SENSOR AND SYSTEM TECHNOLOGY FOR INDIVIDUAL PLANT CROP SCOUTING

A.Ruckelshausen, L.Busemeyer, R.Klose, A.Linz, K.Moeller, M.Thiel

University of Applied Sciences Osnabrück
Faculty of Engineering and Computer Science
Osnabrück, Germany

K.Alheit

University of Hohenheim
State Plant Breeding Institute
Stuttgart, Germany

F.Rahe

Amazonen-Werke H.Dreyer GmbH & Co. KG
Hasbergen-Gaste, Germany

D.Trautz

University of Applied Sciences Osnabrück
Faculty of Agricultural Science and Landscape Architecture
Osnabrück, Germany

U.Weiss

Robert Bosch GmbH
Corporate Sector Research and Advance Engineering
Stuttgart, Germany

ABSTRACT

Sensor and system technologies are key components for automatic treatment of individual plants as well as for plant phenotyping in field trials. Based on experiences in research and application of sensors in agriculture the authors have developed phenotyping platforms for field applications including sensors, system and software development and application-specific mountings. Sensor and data fusion have a high potential by compensating varying selectivities of single sensors. Sensors systems used for the detection of morphological and spectral signatures are 3D-Time-of-flight cameras, spectral imaging, light-curtain imaging, color cameras and optical distance sensors. For online detection and data storage a modular and flexible system architecture has been designed and realized including Gigabit Ethernet, a data base, error handling and human-machine interfaces.

Two very different application-driven setups of phenotyping platforms have been developed: For triticale *(×Triticosecale Wittmack*) the trailer “BreedVision” allows measurement of high-density plants for growth stages up to 1.50 m. Properties of single plants and plot-related values are detected for offline analysis. For corn (*Zea mays*) the autonomous crop scout “BoniRob” has been developed. The robot is equipped with a RTK-DGPS allowing the re-detection and characterization of single plants. The sensor and system technologies are evaluated using test setup, such as laboratory carousels or a band-conveyor. First outdoor measurements in field trials have been performed.

Keywords: Sensors, field robots, field trials, plant phenotyping

INTRODUCTION

Innovations in electronics, computer science and sensor technologies strongly influence agricultural engineering and have become key competences in this field. In particular sensor information can result in economical as well as ecological improvements. However, the interpretation of the corresponding senor data from an agricultural point of view is of high importance to find the right decision for plant or soil treatment. For example, sensors in the market are already used for fertilizer control (N-Sensor/Yara or Crop-Meter/Claas Agrosystems), measurement of maize plants during harvesting (HarvestLab/John Deere or AutoScan/Krone) or driver assistance (such as AutoFill/Claas or 3D-Scanner/New Holland).

Having a look at field trials the implementation of sensors is of highest importance for interpreting plant breeding or modifications of agricultural processes in the field or machinery. Until now typically samples are evaluated by experts and analysed based on statistical methods (Thomas, 2006). However, this is very time consuming, generates high costs and may cause variations thereby resulting in uncertainties for the optimization of agricultural processes. As a consequence the implementation of sensors and corresponding system technology for data processing and storage has come into focus for field trials, as for example the development of measurement platforms for genetic studies as proposed by Montes et al. (2007). Automatic phenotyping for online applications in the field would be a significant improvement for systematic field trials. The objectivity and comparability of data can be increased and the interpretation of the data is based on larger – automatically generated - data sets.

However, outdoor applications of sensors – such as imaging devices – are strongly influenced by complex and changing field and environmental conditions. In particular the robustness of sensor measurements may be limited by the influence of sun light, dust, humidity or vibrations. As a consequence the robustness of the sensor systems applied in dynamic field tests is of high importance.

Based on experiences in the development and application of sensors and electronic systems in agricultural environments (for example: Ruckelshausen et al, 1999;), the authors recently have developed and realized concepts for tractor-mounted and autonomous plant phenotyping platforms. In this paper the corresponding sensor and system technologies and the implementation in the vehicles are described. This includes the integration of high accuracy GPS information for individual plant detection and dynamic laboratory and field test setups for the evaluation of the sensor systems.

SENSORS FOR PLANT PHENOTYPING

Having a look at the complex and varying field conditions mentioned above the application of a single sensor (even a camera) is not considered to be a solution for plant phenotyping. Thus, the authors have already proposed sensor and data fusion for crop/weed detection some years ago (Ruckelshausen et al. 1999) in order compensate varying selectivities of single sensors. Due to the improvements in sensor and system technologies the advantages of sensor fusion are even more pronounced. As for example recently developed 3D-Time-of-flight cameras supplies online distance images without using image processing as used in stereo imaging (Klose et al. 2009). Figure 2 demonstrates the options of this technique for detecting green plants on a green background by means of their height. Using a distance threshold can filter the plant which can be analyzed with respect to their height or colour as a follow up analysis. This technology seems to be superior to classical 2D colour imaging.

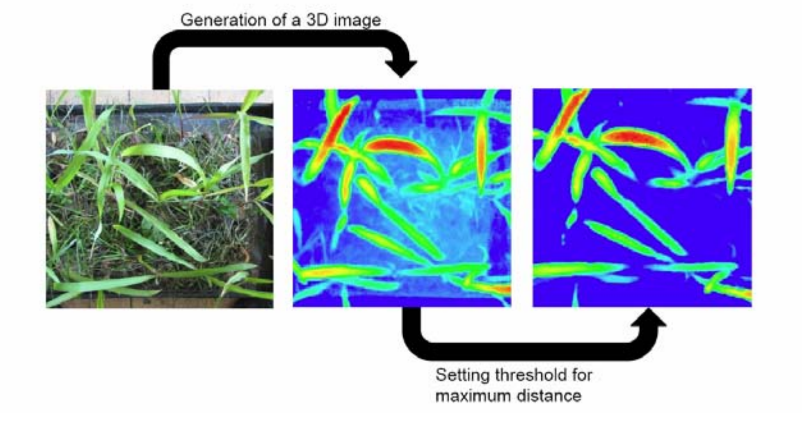


Fig. 1. **3D** Image segmentation (Time-of-Flight camera) **.**

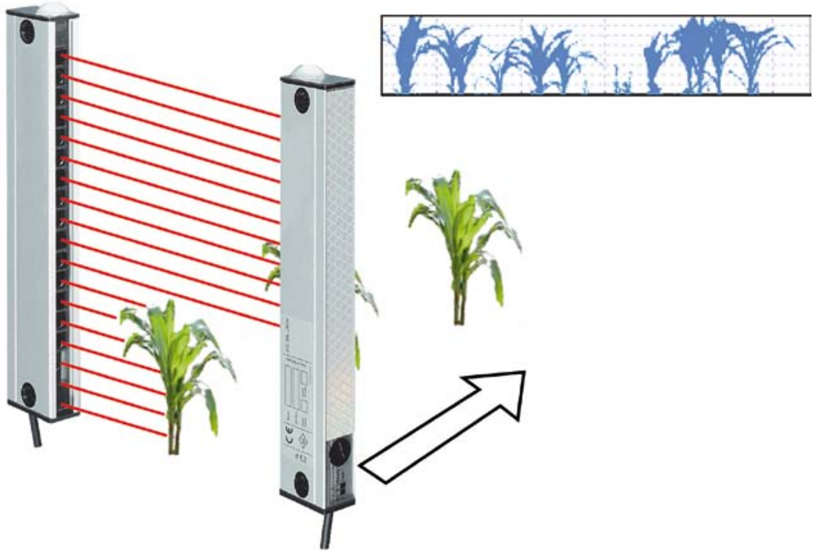


Fig. 2 Light curtain imaging: setup (left) and resulting data (right, Fender et al., 2006).

Another sensor for morphological plant parameters is shown in figure 2. Light curtains supply images which can be analyzed via image processing tools. The information is already binary (and thus “fast”) and can for example be used for height detection.

Single (pointwise) optical distance sensors based on triangulation or time of flight have shown to be very useful for the data fusion (Thoesink et al. 2004). Applying such a high frequency (1kHZ) sensor from the top view can be used as a statistical parameter for morphological parameters, while the application from the side can serve as a stalk detection for single plants.

Next to the 3 examples given above, the authors have applied additional – partly redundant – sensor systems for plant phenotyping, including 3D laser scanner, digital cameras, rotary encoder or sensors for electronic control (illumination photometer, temperature sensor). With respect to the spectral properties of plants in the VIS- and NIR-region spectral imaging is applied, which allows a pointwise spectral analysis and is thus superior to standard spectrometers using a single optical fibre for measuring reflection of field region consisting of plant as well as soil information. Table 1 summarizes the sensors used in this work for plant phenotyping, additional information for the interface, the maximum measurement frequency and the data format are also given.

Table 1. Sensors for plant phentotyping with some characteristic data.

Sensor type	Interface	Maximum measurement frequency	Data format
3D ToF camera	Ethernet	20 Hz	50x64x1 Float
3D Laser scanner	USB	16 Hz	59x29x1 Float
Hyper spectral imaging system (NIR)	Ethernet	330 Hz	320x240x1 Byte
Hyper spectral imaging system (VIS)	USB	330 Hz	320x240x1 Byte
Laser distance sensor	Analogue	1 kHz	Voltage
Light curtain	RS232	330 Hz	String
RTK-DGPS	RS232	20 Hz	String
GPS	USB	1 Hz	String
Digital camera	USB	0,5 Hz	3.456x2.592x4 Byte, Compressed
Rotary encoder	TTL	200 kHz	PWM; 4 Steps per period
Temperature sensor	TTL	4 kHz	Duty Cycle
Illumination photometer	TTL	100 kHz	Frequency

The single plant detection is also based on the usage of RTK-DGPS, thus this “sensor” is included in table 1. The authors have demonstrated that a single maize plant can be detected with the sensor fusion concept. Using RTK-DGPS the absolute position is determined with an accuracy of about +- 2 cm, which is smaller as compared to the typical distance of two plants. As a consequence a single maize plant can be re-detected in a later run (Fender et al., 2006) as shown in fig. 3. Thus the growing process of single plants can be evaluated, a revolution for field trials.

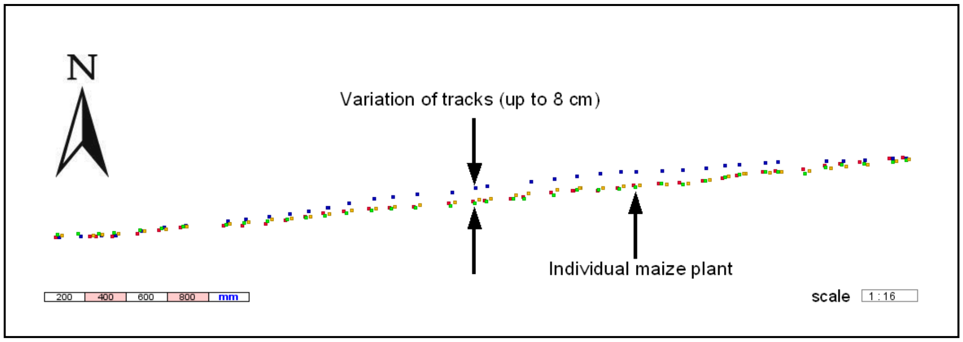


Fig. 3. RTK-DGPS for individual plant detection (Fender et al., 2006).

SYSTEM ARCHITECTURE

The various sensors with different interfaces, data formats and frequencies (see table 1) have to be integrated into a common system architecture. Moreover, it has to be taken into account that the sensors are placed at different positions. The corresponding system structure has to be flexible, extensible, guarantee data consistence and has to be as transparent as possible for debugging, user interaction and data analysis. Figure 4 shows the architecture for plant phenotyping with a selection of sensors based on Gigabit Ethernet. All data information is stored in a MySQL data base together with time and positions stamps and can thus be analyzed offline. Error handling is included.

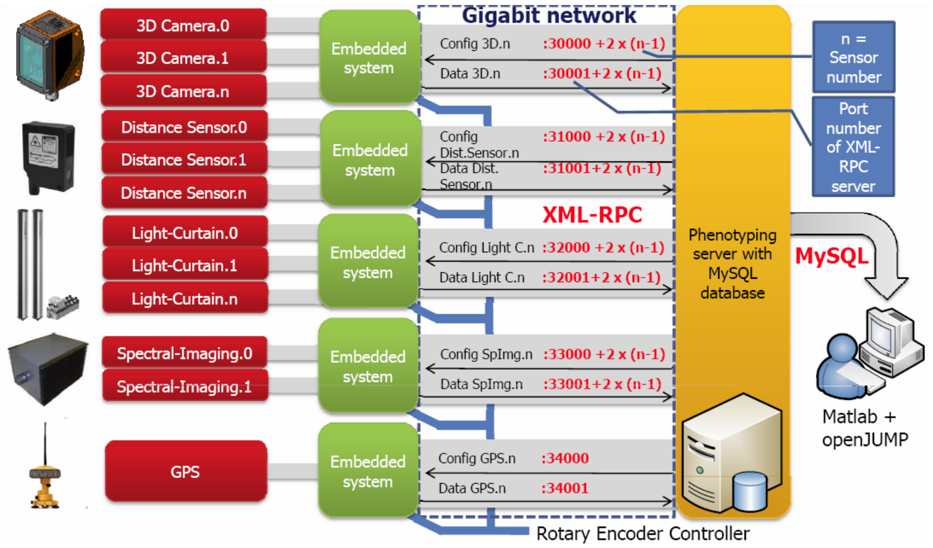


Fig. 4. System structure for sensor integration.

The application of an autonomous robots results in an even more complex system as shown in figure 5. Next to phenotyping control systems for speed, steering and navigation have to be integrated as described by Klose et al. (2010).

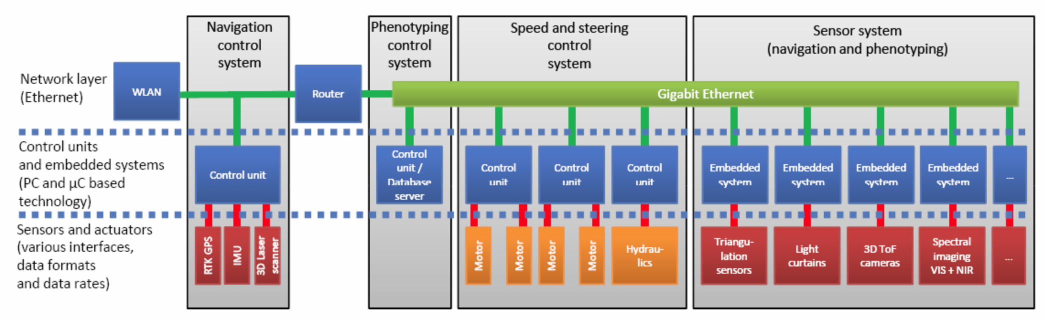
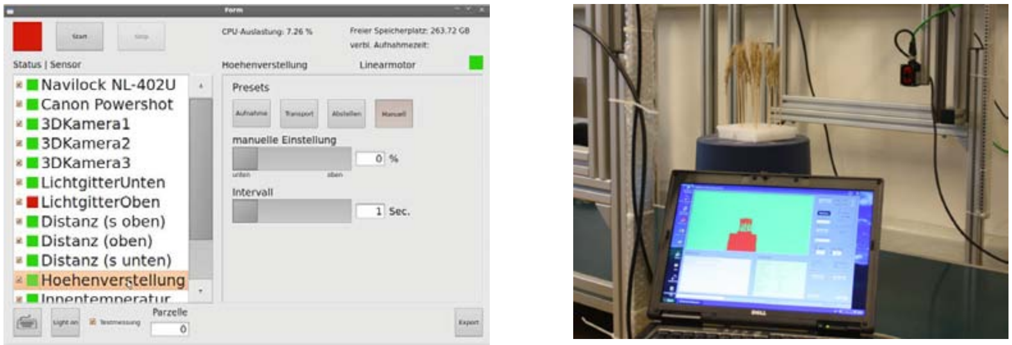


Fig. 5 System architecture BoniRob

It has to be mentioned that real time sensor interpretation is necessary for robot navigation while real time data storage is sufficient for phenotyping.

The human machine interface is important for the development of the phenotyping platforms and for test run control. Sensor settings can be varied and evaluated interactively. Figure 6 shows a screenshot of a user interface for sensor selection and a photograph of the visualisation of test measurements in the laboratory.



CPU-Auslastung: 7.26 %
Freier Speicherplatz: 263.72 GB
verbl. Aufnahmezeit:

Status | Sensor
- 🟩 Navilock NL-402U
- 🟩 Canon Powershot
- 🟩 3DKamera1
- 🟩 3DKamera2
- 🟩 3DKamera3
- 🟩 LichtgitterUnten
- 🟥 LichtgitterOben
- 🟩 Distanz (s oben)
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- 🟩 Distanz (s unten)
- 🟩 Hoehenverstellung
- 🟩 Innentemperatur

Hoehenverstellung Linearmotor 🟩
manuelle Einstellung 0 %
Intervall 1 Sec.
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Fig. 6. Graphical user interfaces for sensor systems control (left) and visualization of measurement results (right).

CONCEPT OF THE PHENOTYPING PLATFORMS BREEDVISION AND BONIROB

The sensor systems and the corresponding electronic equipment have to be integrated into mechanical vehicles or carriers in order to perform field trials. The mechanical system strongly depends on the type of plants and the structure of the field. The work described in this paper has two different applications:

- Plot-related characterization for tritcale *(×Triticosecale Wittmack*)
- Single plant characterization for corn (*Zea mays*)

The corresponding platforms strongly differ due to the selected plants and the corresponding goals of the projects. In this paragraph the concept of both platforms with respect to the specific phenotyping is described.

Phenotyping platform BoniRob (focus: corn)

In order to characterize plants in a field it would be interesting to have information about all plants. In this case, interpretation of the measurements can be given for specific sections of a field together with other site-specific data such as soil properties. Moreover, the usage of RTK-DGPS allows the re-detection of a single plant - in the case of corn - and thus the growth stage history. The related field trial would result in high labour costs and is thus a promising candidate for a first generation of autonomous field robots. As a consequence the authors have developed a concept for autonomous plant phenotyping platform - called “BoniRob” (Ruckelshausen et al. 2009) - with a first application in corn. Table 2 summarizes the plant parameters, which can be covered by the sensor systems given in table 1. The evaluation of the crop status is of highest importance when the plants are still small, e.g. up to about 80 cm height. As a reference the Extended BBCH scale as given by Meier and Bleiholder (2007) can serve as a uniform coding of phonologically similar growth stages.

Table 2. Plant parameters for phenotyping with BoniRob (Ruckelshausen et al., 2009).

PARAMETER	OUTCOME
Number of plants, crop density	Population density
Spacing in the row	Plant distribution
Plant height	Phenotypic characterisation
Steam thickness	Phenotypic characterisation
Spectral reflexion	Plant aberrations, absorption of chlorophyll, moisture
Ground cover, coverage level, Ratio crop/soil	Assimilation area, competitive effect against weed
Phyllotaxis	Phenotypic characterisation
Biomass	Water supply, pathogen stress
Growth	Environmental conditions
Development of single plants/patches	Differentiation of population

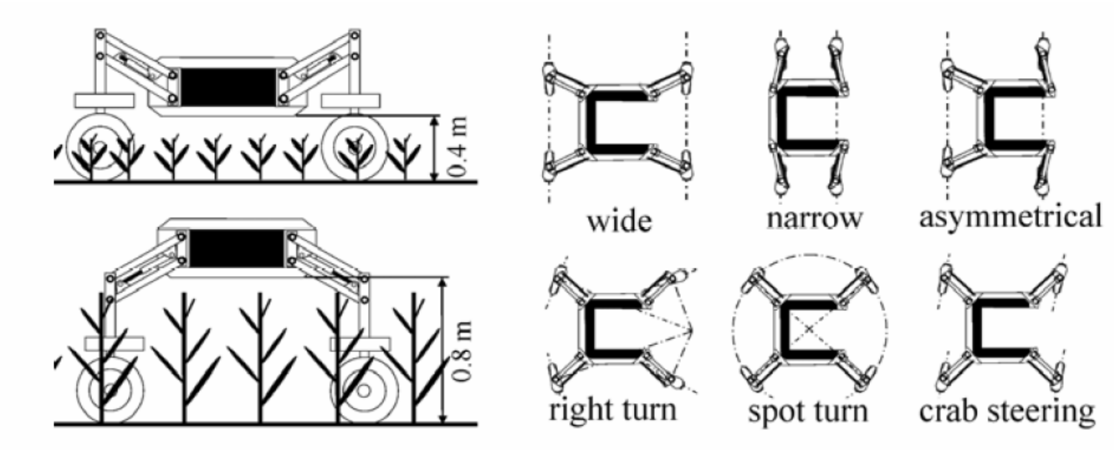


Fig. 7. Concept of the autonomous phenotyping platform BoniRob.

In order to match this boundary condition as well as the implementation of agro-sensors and field navigation the concept shown in figure 7 has been developed. The high flexibility with respect to height variation, turn options and usage of 2 up to 4 lanes is thought to fulfil various application-specific options for an autonomous robot. The concept of BoniRob navigation is based on probabilistic robotics using 3D-lidar sensor information (Weiss and Biber, 2009).

Phenotyping platform BreedVision (focus: triticale)

A cascade use of grain and biomass together with low input of fertilizer is the goal of the project BreedVision. Tritcale has been selected as plant since it is a low input energy grain showing high yield even under low input conditions. In order to evaluate the breeding process sensor information is of high importance, the major outcome is the modelling of the biomass based on sensor fusion. The field trials are plot-related, thus a characterization of all individual plants is not necessary. The measurement of a set of plants results in statistically significant parameters for a whole plot. As compared to the plant-related measurements for corn the phenotyping application in triticale is thus plot-related. Another difference is the measurement height: For triticale measurements up to about heights of 1,50 m are relevant. The concept of the tractor-mounted platform BreedVision is shown in figure 8. The sensor module is mounted to a trailer and is shifted in the case of soil contact. The construction profiles allows flexibility with respect to the sensor mounting which is necessary for taking into account different growth stages.

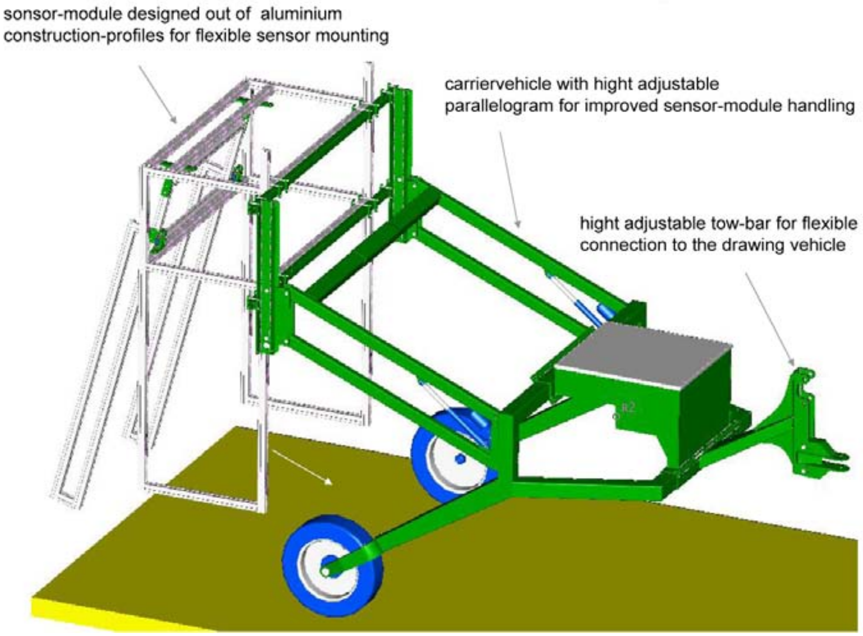


Fig. 8 Mechanical concept of the phenotyping platform BreedVision.

FIRST MEASUREMENTS AND OUTLOOK

The sensor and system technologies have to be tested prior to field applications. In particular dynamic measurements are of high relevance. Thus the authors have built up specific test equipment as shown in figure 9, where the plants are moved and the sensors are fixed. The setup includes a conveyor belt where the plants are moved back and forth and a “high-speed” (25 km/h) carousel with respect to agriculture machinery and a high-precision measurement setup for the development of spectral imaging systems. Moreover outdoor test vehicles – moved by hand – are available for first outdoor measurements.

Fig. 9 Experimental test setups for plant measurements: Outdoor test vehicle (top left), powered spectral imaging setup (top right), powered conveyor belt system (bottom left) and powered high-speed carrousel (bottom right).

Figure 10 shows an example of laboratory measurements, where a colza leaf is measured with spectral imaging technology. By using an NDVI the leaf area can be selected, moreover the image for a wavelength of 900 nm is shown. The picture on the right side shows the relative humidity where spectral signatures at moisture-relevant wavelength are used.

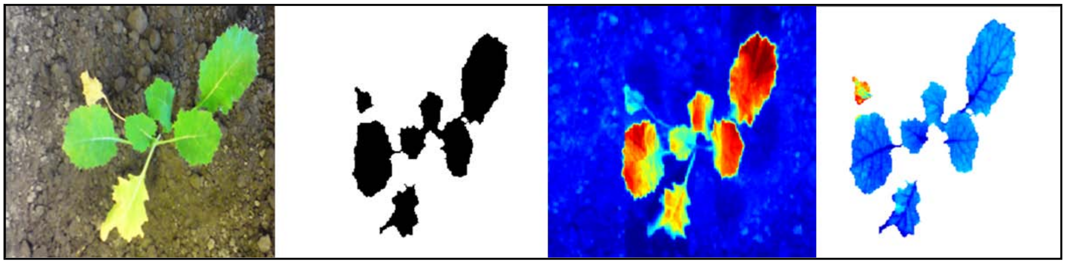
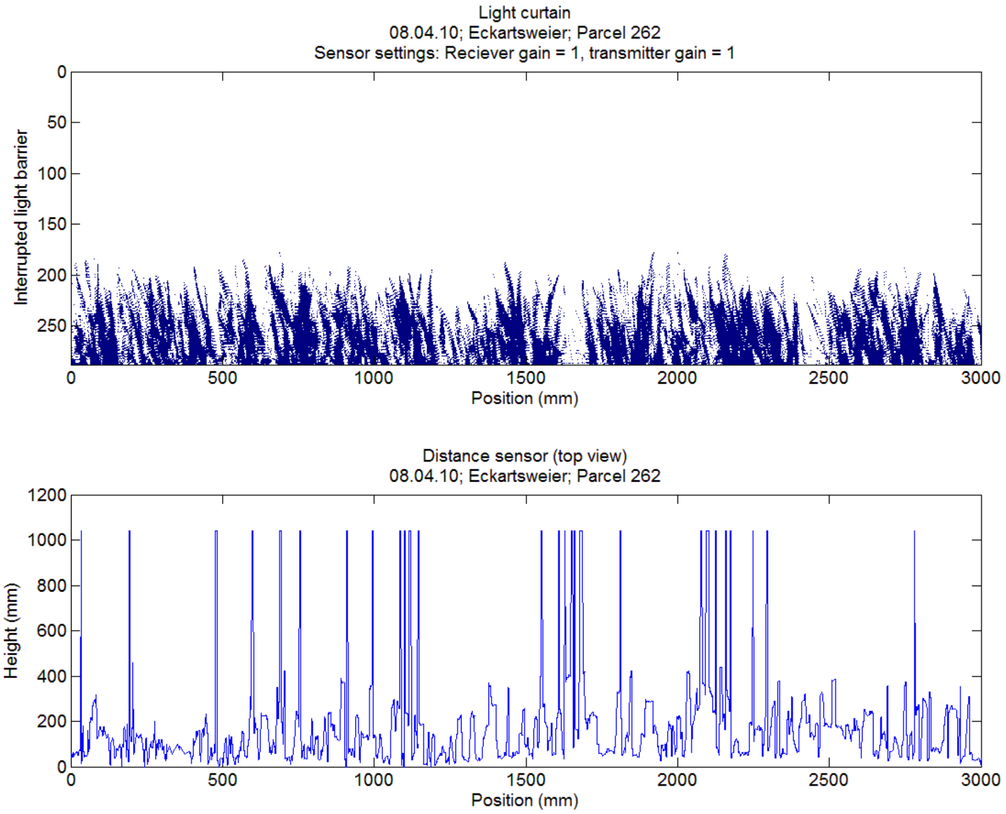


Fig. 10. Spectral imaging of colza (from left to right): image of a color camera, spectral imaging NDVI, spectral reflectance at 900 nm, relative leaf moisture indicator.

Fig. 11 Phenotyping platforms: Autonomous field robot BoniRob (top) and tractor-mounted platform BreedVision (bottom).

Both platforms, BoniRob and BreedVision, have been realized and first test runs have been performed (see fig. 11). Figure 12 shows an example (BreedVision platform) for triticale field measurements on 08-April-2010 in Eckartsweier/Germany. The light curtain information and the data of the optical laser distance sensor (top view) are shown. The laser distance sensor includes an intelligent malfunction option, which results in a height of 1000 m. Using this additional information, the corresponding data can be taken out thereby increasing the quality of the data. The next steps include further measurements and data fusion for plant phenotyping parameters.


Light curtain
08.04.10; Eckartsweier; Parcel 262
Sensor settings: Reciever gain = 1, transmitter gain = 1

Distance sensor (top view)
08.04.10; Eckartsweier; Parcel 262

Fig. 13. Measurement results (BreedVision) in triticale (April 2010, Eckartsweiher/Germany).

To summarize, phenotyping platforms have been developed on a high level of technology with respect to sensors as well as system technology and mechanics. The autonomous platform BoniRob as well as the tractor-mounted platform BreedVision are in the stage of first field tests. Both platforms show a high potential for plant phenotyping in field trials. Moreover, further applications – including actuators – for a robust autonomous platform are in view.

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