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GIS- and sensor-based technologies for individual plant agriculture

A continuously increasing demand of food, limited resources and environmental impacts require optimization of agricultural processes with respect to high yield and low input. Electronics and computer science have thus become key technologies for an economically and ecologically oriented agriculture in the last years. The adoption of innovative technologies has now reached a level to consider individual plant processes. Hereby new options and approaches for the global problems could arise. In this article a first application is illustrated using the example of a single plant phenotyping in plant research. The major focus is put on the technological combination of autonomous field robotics and intelligent sensor systems.

Keywords
Sensors, GIS, individual plant agriculture, phenotyping, field robotics

Abstract
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Due to global demands with respect to food, energy, environmental impacts, limited resources and climate changes agricultural processes and technologies have to be optimized with respect to high yield and low input [1; 2]. Until the year 2050 the production of food has probably to be increased about 70 % to satisfy the demand of the world's population [3]. Computer sciences together with electronics and sensor technologies have thus become key technologies in agriculture. The introduction of these technologies, often called in conjunction with precision agriculture, offers options for site-specific treatments in order to aim at economical as well as environmental benefits. Thereby the introduction of GPS is one of the most important technologies in agriculture due to the fact that the integration of spatial and temporal information is the fundament for documentation and thus for an optimization of agricultural processes. The resulting innovations are the base of an improved ecological agriculture [4]. To achieve optimized processes it is essential to incorporate precise information of the whole crop field, optionally down to single plants. Although the development and appliance of large agricultural machines has achieved strong yield improvements a big part of the needed energy is expended to overcome the resulting soil compaction [5]. Due to this fact the development of smaller intelligent machines could be an alternative way to overcome this problem or complement the classic methods respectively. Thus autonomous field robots are the next step in automation of agricultural engineering [4] as combining options for the reduction of environmental impacts and economical benefits. Innovative technologies offer the option to observe even single plants in row cultures (e. g. maize). In order to demonstrate this potential the authors participated in the development of sensor and system technologies for single plant measurements of crops in plant breeding [6]. In combination with the development of autonomous vehicles, the specific task "plant rating" (or "phenotyping") offers a promising option for an economical application of these technologies. Thus, for the demonstration of these potentials the authors participated in the development of the autonomous field robot "BoniRob" for phenotyping of maize as a first field robot application [7].

Individual plant phenotyping in plant breeding

Plant phenotyping is a very important area of agricultural field trials (plant breeding, plant protection, fertilization) but also a bottle neck because of its low degree of automation [8]. Due to the fact that the determination of plant parameters is mostly done by experts manually, the process is very time consuming resulting in high costs. Beyond that the parameters are influenced by the subjectivity and the time dependency of the measurements. Hence there is a fundamental need for automated phenotyping platforms [8]. With BoniRob a completely autonomous and modular designed platform was developed which is able to be attached with different application modules depending on user requirements [7]. A specific sensor module, attached with different sensor systems and substantial system technology for automated data acquisition and management was developed to perform the phenotyping application [6]. **Figure 1** shows the field robot BoniRob on a field measuring single maize plants. The application of different sensors enables the detection of different plant parameters of each single plant. In order to detect the position of the robot, a high resolution RTK-

Fig. 1

Measurements of individual plants on a maize field with the autonomous field robot BoniRob

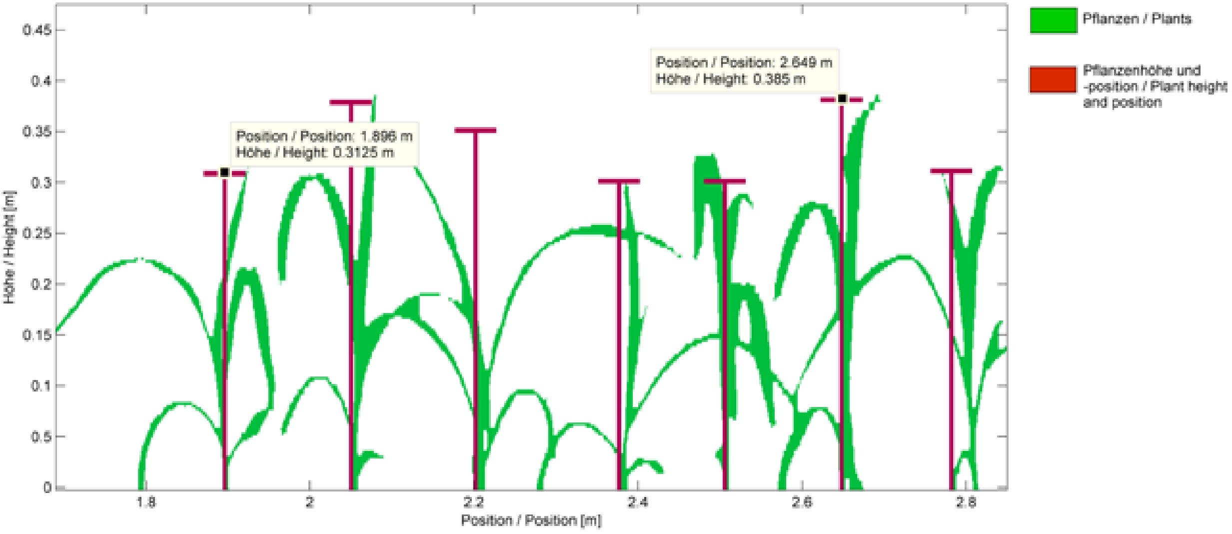
DGPS-system combined with a rotary encoder is used, thereby resulting in an accuracy of about two centimetres. Using this high spatial resolution the redetection of single plants has become possible. The identification of plants itself is realized by sensor fusion in which especially light curtains play a major role. Additionally multiple 3D time-of-flight cameras are used offering a complete three dimensional reconstruction of single plants to determine leaf parameters [9]. Furthermore laser distance sensors are used for the detection of stem thickness because of their very high sampling frequency. Beyond the detection of morphological parameters a spectral imaging system is adopted for measuring spectral signatures of plants leaves. Based on these data the relative plant moisture can be modelled [10]. During data acquisition all sensor information is stored in a mySQL database and marked with the current time and the rotary encoder position thereby allowing the offline correlation of sensor data.

In the next step the autonomous platform was used to measure single maize plants repeatedly in test plots for a time period of several weeks. Taking these measurement data different algorithms for the modelling of plant parameters were developed (e.g. the plant height). Beside the calculation of these parameters the detection and redetection of individual plants was a great challenge. To be able to address parameters to its specific plant the measured structure has to be identified as a plant.

At the initial step the algorithms are using the light curtain data – generating a shadow side view – for plant identification. Afterwards a skeleton structure is generated. In the further analyses the height of the plant structure is determined. Based on the number of branches and endpoints an indicator for the number of plant leaves is given. In order to detect overlapping plants criteria have been implemented in the analyses sequence to stop the analysis of a frame structure. In case of termination the algorithm continuous its analysis at the lower end of the next frame. Frame points at which a termination appears are marked as endpoints of neighbouring plants. If selective conditions for the height, distance to neighbouring plants and number of leaves are fulfilled, the object are classified as a maize plant and marked with the precise GPS position. The parameters of each plant are stored in a data structure with a unique identifier. For follow-up runs of the robot the data of the re-measured maize plants are assigned to the existing ones based on the GPS position. This is enabled by applying the iterative closest point algorithm [11].

To visualize the determined plant parameters the geographic information system OpenJUMP is used. GIS tools in general have proved itself in many cases and are already known from precision farming where they are normally used for site specific applications. In the case of single plant phenotyping the single plant is considered as a partial area so that every

Fig. 2



Light curtain measurements (green) marked with the plants positions and the modelled plant heights single plant can be visualized with its individual parameters. GIS tools offer many solutions for data visualization as well as extensive analyses [12]. Using this e.g. position maps of the measured crops were created and their different parameters were displayed.

Results

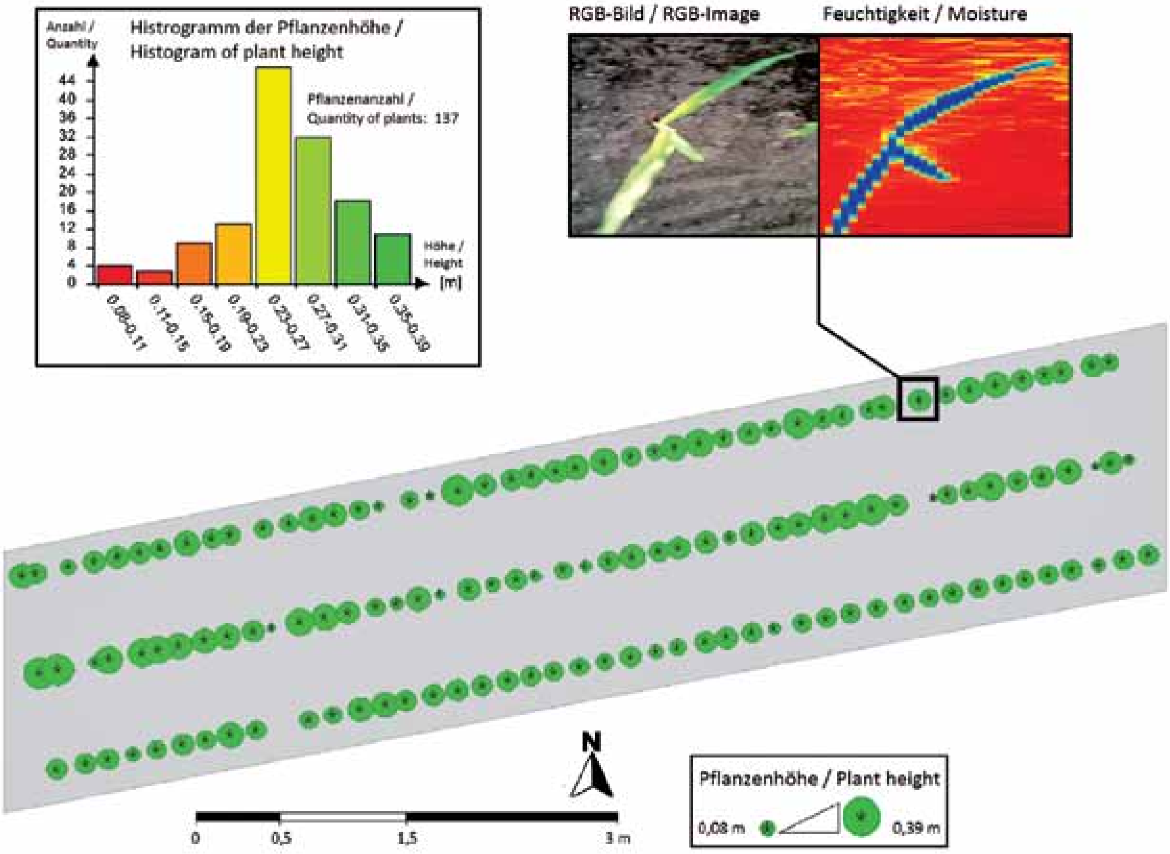
Figure 2 shows an example of field measurement results for maize. The given structures were measured by the light curtain and are showing the side view height profile of seven maize plants. The figure shows that in this case the applied algorithm has detected all seven plants as single maize plants. The positions of these plants have been determined with high precision and are marked in the diagram together with the modelled plant height. The position of the plant at the very right has not been detected exactly. But although this plant position couldn't be detected exactly due to a hanging leave, the algorithm was still able to identify the plant and detect its height. The high detection rates of the algorithm demonstrate the potential of the method, also for other plant cultures.

Next to the plant identification further parameters can be modelled, examples are the number of plants, height, width, distance between plants, stem thickness or the relative moisture of plant leaves.Importing the generated plant information into the GIS tool OpenJUMP it is possible to visualize these parameters clearly and perform statistical analyses using the available toolboxes. In the lower section of figure 3 a GIS map of a field test with in total 137 maize plants is shown. The position of each plant is marked by a black star symbol. The diameters of the surrounding green circles are representing the different plant heights. In the upper left section of **Figure 3** a histogram of the measured plant heights is displayed exemplarily for the many different possibilities of graphical and statistical evaluation with this standard GIS tool. Moreover, all data points are linked to the extensive plant information and can also be displayed directly in the GIS map as demonstrated in **Figure 3** (in the upper right section). This visualization of data allows the user to get a fast overview and to detect abnormal parameters of plants in an early stage. The temporal change of plant parameters - based on the redetection – can be measured and displayed for individual plants. The corresponding maps and data have high relevance for plant breeding, moreover combination with further information (e.g. soil maps) is possible.

Conclusion and perspective

Based on the example of sensor-based plant phenotyping the developments and applications have demonstrated the option of a single plant based agriculture. In the first approach already several plant parameters can be modelled. With multiple measurements using a sensor based redetection of the plants,

Fig. 3



GIS-map of three measured maize rows (bottom) as well as an example of a statistic analysis (histogram of plant height) and exemplary data of a single plant

Fig. 4

Mechanical weed control within the row (intra row, „Querhacke", [13]) (left) and weed robot survey „Weedy" for selective chemical weed control in a field test (right, [14])

growth processes of plants can be visualized by comparing the different parameters as a function of time. The linking of the measurement data and the detected plant positions also provides the user with raw data – for example 3D images, spectral data or RGB images – for further analyses. The combination of the generated plant data structure and the GIS tool OpenJUMP supports the user with respect to the processing of the data, such as visual illustrations or statistical analyses. The research and development projects to combine sensor fusion, GIS technology and autonomous field robots have already led to practical solutions for the specific phenotyping application. For this reason the potential for further applications in agricultural engineering is established.

Due to their complexity the development of further single plant agricultural processes and its system integration require great efforts from crop farming as well as from technology. However, already many results of research and development projects working on this topic are available. As for example the authors have also worked on mechanical weed control in maize rows (**Figure 4** left, [13]) as well as on studies for robots with selective chemical weed control (**Figure 4** right, [14]). The potentials for selective plant protection based on autonomous field robots are pointed out in [15]. In the area of field robotics many options are possible, e.g. the combination of autonomous and manned vehicles or the appliance of big and small machine. First practical experiences are also available (e.g. [16]).

The single plant detection presented in this work as well as the conception and realization of the adaptable field robot BoniRob provides first experiences for the development of individual plant agriculture.

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