MEASURING SOLAR-INDUCED FLUORESCENCE FROM UNMANNED AIRCRAFT SYSTEMS FOR OPERATIONAL USE IN PLANT PHENOTYPING AND PRECISION FARMING

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ABSTRACT

Demand for high spatial and temporal resolution measurements has triggered a rapid development of unmanned aircraft systems (UAS) for plant phenotyping and precision farming purposes. Similarly, recent progress in low-altitude remote sensing of solar-induced chlorophyll fluorescence (SIF) resulted in several studies aiming at the development of SIF proximal sensing approaches. Although first experimental results are promising, the requirements for reliable and repeatable measurements in agricultural experiments still constrain applicability of these platforms. In this study, we analyze current capabilities and potentials of SIF measuring UAS for operational use. We highlight existing challenges and outline how UAS SIF sensing could be used more frequently and reliably in precision agriculture applications in the near future.

Index Terms— chlorophyll fluorescence, drone, spatial and spectral scaling, photosynthesis, spectroscopy

1. INTRODUCTION

Onset of solar-induced chlorophyll fluorescence (SIF) remote sensing has triggered a rapid development of SIF measuring systems, enhancing our understanding and monitoring capabilities of plant photosynthesis. After the first SIF maps became available from satellite observations, data acquisition was quickly broadened to proximal tower-based systems and also airborne platforms on full-sized planes and small-sized unmanned aircraft systems (UAS) [1], [2]. Simultaneously, the phenotyping and precision agriculture community is striving to adapt novel technologies for increasing automation in analyzing plant field trials [3]. UAS have been adapted for plant phenotyping in order to provide information about green biomass, growth rates, estimates of biochemical traits from canopy reflectance, and plant stress assessment through canopy temperature sensing. SIF UAS observations can provide us with additional information, such as potential photosynthetic performance of the plants, an indication of transpiration, and early stress detection [1]. Hence, the objective of this work is to explore current challenges specific to measuring SIF from UAS, specifically: payload requirements, the data acquisition strategies, and data post processing techniques. We analyze those challenges from the perspective of future operational applications in plant phenotyping, precision farming and vegetation management.

2. UAS IN PLANT PHENOTYPING AND PRECISION AGRICULTURE

UAS have been adopted for use in precision agriculture and field phenotyping due to their low cost, easy availability, flexibility, and fast data acquisition capabilities. High-throughput field phenotyping requires measuring certain plant traits every few days, or multiple times within a day, preferably for every plant or experiment plot in a field. Since manual measurements cannot satisfy this demand, the only alternatives are mobile field platforms and UAS [3]. Mobile field platforms, for example modified field vehicles or gantry systems, have the advantage of a nearly unlimited payload weight restriction and autonomous data acquisition. Unlike UAS, they lack spatial and temporal flexibility, as movement and travel speed (i.e. sampling frequency) can be restricted by rows and plant density. Furthermore, while photosynthesis is a critical plant trait, traditional measurements of photosynthetic gas exchange or chlorophyll fluorescence are particularly limiting because they can only be reliably measured by physically attaching a cuvette or sensor to a single leaf or branch with measurements taking up to several minutes each. Using such time and labor-intensive techniques heavily constrains the ability to sample plant photosynthetic responses to changing light intensities and other environmental conditions, e.g. water availability, across space and time [1]. As photosynthetic processes may change within the order of minutes, fast data acquisition is the essential requirement for consistent monitoring of plants across large fields (>1 ha). Despite their flexibility, UAS have certain limitations too. Compared to mobile platforms, their deployment may be more restricted by daily weather conditions (e.g. wind gusts, clouds) and limited battery capacity that may reduce the required sampling frequency per day. Required spatial coverage of several hectares large experimental fields can also be a challenge, especially for multirotor UAS platforms. Finally, the biggest challenge is rapid data processing of the acquired data. This data bottleneck is not exclusive to UAS data, but well known in high throughput field phenotyping in general [3].

3. SIF-UAS OPERATIONAL REQUIREMENTS

To our best knowledge, five SIF-UAS were built and deployed until today. All the systems, overviewed in [4], with the addition of [5] (FluorSpec), are using non-imaging point-measuring spectroradiometers, ensuring the required spectral resolution (i.e. full width at the half maximum) <1 nm in the O_2-A/B absorption bands. Furthermore, all systems use multirotor platforms, having the advantage of high maneuverability and agility. Yet, for an operational use in agricultural trials the SIF-UAS must provide also sufficient geometric accuracy, radiometric quality, and high flight operability and robustness.

3.1. Geometric accuracy of measurements

Geometric accuracy is crucial for phenotyping applications, as the SIF-UAS measurements have to be reliably assigned to small, sometimes e.g. less than 15 m^2, areas. To achieve this goal, the following criteria have to be met: a) the field of view (FOV) of the sensor has to be able to capture only one plot per measurement, b) UAS navigation has to be precise enough to reliably, and repeatedly position the sensor FOV over the plot (can be influenced by wind), and c) the shape and location of a measurement footprint have to be reliably retrievable for further spatial data analysis. The footprint is given by the optic's FOV, the distance from the target, the spectroradiometer's integration time, flying speed, and terrain morphology (i.e. a digital surface model) [6]. Reconstructing a spatial representation of the footprint requires exact knowledge of the optic's pose and orientation, as well as a sufficiently exact representation of the terrain.

3.2 Radiometric data quality

Due to the low intensity of the SIF signal, the sensor's spectral resolution, sampling and signal-to-noise ratio must be sufficient for reliable SIF retrieval. For current conical-hemispherical optical systems (AirSIF [6], Piccolo Doppio [7], FluorSpec [5]), optical shutters, switching between downwelling irradiance and upwelling vegetation radiance measurements, may result in a loss of signal and potential inaccuracy of radiometric calibration due to too fast channel switching [4]. The signal loss may also occur when using restricting fore-optics, such as Gershun tubes, narrowing the sensor's FOV and lowering the signal strength at the same time. Nevertheless, a narrow FOV is required to capture small experimental plots. Finally, some fore-optic cosine correctors, used mainly for the downwelling irradiance measurements, have been shown to underestimate the signal intensity in certain sun-sensor constellations. The most significant impact was noted under direct illumination and high zenith angles >50° [8]. To compensate for these signal losses, one can set longer spectroradiometer integration times and/or perform multiple repeated measurements (i.e. through hovering over a target). However, both approaches increase the radiometric data quality but result in a smaller area covered per a single UAS flight. Chang et al. [4] have approached the radiometric data quality challenge by designing a bi-hemispherical system that replaces the optical shutter with a mechanical arm with a single rotating fore-optic. They further exchanged the opaline glass in the cosine corrector by Teflon to improve the Lambertian light diffusion. Although this modification increased radiometric quality, it is inapplicable in phenotyping due to a c. 100°-wide FOV. Other aspects that may impact radiometric data quality include temperature stability of spectroradiometers, atmospheric correction of radiance data, and SIF accuracy assessment. Most of the existing SIF-UAS use thermo-electrically cooled (TEC) charge coupled device (CCD) sensor arrays, but the spectroradiometer housing is not temperature-regulated. Proximal tower sensing setups usually use additional spectrometer cooling mechanisms but they cannot be implemented in UAS due to the payload weight constraints [4]. Consequently, an impact of ambient temperature on SIF-UAS measurements has not been resolved yet. Recent studies revealed that atmospheric correction of SIF radiance must be conducted for proximal measurements from towers and thus, similarly, also for measurements from UAS [9]. Nevertheless, if a UAS is flown at a low altitude (e.g. 25 m above ground level (AGL) or lower), the atmospheric attenuation will be less prominent (irradiance relative difference at 760 nm <0.5%) than for high towers >60 m (>0.5%), where the fore-optic might be oriented in an off-nadir direction, as opposed to nadir sampling from the UAS. Further, as demonstrated in Wang et al. [5], the atmospheric attenuation correction of SIF-UAS data is also feasible. Finally, SIF-UAS observations face the same shortcoming as all SIF-measuring platforms, the lack of validation reference targets of a known SIF emission. Gautam et al. [6] attempted an indirect validation through reflectance factors of pure target observations and Burkart et al. [10] suggested using LEDs with emission similar to SIF for such a validation. However, design of LED panels of the size and performance usable for UAS and airborne observations is still under development.

3.3 UAS operability and measurement robustness

Plant phenotyping and precision farming applications require repeatable and reproducible UAS flights to achieve the desired temporal sampling and required spatial coverage. Due to the very high spectral resolution required for SIF measurements, all current SIF-UAS rely on light-weight non-imaging spectroradiometers. Payloads usually weigh between 2 and 5 kg, allowing for flight times between 10 and 15 min [4], [5]. In case of an imaging sensor, one could easily cover a field of >1 ha in a single flight. Non-imaging spectrometers, however, acquire point measurements either in a transect (i.e. a *continuous mode*), when the platform is moving during data collection, or as multiple measurements taken around a single point and then moving on to the next point of interest (i.e. a *stop & go mode*) [8]. Both modes limit the number of measurements per flight considerably compared to a snapshot camera or a scanning system. Moreover, for fields with a low canopy cover (e.g., early growth stages of crops), the signal measured with a non-imaging system is influenced by the amount of soil background present in the footprint, which is difficult to quantify [11]. A related issue stems from the navigation precision of the UAS. If interested in measuring a single plant with a known geospatial location, one would set a waypoint at that location in the UAS flight plan. How well the UAS is actually positioned over the plant depends on the precision of the on-board global navigation satellite system (GNSS) unit. Gautam et al. [6] demonstrated that it is possible to reliably resolve geometric position of a non-imaging spectroradiometer footprint, although the processing of the required auxiliary geometric positional data is complex and time consuming (±15 cm 1σ for 10 m AGL). Even if the location of a sensor footprint is resolved with a cm-accuracy during post-processing, it is useless if the measurement is taken too far away from the actual plant position. Hence, to reliably sample crops planted in experimental plots of <15 m², the UAS navigation accuracy has to be precise enough to navigate reliably to the center of those plots. Since most of the developed SIF-UAS are prototypes, their engineering is not at a stage allowing for a high frequency, repeatable usage as required by agricultural phenotyping experiments. Moreover, most of the above-described SIF-UAS are not equipped with the appropriate on-board instrumentation to accurately resolve the spectroradiometer footprint, as they were not expected to be deployed for such a purpose. An obvious future solution for the geometric and spatial determination of the experimental plants or crops is a multi-channel spectral snapshot camera or scanning imaging spectroradiometer with arrays specifically designed for SIF measurements. An example of such a two-channel spectral frame camera, designed for measuring a shortwave infrared vegetation index, is presented in Jenal et al. [12].

4. CHALLENGES IN SIF DATA INTERPRETATION

As mentioned above, SIF-UAS may provide additional and unique information for monitoring photosynthetic activities of crops. However, to make meaningful interpretation of SIF in relation to the photosynthetic state of plants, auxiliary information, ideally a complete characterization of CO_2, water and energy fluxes, is required [13]. Photosynthetically active radiation (PAR) absorbed by plants is used for photosynthesis, but its excess is dissipated either as heat or re-emitted as chlorophyll fluorescence [1]. Thus, measuring SIF alone does not give sufficient information about energy partitioning in plants. The photochemical reflectance index (PRI) has been investigated as an indicator of the heat dissipation in plants, but it may be difficult to interpret due to a strong influence of canopy structure and atmospheric light scattering. Considering the influence of canopy structures is equally important for interpreting SIF-UAS data. Biriukova et al. [13] found that both SIF and PRI are higher in the backscatter direction, and lower in the forward scattering direction of horizontally homogeneous canopies. They concluded that off-nadir viewing geometries strongly influence the measured values and should be corrected for. Although UAS nadir observations are easier to interpret, data still has to be corrected for an angular non-Lambertian reflectance behavior of the canopy surface. Furthermore, the assumption of a homogeneous canopy is not always valid, especially for early growing stages of crops, row crops, or grain crops impacted by lodging. As pointed out by Chang et al. [4], a small sensor FOV is compulsory for applications in experimental field trials, but it complicates data interpretation due to increasing heterogeneity given by capturing shaded or sun-lit or both areas of the canopy. These aspects further complicate SIF data interpretation and require that the canopy is well characterized for its predominant leaf angles and leaf area density in order to separate the shaded and sunlit parts. If such a detailed characterization of the canopy structure is available, it still needs to be matched with the UAS-SIF footprints captured by the non-imaging system, as mentioned in section 3.1. It has to be considered that the accuracy of the reconstructed footprint also depends on the canopy structure. It is accurate in closed crop canopies, but less accurate in open or heterogeneous canopies (e.g. bushlands, and orchards), or if a digital canopy surface model is not available and a more generic digital elevation model has to be used to compute the footprint instead. The implemented use of footprint values is further restricted by the assumption that all parts of the footprint contribute equally to the measured signal. However, fiber optics usually have a Gaussian response steeply decreasing towards the edges of the fiber FOV. In addition to corrections for canopy structure, any SIF measurements are strongly driven by the intensity of downwelling irradiance at the time of measurement. It means that SIF follows the intensity of the apparent PAR within a diurnal course, attenuated by shadow propagation induced through canopy structure. Thus, normalization of SIF radiance into SIF canopy yield or efficiency, for instance by specifically designed optical vegetation indices such as NIRv or FCVI [14], has been suggested and must be applied on SIF-UAS observations. Another aspect that complicates data interpretation is that no standard SIF retrieval method has been agreed on, which impairs comparability between datasets. The spectral fitting method (SFM) could be a good standard, as it is easy to implement, while being sufficiently robust to noisy data [1]. Finally, as one of the aims of measuring SIF from UAS is to track an early onset of vegetation stress reactions, challenges of such undertakings should also be discussed and tackled. The SIF signal of green plants is made up of contributions from two photosystems (PS), PSI and PSII, which create the double peak shape of the SIF emission [1]. The ratio of the PSI and PSII peak heights was suggested as a potential indication of plants' stress status. However, studies have been inconclusive, as the pattern observed on single leaves does not match observations on entire canopies. One reason for this inconclusiveness may be the data quality of canopy measurements. The SIF signal of the first peak at 685 nm, originating predominantly from PSII, is weaker and significantly reabsorbed by the canopy, compared to the second, combined PSI and PSII peak, at 740 nm. Therefore, as discussed in section 3.2, a higher signal-to-noise is needed to enable investigation of the SIF double-peak ratio as a plant stress remote sensing proxy.

5. CONCLUSIONS & OUTLOOK

Several independent activities developing SIF-UAS capabilities have resulted in UAS platforms that emphasize either technical simplicity, data geometric accuracy, or radiometric stability. However, SIF-UAS platforms suitable for operational, reliable measurements in plant phenotyping and precision agriculture should ideally combine the aspects of all existing prototypes, specifically: technical robustness, simplicity of use, high radiometric quality achieved through adequate instrumentation (e.g. a good quality cosine corrector, gimbal, and temperature stabilization), and geometric accuracy through spatially explicit and precise footprints, indicating the part of canopy responsible for the measured SIF signal. In addition, new studies and technical development are required to address the challenges outlined in section 4. Apart from further developments of non-imaging sensors, a possible use of UAS imaging solutions (e.g. multi-channel camera arrays or even spectral scanning systems) should be investigated. On one hand imaging systems will make geometric data processing and data interpretation easier, on the other hand their miniaturization will likely require a trade-off in radiometric sensitivity, spectral resolution, and spectral sampling optimal for robust and operational SIF-UAS measurements.

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