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Portable optical fiber coupled low cost visible spectrometer

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Abstract

We developed, implemented and tested a portable low cost spectrometer that covers the visible wavelength range between 400-800 nm. The system is intended to be employed mainly for educational purpose. Hence, open source platforms have been extensively used both in software (Python) and Hardware (Arduino). Main elements of the system are the optical coupling unit based on duly collimated multimode fiber, a ruled linear grating as dispersive element, and a RGB three line optical sensor with 5300 elements. Digitalization is realized by a microcontroller platform from the Arduino family. Data is send over serial USB to a Python based application that permits further data processing and visualization. Calibration is done backed on a LED ladder that covers the whole visible range. Good linearity is observed, and also resolution is comparable with commercial spectrometers. However, a moderate signal to noise ratio is observed.

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Keywords: Spectrometer, visible wavelength range, CCD, diffraction grating, microcontroller, data acquisition, Arduino, Python

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1. Introduction

Spectrometers are a valuable resource in the engineering sciences, both in the scientific lab as for educational purposes. Though there are now available several portable spectrometers on the market with acceptable performance and interesting price/quality ratio, still most are out of reach of some, if not most, institutions.

The objective of this work is to develop, implement and test a portable optical fibre coupled low cost visible spectrometer. In particular, the aim was to explore adequate open source technologies and tools that eventually will permit a more or less technology affine public to gain access to this fascinating didactic tool.

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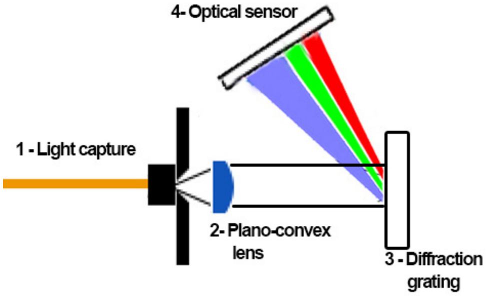

Fig. 1 Schematic light path and configuration of fundamental building blocks of low cost spectrometer light

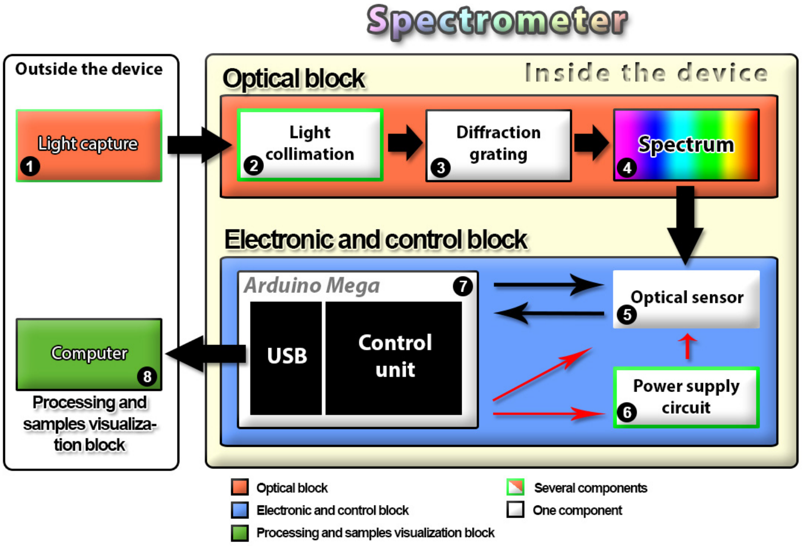

Fig. 2: Functional and System block diagram

In figure 1 we show the physical front end unit, the characteristic configuration of the optical elements. The light is captured through a lens coupled multimode fiber and guided to the spectrometer through the fiber. If considered necessary, the slit width can be reduced from the multimode core diameter to lower values by inserting an additional slit. The aperture fiber light cone is then collimated through a single lens and steered to a reflective or transmissive diffraction grating, where it becomes spatially dispersed towards an optical line sensor.

The project specifications are shown in table 1.

Dimensions	250x150x100 mm
Optical sensor	RGB Linear CCD NEC uPD3797y
Number Pixels	5300
Resolution	1-10nm
Interface	USB
Price	Less than 200 euros

Table 1 - Spectrometer specifications

2. System and selection of modules, components and tools

In Fig. 2 we show the functional and system block diagram. The optical block comprises the capture, guidance and collimation of the light towards the dispersive elements. This is challenging with respect to mechanical precision and optical adjustment, given that the final device is expected to be small and portable. It also has a major impact on the final system performance, for example the resolution and the all over light gathering capability. The electric block comprises the system control and the data acquisition. The main challenge is to guarantee a good signal synchronization and integrity at comparatively high frequencies.

Finally, we have a data processing and visualization block that should be user friendly and give results in real time.

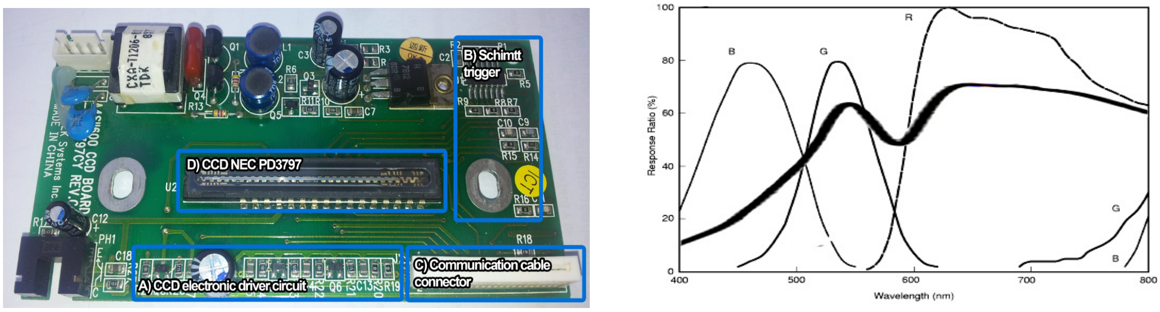

Fig. 3 – (Left) Old scanner board with integrated CCD line sensor and respective driving circuits. (Right) Diffraction grating efficiency, single bold line, and linear CCD response rate between 400-800 nm.

The selection of modules and components required a careful trade-off between simplicity and effectiveness. With the spectrometer specification in mind, we decided to centre our project on an optical sensor based on the NEC PD3797 CCD line sensor with 5300 pixels and three lines for direct dispersion-less RGB colour detection. This chip, though maybe slightly over dimensioned for the current project, was readily available from an old scanner and is shown in figure 3. As illustrated, only blue zones were used from this board. Represented are the CCD electronic driver circuit, a Hex inverting Schmitt trigger, a connection band for microcontroller-board interface and power supply. On the right hand side of Fig. 3 we show the spectral efficiencies of the RGB colour filter according to the CCD datasheet. It is clear that all three lines are to be acquired in order to detect faithfully spatially dispersed light.

We know that only at system level it is possible to compare directly the performance variation of different components, for example lenses, gratings or slits. Hence, we focused on the development of a robust and accessible data acquisition, communication and processing system. Our choice was to rely extensively on the open source platform Arduino (microcontroller hardware platform) and Python (data processing). Digitalization is realized by a microcontroller platform from the Arduino family. Data is send over serial USB to a Python based application that permits further data processing and visualization.

Regarding the collimator optics, we tested several configurations. Most reproducible results are now obtained by using a fixed focus point optical fibre collimator lens, mainly due to the ruggedness of this solution.

For the diffraction grating we explored also several options, but the most promising results came along with a reflective ruled diffraction grating with a 750nm blaze wavelength, with 1200 grooves/mm and 25x25x6mm dimensions, despite its significant spectral efficiency variation, as shown in figure 3.

3. Implementation

In figure 4 we show the physical implementation of the optics setup as discussed in figure 1. The system is flexible and allows e.g. for the easy change from reflection to transmission gratings.

The RGB CCD line sensor is driven by two distinct clock regions. The required waveform variations are shown in figure 4 and 5. By comparing with the application notes is can be concluded that the Arduino MEGA's A port can be effectively used to control and read out stored CCD data. Here it is shown the inverted shift register clock. It should be remembered that commonly used *digitalwrite* commands are not in order due to the significant Arduino-characteristic redundancy burden, and that in this case would prevent the system to achieve the necessary transmission speeds. This becomes still more obvious from the inverted transfer-gate clocks shown in figure 5.

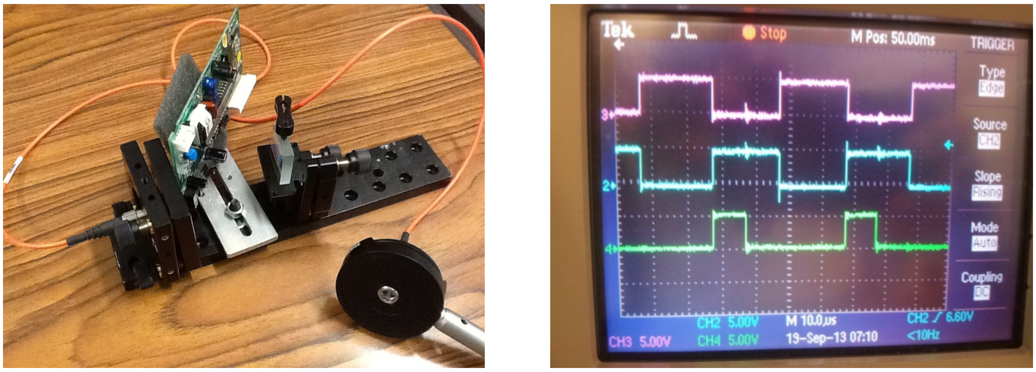

Fig. 4 –(Left) State of the art of the spectrometer mounted without black box; (Right) Inverted shift-register clock.

When the correct shift register clock and transfer gate clock are applied, we can immediately observe the signal from the CCD on the oscilloscope. This is shown in figure 5 (right). Note that the colour used in the viewgraph corresponds to the respective RGB filter on the line sensor. All three RGB channels prior to digitalization show a low noise figure and a sound chromatic correlation. Note that the signal is inverted, and that we visualized here is the envelope function that on this time scale does not reveal all the digital features of the signal. It is clear from this that synchronization timing is key to extracting the correct signal.

The signals of the three colour channels are then added and digitalized. Data is sent through serial communication through a USB connection to the PC. An application was developed in Python that permits the control of the spectrometer, includes basic data processing, as well as the visualization in real time.

Both applications in Arduino and Python are implemented as two communicating state machines.

4. Wavelength calibration and linearity test

Calibration is done recurring on a LED ladder that covers the whole visible range, as shown in figure 6 (left). These were measured with a commercial and calibrated spectrometer. For the wavelength calibration we used the well defined LED centre wavelength, as given on the top line of Fig. 6 (left). The wavelength vs. Pixel number calibration is shown in figure 6 (right).

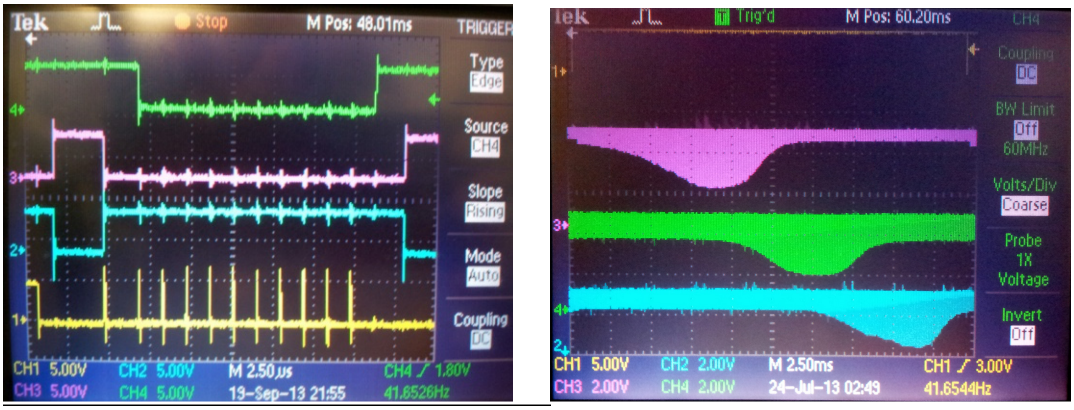

Fig. 5 – (Left) Inverted transfer-gate clock. **(Right)** Linear CCD RGB readout test.

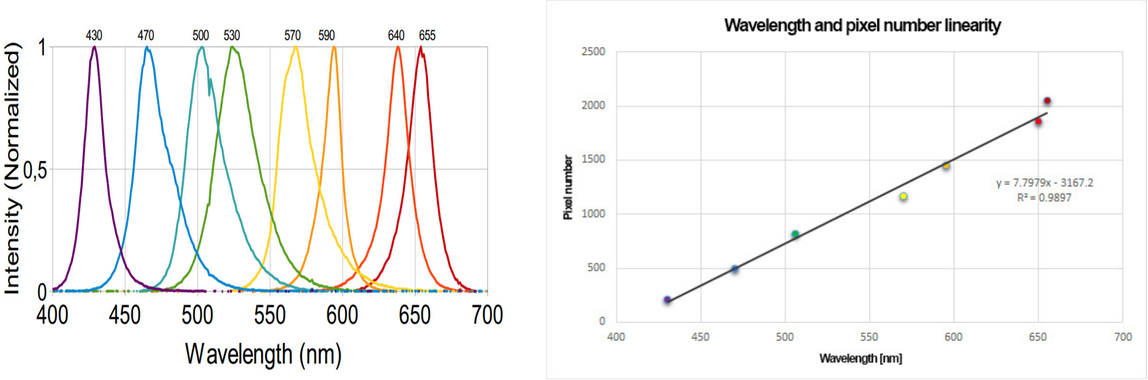

Fig. 6 – (Left) Reference LED ladder as measured with a commercial spectrometer (Right) Wavelength calibration

In figure 7 we present a measurement of the LEDs with the novel spectrometer. It has to be pointed out that the data shown is as-is, so no data processing was applied. From the viewgraph we can conclude that there is a good near to linear correlation of the interpolated spectra to the reference spectra. Nevertheless, it is apparent that the noise level is significant in all measurement, and that some, with an allover smaller LED luminous emission efficiency, have modest signal to noise ratios. We attribute the significant noise to aging effects the age of our line CCD. The data shown

We also observed that the system resolution is comparable to commercial spectrometers. It is speculated that this eventually is due to poor quality of the CCD line sensor employed, which was recycled from an old scanner. It is speculated that other bottlenecks include modest optical throughput and additional digital signal processing techniques.

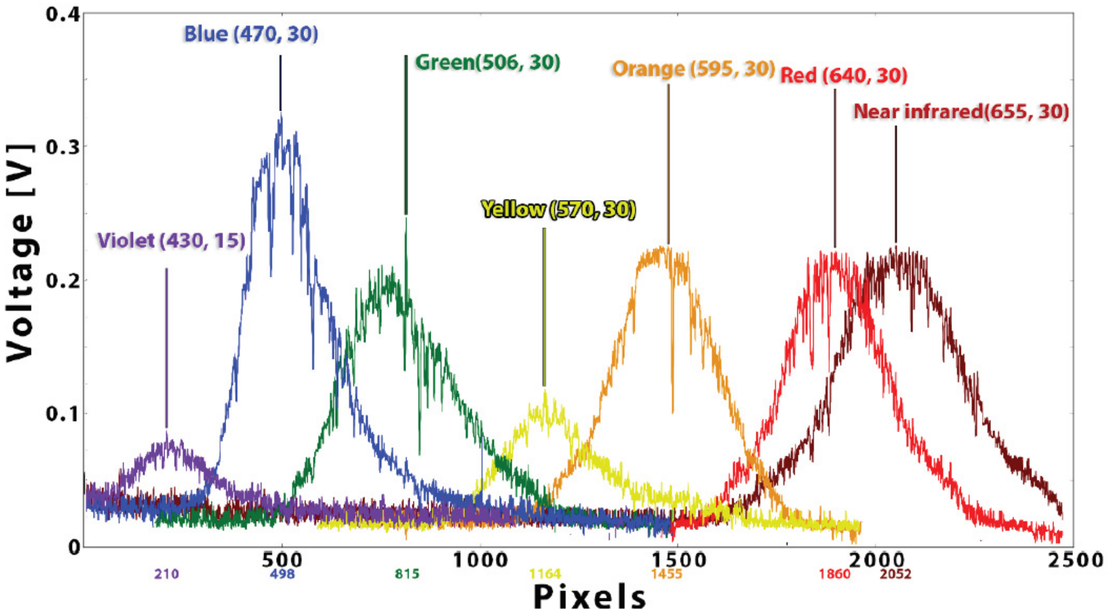

Fig. 7 – Acquired Led spectra with significant noise component

5. Discussion and outlook to future work

We presented a low cost spectrometer that can be set up with modest effort and at low cost. It can be employed for general purpose VIS absorption, transmission, reflectance, and light emission and colour measurements in several branches of the physical sciences and in chemistry and biology applications. The project combines knowledge of physics and electronics, communication and programming, and matches a multidisciplinary thematic of technology-affine students. Our approach was based on a 5300 pixel RGB line sensor. The moderate observed SNR is attributed to CCD aging effects. It is therefore important to compare the results with a simpler non-RGB grayscale line sensor. This work is now in course, and we expect it to result in a kind of CCD break out board to be commercialized within the Arduino community.

It is also considered that a modular approach for the spectrometer best would meet the variance of expectation of potential end users (“There is no such thing as a single best solution.“). We are now exploring the possibility to substitute one or more of the more expensive parts of the spectrometer, as for example the diffraction grating, in order to reduce the bill of materials.

All results of this project will be published in a journal with focus on scientific and engineering education, and where all details for building the spectrometer will be given.

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