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Vegetation detection in agricultural applications with a single-chip camera

The application of (smart) cameras for process control as an element of precision farming saves fertilizer, pesticides, machine time, and fuel. Although research activities have increased in this topic, high camera prices reflect low adaptation to applications in all fields of agriculture. Smart and low-cost cameras adapted to agricultural applications can overcome this drawback. The normalized difference vegetation index (NDVI) is an applicable algorithm to discriminate between plant and soil information (background). In this study, the advantage of a smart one-chip camera design with an adapted algorithm for NDVI image performance is demonstrated in terms of low cost and simplified design.

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Smart camera, NDVI, image processing, plant sensor, embedded system

Abstract
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Research activities in the field of precision farming concentrates mainly on the reduction of carbon dioxide, environmental pollution, and costs. This is to be done by optimizing the operating supplies. To increase the efficiency in agriculture, different information and databases are pooled [1; 2; 3]. Numbers of plants, coverage level or biomass are typical information which can be detected by sensors [4]. The information can be processed directly on the agricultural machine, for example to control a field sprayer [5]. The coverage level can be located on a field based on NDVI images [2]. The NDVI is used to differentiate pixels with chlorophyll-active plant material from those with dead plant material or soil. The differentiation is made by two wavelengths: red (620–660 nm) and near infrared (NIR, > 780 nm). In doing so, the different degrees of reflection of the active plant compared to its environment (soil) is used. The plant absorbs mainly the red content and reflects the NIR content, in contrast to soil and inactive plant tissue [6; 7]. High-grade plant or NDVI cameras use at least two CCD-chips (e. g., DuncanTech MS2100 or MS3100, Redlake Inc., San Diego, CA, USA). The calibration of the chips makes the cameras more expensive so that they can only be used in research. On the contrary, no calibration is needed for the single-chip camera like the one presented here. Instead it needs a double-bandpass filter for the red and NIR-band. Rabatel et al. [8] show in principle the possibility that normal cameras with changeable filters can be used for red and NIR detection. Normally, camera systems have control loops for exposure time and white balance. Because of a filter change the control loop does not work accurately anymore, this leads to overexposure and misinterpretation. Therefore, the camera control has to be intervened and the NDVI algorithm has to be modified.

The single-chip camera of the low-price segment presented here (USB uEye LE Kamera, type UI-1226LE, by Imaging Development Systems GmbH, Obersulm, Germany, ca. 230 €) is a base for a new NDVI camera system compared to the three-chip camera DuncanTech MS2100. The disadvantages of the standard NDVI algorithm for a single-chip camera are discussed and solutions in the way of extended NDVI algorithms are demonstrated. The goal is to reconfigure a low-price field camera with suitable algorithms which can handle the typical light situations on the field without following up the threshold.

Material and methods

In the following the usage of NDVI in a multispectral camera (15,000 €) is shown which is applied for scientific purposes. Furthermore, the change in the NDVI algorithm will go into more detail. That is necessary for the application in a single-chip camera. Instead of a NIR-Cut filter of a single-chip camera, that usually blocks NIR wavelengths > 650 nm, two different filters were used: a low-pass filter with an edge wavelength of 645 nm (RG645, Schott AG, Mainz, Germany) and a double-bandpass filter that was produced especially for this project (ET620_60bp_780_900bp by Chroma Technology GmbH, Olching, Germany). The low-pass filter allows wavelengths > 645 nm (lower energy) to pass and stops wavelengths < 645 nm (higher energy). The double-bandpass filter consists of two specific bands, one with 620–660 nm and the other with 780–900 nm in which light with that wavelength can pass the filter. All other wavelengths are blocked. This change in a single-chip camera allows the detection of the NIR-range and blinds out the blue and green range.

NDVI

Using NDVI, chlorophyll-active plants can be discriminated from soil or dead plant material. This cannot be done by the green channel of a RGB camera. The NDVI bases on the great absorption in the red wavelength band and the great reflection in the NIR range of chlorophyll-active plants in contrast to the almost identical reflection/absorption of not-active plants and soil using equation 1:

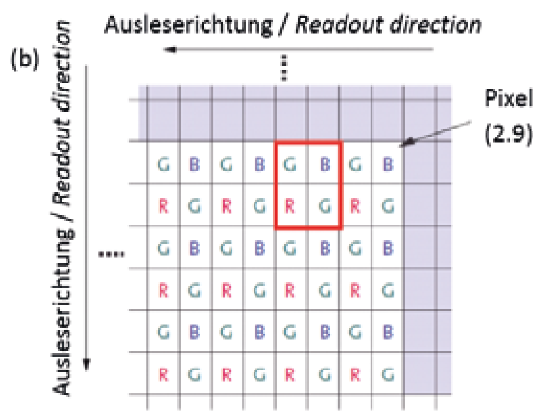
$$NDVI = \frac{NIR-Rot}{NIR+Rot} \quad \text{(Eq. 1)}$$

Equation 1 can be directly adapted to the pictures of the red channel and the NIR channel of the multispectral camera. By means of an appropriate threshold the NDVI picture can be binarized whereby in an ideal case chlorophyll-active plants are shown as white pixels (value = 1) and all other pixels as black pixels (value = 0). Out of this, for example, the coverage level can be calculated.

Single-chip plant camera

For the design of the single-chip camera, that should work under field conditions, are the worst conditions to be assumed. The developed algorithms have to be adjusted to the used RGB

Fig. 1



Bayer pattern (source: Aptina datasheet)

camera chip. But there are difficulties along the way from the realization to the digital image [10].

Spectral response of a RGB single-chip camera

In this study a single-chip camera is used from the company IDS with the Aptina-Chip MT9V032STC-CMOS image sensor with 752 H × 480 V pixel (Aptina Imaging Corporation, San Jose, CA, USA). Because of its image sensor this camera has the advantage that after the removal of the NIR-cut filter all pixels (red, green, blue; **Figure 1**) are sensitive (**Figure 2**) and all information can be detected from this wavelength range [11].

Instead of the NIR cut-off filter a low-pass filter can be installed. This one blinds out the blue and green range (**Figure 3**), as described above, so that new information can be generated which can be detected with the former RGB pixels. The former red channel contains now red and NIR information (R+NIR), the channels blue and green contain only NIR information. For a better separation of red and NIR, the low-pass filter is replaced by a double-bandpass filter (**Figure 4**). Using this filter, the transition between red and NIR is blanked out. Whereby the wavelength range with its containing information that is represented by the pixels, is sharpened. The camera can now be used as NDVI camera. **Figure 5** shows a false color NDVI image with its typical red-white coloration. The red coloration emerges through the sensitivity of the red channel in the red and the NIR range (**Figure 4**). The white coloration emerges through the sensitivity of all three channels in the NIR range. Plants appear white in the image because they reflect NIR light particularly strong.

The image in **Figure 5** is made under stray light circumstances, i.e. with homogenous illumination. Images made under direct sun insolation and the related problems are discussed hereinafter.

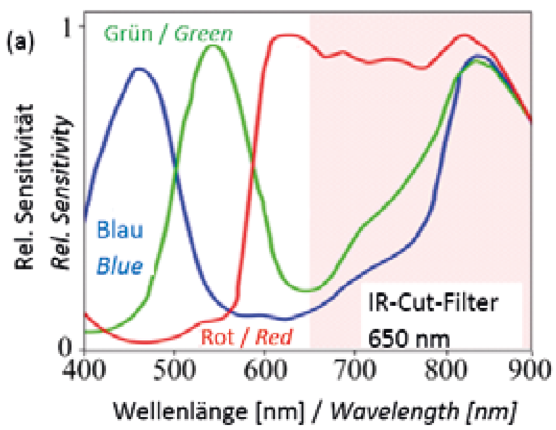
Demosaicing or debayering

According to the Bayer-cluster (**Figure 1**) every pixel of a single-chip camera can only detect one color range. The interpolation technique, that calculates the two missing color ranges for the physically existing pixels, is named demosaicing. Out of the numbers of interpolation algorithms the one by Malvar et al. shall be shown (**Figure 6**). All those algorithms base on one scene assumption which interpolate an image in a way that it seems reality for a human eye. The demosaicing example presented in **Figure 6** shows that different color channels are used for interpolation. But this eliminates information given in the channels of the NDVI camera. If a pixel offset is acceptable, a red framed quadruplet in **Figure 1** can be summed up as a NDVI pixel and the NDVI algorithm can be adapted to this camera.

Adapted NDVI for a single-chip camera

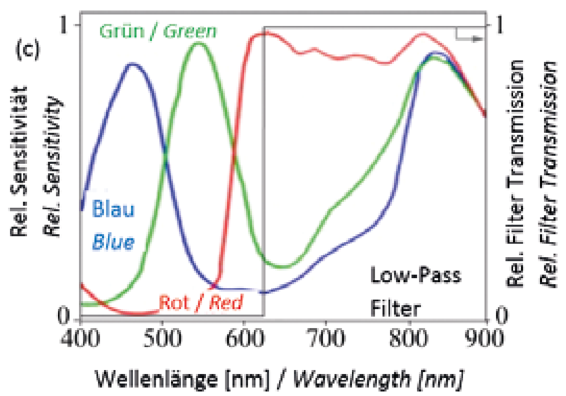
Because of the changed information content of the channels of a single-chip camera the NDVI algorithm must be adapted. As mentioned above the R-channel of the single-chip camera

Fig. 2



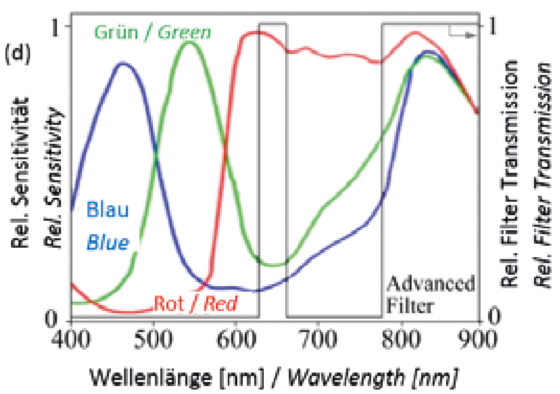
Spectral response of the MT9V032STC CMOS image sensor (IDS datasheet)

Fig. 3



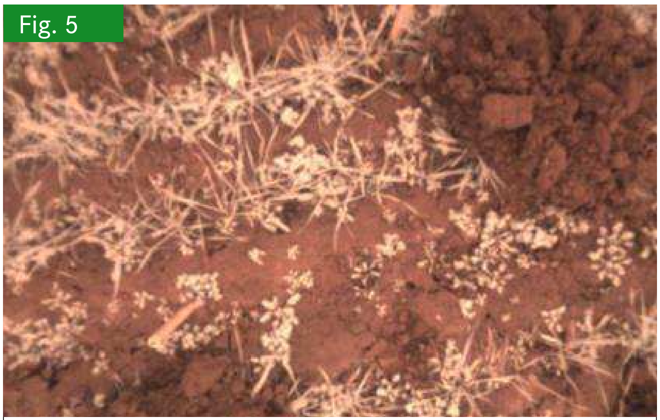
Enabling the RGB CMOS chip for red and NIR sensitivity through ideal low-pass filter

Fig. 4



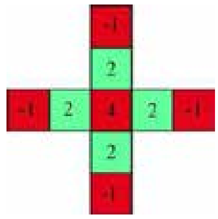
Enabling the RGB CMOS chip for red and NIR sensitivity through ideal double band pass filters

Fig. 5



False color image of the modified camera, weed in winter wheat (Photo: J. Selbeck, V. Dworak, M. Hoffmann)

Fig. 6



Example of a demosaicing pattern with coefficients corresponding to Malvar et al. [12]

contains red and NIR information whereas the G-channel und the B-channel just contain NIR information. So the algorithm changes into equation 2:

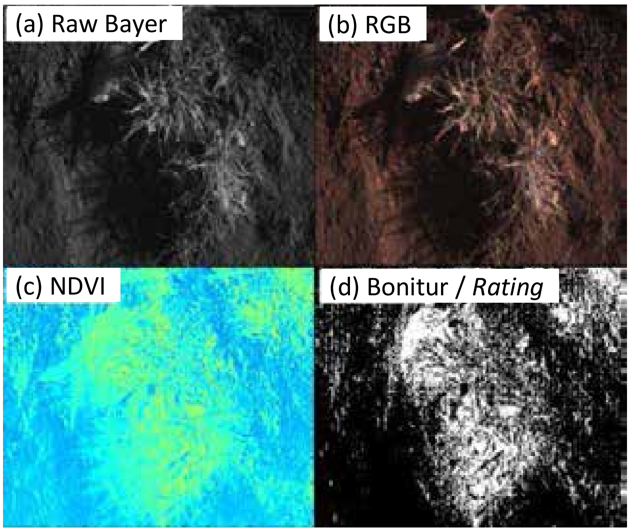
$$NDVI = \frac{NIR-R}{NIR+R} \rightarrow NDVI_{CMOS} = \frac{(B+G)-R}{R} \qquad \text{(Eq. 2)}$$

Since the used image sensor in a range about 850 nm shows almost identical sensitivity for all three color channels, an individual amplification adjustment for each channel was not made.

Amplification control

For the correct calculation of the NDVI it is necessary that no pixels are in saturation (overloaded). The green channel is used for exposure control in standard RGB cameras. Since the red channel of the single-chip camera goes most likely into saturation because of the addition of the red and NIR range, an own autonomous amplification control algorithm was developed. Some camera sensors give directly a histogram of the intensity distribution of the pixels while for others it has to be done by an additional software. If there are pixels in the histogram at highest intensity, the amplification must be reduced. Otherwise the amplification can be raised, as long as no pixel appear in the highest and second highest intensity. The amplification starts with a medium adjustment and is raised or reduced by half according to the histogram. It is the same like, e.g., in a succes-

Fig. 7



Raw image of tufts of grass and leafs added by wind (a), false color image (b), NDVI image in rainbow colors from blue (zero) to red (256) (c), binary image under direct angular sunlight (d)(Foto: J. Selbeck, V. Dworak, M. Hoffmann)

sive-approximation analog-to-digital converter. An implemented hysteresis is responsible for the required stability of the amplification so that it does not oscillate around one value. The camera is connected to the PC via an USB-2.0 port. The control of the amplification and of the image rate is made with the software MatLab (The Mathworks, Natick, Massachusetts, USA).

Measuring condition

Like implied above the measurements at homogenous cloudiness that produces pure stray light, are best because no hard shadows appear. However, bright sunshine with hard shadows are difficult circumstances for the NDVI algorithm because the dynamic range must be significantly larger to calculate a quantification. Additionally, the proportion between red and NIR amount changes because the distribution of both wavelength ranges in the atmosphere and at a cloudy sky has different degrees. The change goes into to the power of four of the wavelength. Likewise, the transmission behavior of light is reverse to scattering properties for both wavelength ranges in the atmosphere. Hence, looking at the NDVI it can happen that soil appears brighter in shadow than in sun light.

Results and discussion

It is already shown that the single-chip camera works well under ideal circumstances (**Figure 5**). The problem with direct sunlight is illustrated in **Figure 7**: the raw data image (a), the false color image after calculation (b), the NDVI image calculated by equation 2 (c), and the binary image (d).

Since there is almost no contrast between plant and soil in the binary image in the shade area, this binary image contains a huge amount of wrong classified pixels. That means that the NDVI algorithm has to be extended so that this lightning conditions are covered, too. Conclusions concerning the dynamic range and the lightning conditions can be made on the bases of the minimum and maximum values of the pixel intensity. Following problems need to be solved to get a suitable single-chip camera for the usage as plant camera:

- The $NDVI_{CMOS}$ is prone to overexposed pixels because of the sensitivity of the R-channel to red and NIR wavelengths.
- The threshold for binarization alternates for ranges in direct sunlight in contrast to ranges in the shadow.
- Even with stray light the threshold is not easy to determine because the values for soil and plants overlap.
- An extended algorithm should be easy to calculate so that it can be implemented in embedded systems.

Range extended NDVI

Most embedded systems have significantly less computing power than a PC. Therefore, while implementing the NDVI other important calculations have also to be integrated in the system like the automatic gain control. Because of the high NIR reflection of plants the equation can be extended by the NIR value as a first step:

$$NDVI_{CMOS} = \frac{(B+G)-R}{R} * \frac{B+G}{2} \qquad \text{(Eq. 3)}$$

Through this the contrast between plant and soil is raised because the intensity of the pixels, which represent soil, is reduced. A misclassification (**Figure 7**) is almost completely eliminated because of equation 3. The elimination of single pixels and a 2D five-point Gaussian filter raise the classification safety. The algorithm can easily be placed in an embedded system. This overall system is usable for the application on field sprayers (even part-width-sections specifically), not at least because of the low price. The information can also be used for masking to perform following analysis of shape and contour or to evaluate NDVI information quantitative. Under direct sunlight mainly the dynamic ranges, which the camera has to handle, and the already described ratio of wavebands intensities change. Here it is not possible to work with a fixed threshold that is tuned to sunlight because the shadow regions can be underrepresented throughout. So a non-linear amplification factor is included in the equation:

$$reNDVI_{CMOS} = \frac{(B+G)-R}{R} * \frac{B+G}{2} * f(x) \qquad \text{(Eq. 4)}$$

$f(x) = 1;\ 0{,}2 < x < 1{,}0$

$f(x) = 3 - 10 * x;\ \ 0{,}1 < x < 0{,}2$

$f(x) = 2;\ 0{,}0 < x < 0{,}1$

This range extended NDVI solves this task by amplifying the ranges in the shadow. The values for the function f(x) in

Fig. 8

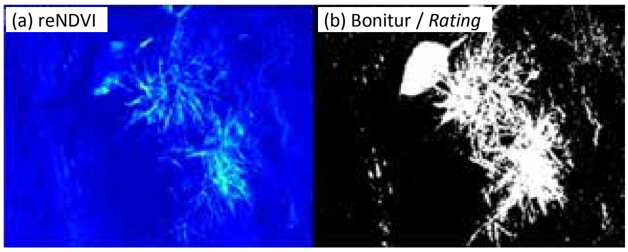


Image of the applied reNDVI$_{CMOS}$ in rainbow colors from blue (zero) to red (256) (a), five-point Gaussian filtered binary result (b) (Foto: J. Selbeck, V. Dworak, M. Hoffmann)

equation 4 are determined experimentally through the analysis of different normalized images under different lightning conditions.

The combination of the extended NDVI with the non-linear amplification function solves the problem of the high dynamics in the image data. The extension of the NIR value (equation 3) raises the contrast between plant and soil in the shadow like the leaf top left in **Figure 8**, which is partly directly illuminated and partly in the shadow. The amplification function of the range extended NDVI weights the pixel with lower intensity so that plants can be distinguished from the soil by a simple threshold. **Figure 8** (b) shows an almost ideal contour of the leaf after the usage of reNDVI$_{cmos}$.

Conclusion

The results show the utilizability of a low-cost single-chip camera with a new filter assembly. The customized double-band-pass filter sharpens the separation of the red and NIR range. By using the raw data in terms of the Bayer pattern, without conversion into a classical RGB image, it is prevented that the image data increase to the factor of three. That can be essential in embedded systems with limited memory and limited power. Since the automatic exposure control had to be new implemented, a broad control of the camera chips and the camera, respectively, was necessary. The known NDVI cannot be used without further ado in a single-chip camera. Known and new problems would occur during application. The presented extended NDVI improves the separation of plant and soil under homogeneous lightning conditions. To get good results also under inhomogeneous lightning conditions, the range extended NDVI is developed for. By this, the ranges in the shadow can be separated into plant and soil. Concerning the embedded systems the extensions of the NDVI equation can be implemented and managed without great calculation efforts.

The next steps are the implementation of an automatic threshold for an automatic plant camera which needs no more calibration. Furthermore, an additional increase of discriminatory power between plant and soil and a lateral resolution could be achieved through the raising of the pixel amount or through a camera with "high dynamic range" skills and/or less pixel noise. But this would have a direct effect on the price of the camera. So this is only useful for single cameras. This is in contrast to the single-chip camera which could be used, e.g., for a part-width-section control of field sprayer because of its low price.

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