Design and development of a hyperspectral data measurement system used in precision agriculture

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Abstract. The paper presents the design and development of a hyperspectral data acquisition system which provides high precision measurements for vegetation reflectance. The system was developed using four spectrometers, two of them for the visible domain and two for near-infrared. They measure the incident radiation and the reflected one simultaneously. In order to establish the optimal value of the integration time, an iterative algorithm was used for each spectrometer. A software platform was developed on the Raspberry Pi microcontroller system for data acquisition, data processing and remote control. The system provides real-time data processing and graphical representation of the acquired data.

1. Introduction
The physical characteristics of the vegetation cause the electromagnetic radiation to be reflected or absorbed in a way that is unique to each type of vegetation and may indicate its development and health status. Within the electromagnetic spectrum were considered mainly the visible (VIS) and near-infrared (NIR) domains.

In the last decades several vegetation indexes were introduced which are defined as combinations of the measured reflectance properties at two or more wavelengths. The Normalized Difference Vegetation Index (NDVI) is the most well-known index, which normalizes green leaf scattering in the NIR domain and chlorophyll absorption in the red wavelength [1], [2], [3].

The majority of optical sensors which are used for reflectance and NDVI measurements are of multispectral nature, i.e. they measure the radiation at discrete wavelengths along the VIS and NIR spectrum. The number of wavelengths is usually between 12 and 16. On the other hand hyperspectral sensors provide an almost continuous reading, the number of wavelengths being around 1000 or more [4], [5].

2. Hardware setup
A remotely controlled data acquisition system for hyperspectral measurements of vegetation parameters was designed and developed. The hardware setup consists of four Ocean Optics STS spectrometers (two for VIS and two for NIR) connected to a Raspberry Pi single-board computer via USB interface. The STS spectrometers provide hyperspectral measurements for 1024 wavelengths in the VIS and NIR domains. This allows us to make very precise measurements for the domain of wavelengths between 400 and 1000 nm, practically eliminating the need of interpolation parameters and minimizing the data processing after acquisition.

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Two STS spectrometers measure the incident radiation and the other two the reflected one. The spectrometer that measures the incident radiation uses a corrector cosine, which collects signal form 180 degree field of view. The spectrometer used for reflected radiation has a smaller field of view [4], [5].

3. Software setup

The software setup consists of the following components:

- Applications which access the STS device through the SeaBreeze driver interface [6];
- Ruby scripts for launching the above mentioned applications;
- Web server based on the Ruby on Rails framework [7] which allows the remote access through a web interface;
- Real-time graphical representation of the acquired data using the Flot Javascript library.

Our applications, which access the STS spectrometers through the SeaBreeze driver interface [6], were written in the C programming language. These applications set the acquisition parameters, such as integration time and number of iterations. An iterative algorithm which finds the optimal value of the integration time for each spectrometer was used. The pseudocode for the respective algorithm is presented in Listing 1.

**Listing 1.** Pseudocode for the iterative procedure which finds the optimal value of the integration time

```plaintext
maxval ← 16383;
tint ← 1200;
while maxval == 16383 do
    if tint > 500 then
        tint ← tint - 200;
    end
    else if tint > 200 then
        tint ← tint - 100;
    end
    else if tint > 10 then
        tint ← tint - 10;
    end
    else
        tint ← tint - 1;
    end
    for i ← 1 to niter do
        get formatted spectrum;
    end
    compute averages for each wavelength;
    maxval ← Max (averages);
end

tintval ← tint;
write tintval to file;
```

For easier debugging we created three standalone applications for the dark measurement, reference spectra and the actual measurement. These applications can be launched from the command line (via SSH access to the Raspberry Pi) or through the web interface.

The acquired data is written to files with the name VIS-index.txt, respectively NIR-index.txt, where the index is automatically incremented. Each file contains the values for the wavelengths and the
corresponding reflectance/ transmittance. The raw data can be transferred to computer via SFTP for further analysis and graphical representation.

Figure 1 shows the components of our software setup and their interactions.
The reflectance values for each wavelength can be computed by means of the following relation:

\[ R(\lambda) = \frac{R_{\text{white}}(\lambda)}{F(\lambda)} \cdot \frac{I_{\text{down}}(\lambda)}{I_{\text{up}}(\lambda)} \]

(1)

where

\[ F(\lambda) = \frac{I_{\text{ref, down}}(\lambda)}{I_{\text{ref, up}}(\lambda)} \]

(2)

In the above equations \( R_{\text{white}}(\lambda) \) represents the reflectance value for the white reference panel, \( I_{\text{down}}(\lambda) \) and \( I_{\text{up}}(\lambda) \) are the dark subtracted intensities measured as counts by the spectrometers pointing downward and upward respectively, \( I_{\text{ref, down}}(\lambda) \) and \( I_{\text{ref, up}}(\lambda) \) denote the intensities measured in the case of the white reference panel.

The reflectance values for the white reference panel were obtained in laboratory conditions using a reflection probe with holder and a white reflectance standard (barium sulfate). We made several measurements and performed averages for each wavelength. Finally we applied a smoothing algorithm using Bezier curves [8]. The reflectance values were stored in a file and uploaded to the Raspberry Pi microcontroller board. Figure 2 shows the plot of the reflectance as function of wavelength for the white panel.

![Figure 2. Reflectance vs. wavelength for the white reference panel.](image)

4. Testing the data acquisition system
In order to test the accuracy of the developed data acquisition system for hyperspectral measurements, transmittance measurements in laboratory conditions were made. We measured the maximum value of
the transmittance for some optical filters, as well as the wavelength corresponding to the transmittance maximum. We computed also the error in the estimation of the above mentioned parameters. The obtained data is presented in the table 1.

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>Δλ (nm)</th>
<th>T&lt;sub&gt;max&lt;/sub&gt; (%)</th>
<th>ΔT&lt;sub&gt;max&lt;/sub&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>419.050</td>
<td>0.460</td>
<td>51.153</td>
<td>0.356</td>
</tr>
<tr>
<td>470.225</td>
<td>0.470</td>
<td>42.757</td>
<td>0.006</td>
</tr>
<tr>
<td>575.775</td>
<td>0.470</td>
<td>29.377</td>
<td>0.137</td>
</tr>
<tr>
<td>577.440</td>
<td>-</td>
<td>35.843</td>
<td>0.079</td>
</tr>
<tr>
<td>625.200</td>
<td>-</td>
<td>18.158</td>
<td>0.815</td>
</tr>
<tr>
<td>715.015</td>
<td>0.470</td>
<td>36.221</td>
<td>1.390</td>
</tr>
</tbody>
</table>

Table 1. Transmittance maximum and the corresponding wavelength for some optical filters.

These preliminary results show that in laboratory conditions the error in the evaluation of the transmittance maximum is smaller than 3.84%. For the corresponding wavelength estimation the error is smaller than 0.5 nm, comparable with the resolution of the optical sensor in the STS spectrometers. The results presented in the above table were obtained by averaging the experimental results from 5 independent measurements.

For vegetation reflectance measurements the reference spectra must be acquired using a white reflectance standard. The plots from figure 3 and figure 4 show the reflectance values as function of the wavelength for green and dry vegetation.

Figure 3. Reflectance vs. wavelength for the visible domain.

Figure 4. Reflectance vs. wavelength for the near-infrared domain.

In order to ensure repeatability we made successive independent measurements and we compared the obtained values for the reflectance. The uncertainty for the reflectance was smaller than 3.98% for the visible spectrum (at 681.6 nm), respectively 2.13% for the NIR spectrum (at 938.33 nm). The results presented here were obtained as averages over 5 measurements.

The main sources of errors are:
- variation of solar intensity;
- instability of the incident angle;
In order to reduce the influence of the solar intensity variation we must repeat the reference measurement if it is necessary (cloudy sky). Air attenuation influence can be minimized if we ensure that all measurements are made at the same height (for example 5 m over ground). For optimal results the integration time should be located in the interval [10, 500] ms.

5. Conclusions
The proposed measurement system provides high precision data due to the acquisition of a larger amount of experimental values, which allows the computation of the reflectance for the visible and near-infrared domain (1024 wavelengths in each domain). The method uses four spectrometers, two for the visible and two for the near-infrared domain, which measure the incident, respectively the reflected radiation simultaneously. The system provides real-time data processing and graphical representation of the acquired data.

References

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