Taniguchi and Jonathan S Lindsey. Database of absorption and fluorescence spectra of¿ 300 common compounds for use in photochem cad. *Photochemistry and photobiology*, 94(2):290–327, 2018.

[17] Guido Schmuck and Ismael Moya. Time-resolved chlorophyll fluorescence spectra of intact leaves. *Remote sensing of environment*, 47(1):72–76, 1994.

[18] AW Rutherford and P Faller. Photosystem ii: evolutionary perspectives. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 358(1429):245–253, 2003.

[19] F Pellegrino, A Dagen, P Sekuler, and RR Alfano. Temperature dependence of the 735 nm fluorescence kinetics from spinach measured by picosecond laser-streak camera system. *Photobiochemistry and photobiophysics*, 1983.

[20] Mathias Senoner. The nanosecond decay of variable chlorophyll fluorescence in leaves of higher plants. *Biochimica et Biophysica Acta (BBA)-Bioenergetics*, 849(3):374–380, 1986.