BoniRob: an autonomous field robot platform for individual plant phenotyping

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Abstract

Electronics, software and sensor systems have become key technologies in agriculture. Future development steps are autonomous field robots with high technological challenges and options for economical and ecological benefits. The robustness of autonomous robots is considered to be of highest relevance for a step from present research activities towards prototypes. The application 'crop scout' has been identified as a promising option to realise such a robot, called BoniRob, in an interdisciplinary cooperation with partners from electronic and agricultural industry as well as research institutions from engineering and agriculture. The vehicle is based on four wheel hub motors and hydraulic components, thereby offering a high flexibility with respect to navigation and changing height positions. Multi-sensor fusion – including complex sensor systems like spectral imaging and 3D time-of-flight cameras – and a RTK-DGPS system are applied for an individual plant phenotyping. The navigation concept of BoniRob is based on probabilistic robotics. A Gazebo-based 3D simulation environment for BoniRob is developed, including options for data and software exchange between the simulator and the real robot. In the first stage maize and wheat are considered for phenotyping, sensor and plant parameters have been defined according to the extended BBCH scale. As an additional option mapping of plant diseases based on spectral imaging information will be evaluated. The automatic phenotyping and mapping of all plants in a field will be a revolutionary change in the methods of field trials. Moreover, the availability of a robust crops scout platform will offer options for other field applications.

Keywords: agricultural robots, agro-sensors, multi-sensor fusion, probabilistic robotics

Autonomous field robots

Agricultural engineering has become a technology field of highest worldwide relevance with respect to food, energy as well as landscape conservation. In particular, electronics, communications and sensor technologies are strongly pushing innovations in agriculture and have become key technologies in this field, thereby offering options for economical as well as ecological benefits. The state-of-the-art technology already allows the autonomation of existing agricultural machines (Niehaus *et al.,* 2007). Thus partially autonomous fleets are an option for the next years. Recently, increased research activities have been started to develop small autonomous field robots for future applications in agriculture. Moreover, autonomous robotics in general has become a major field of research in the past years and high volume future markets are expected in various applications, including agriculture and forestry (Siciliano and Khatib, 2008). For example Blackmore *et al.* (2007) have given a specification for an autonomous crop production mechanization system including a variety of future technical applications in agriculture. Pedersen *et al.* (2006) have already investigated economical aspects for agricultural robots.

However, whenever technology meets nature, considerable technical and non-technical challenges have to be solved. In most applications the robots are acting outdoor, in a complex and changing environment with varying conditions, such as light, wind, temperature or dust. In practice, the yearly International Field Robot Event as described by Van Henten *et al.* (2007) gives an insight into these problems. During this competition completely autonomous navigation in maize fields and application examples – such as weed control – are major tasks. The high challenge for the related technologies under complex and dynamic field conditions has shown so far that the low robustness of the single robot is a major hindrance for the introduction of a first prototype of an autonomous agricultural field robots or even robot swarms. As a consequence the availability of a robust platform will be an important next step for autonomous agricultural robots. Since the robot development already includes a high complexity, the application itself should be of comparably low complexity. The implementation of additional mechatronic systems, such as weeding or seeding, will increase the complexity due to technical and logistical aspects and thus reduce the probability for the development of a robust system. Furthermore, the economical competition of large machines for these applications is very high. The authors have identified crop scouting as a perfect first application for an autonomous platform. The extension of sensor technologies and its interpretation – already necessary for navigation – will lead to a benefit for plant breeders as well as farmers. Moreover, a continuous complete characterisation of all single plants in a field would be a revolutionary method for agricultural field trials.

Plant phenotyping

In order to evaluate breeding processes or the crop status, the characterization of plants and environmental parameters is of highest importance, a detailed description of field trials is given by Thomas (2006). There is a need for further development of corresponding methods and sensor systems with high accuracy. Moreover, the correlation of interpreted sensor data with plant parameters should be based on a standardized description of plant development stages. The Extended BBCH (Biologische *B*undesanstalt, *B*undessortenamt and *Ch*emical Industry) scale as described by Meier and Bleiholder (2007) is such a system for a uniform coding of phonologically similar growth stages. If the non-destructive dynamical measurement of plant parameters is combined with a high-resolution Global Positioning System (GPS), the absolute position of a single plant can be determined and this plant can be relocated (and measured) in a later stage as demonstrated by the authors (Fender *et al.,* 2006) in maize. The combination of an extended sensor system with an autonomous field robot is the major application of this work. As compared to the state-of-the-art phenotyping of plants based on sampling methods, the crop scout would be a fundamental step towards an automatic data generation for all plants as described by Ruckelshausen (2007). Based on the German word 'Bonitur' for rating, 'BoniRob' has been chosen as the name for the crop scout. The plants chosen for the measurements are corn (*Zea mays*) and winter wheat (*Triticum aestivum L*) as very important types of grains, plant parameters are given in table 1. The methods and technologies described in section 3, however, can be extended to other plants. Using spectral imaging, the detection of three fungal diseases of winter wheat will be evaluated: Leaf and glume blotch (*Septoria nodorum*), Septoria blotch (*Septoria tritici*) and Powdery mildew (*Blumeria [syn. Erysiphe] graminis*). This selection is based on the high amount of yield reduction of the diseases. After Obst (2002) Leaf and glume blotch causes a yield reduction of 30%, Septoria blotch of 30% and Powdery mildew of 25%. Gerhards and Christensen (2003) said that several parameters like vitality, nutrient supply and phyllotaxis have an exert influence on the distribution of plant diseases. Furthermore they found out that diseases appear in patches before it expand over the field. To ensure the course of diseases, it is necessary to detect the actual development status of the plants using parameters from Table 1.

Table 1. Plant parameters for phenotyping with BoniRob.

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

Field robot BoniRob

The realisation of such a system strongly depends on interdisciplinary competences. As a consequence industrial partners from electronics, sensors and agricultural machines as well as research institutes (engineering and computer science as well as agriculture) are working together. Experiences in the development of autonomous systems inside and outside agriculture are available. (Biber and Duckett, 2005; Niehaus *et al.,* 2007; Klose *et al.,* 2008). Moreover, the feedback from potential users of BoniRob is already integrated in the development process, namely the panel of field trials of the DLG (German Agricultural Society) and the GFP (Gemeinschaft zur Förderung der privaten Deutschen Pflanzenzüchtung e.V.) are cooperative partners. Details of the system architecture, vehicle, navigation, multisensor fusion and the safety concept for BoniRob are given below.

System architecture

The system architecture is illustrated in Figure 1. Horizontally the different systems are given. The control systems for navigation and phenotyping are using the data of several sensor systems (including GPS) and maps. The speed and steering control system is in charge of the motor and hydraulics of the vehicle. The internal system communication (control units, sensors, documentation and user interface) is based on Ethernet and thus allows a real-time implementation at high data rates. Sensor data for the navigation are necessarily treated in real-time, some other data are less time critical as for example disease mapping data. A timestamp concept is used for synchronisation and correlation of the various data. On lower levels CAN-bus communication is implemented. In order to optimise timing and handling of the data volume a middleware concept has been implemented. The software of the navigation module is based on a component-based software architecture. Components are realised using a robotic-specific software framework with operation system abstraction and communication patterns for inter-component communication. The framework supports several real-time and non-real-time operation systems (OS) which enables a very flexible deployment of components, depending on their functionality, e.g. navigation control needs to run under a real-time OS and mapping of plants can be deployed on a non-real-time OS.

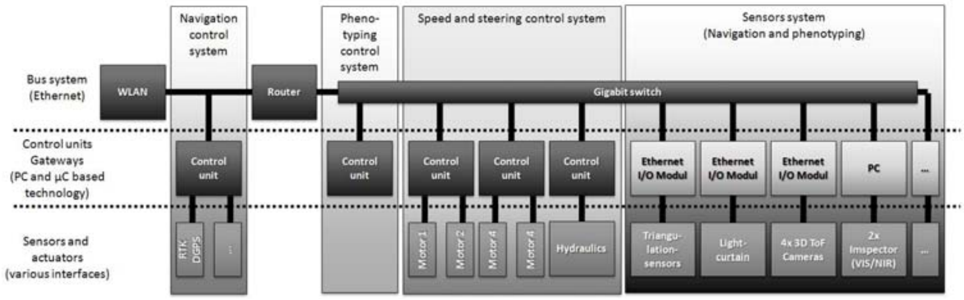


Figure 1. System architecture for BoniRob.

Vehicle

Each wheel of the vehicle is driven by a hub motor and equipped with a brake. In case of a power breakdown each wheel is stopped and prevents the robot from further movement. The wheels are fixed to arms in that way they can be steered separately and each arm can be moved separately too. All movements are powered by a hydraulic system which was incorporated in the frame. The arms can be changed in height allowing a chassis clearance of 0.4 m to 0.8 m. Therefore the sensors can be adjusted to the height of the plants to observe without the need of changing the sensor setup. Additionally each arm allows changing the track of the attached wheel from approx. 0.4 m to approx. 1.0 m to the centre. This allows driving with a narrow track of 0.75 m width or a wide track with nearly 2 m width. Also all combinations in between can be chosen. With this flexibility different kind of test fields can be analysed and even the position of the sensors within the test field can be changed. A few possibilities are shown in Figure 2 (left). Each wheel can be steered separately by an angle of ±90°. Respecting the Ackermann condition, a wide range of different tracks like simple turns, spot turns or crab steering can be driven. These are visualised in Figure 2 (right).

Navigation

A RTK-GPS receiver is the main sensor for localization. Additionally, information from the robot's odometry and inertial sensors is incorporated using a *Kalman* filter. The output of this filter provides a sub-decimetre localization accuracy even if the RTK-GPS receiver temporarily loses its high accuracy fix. Besides the estimation of the robot's pose, sensing the environment, especially object detection is an essential task for reliable navigation and mapping. This will be done by a 3D laser sensor mounted on the robot's front, which recognises the crop rows, as well as single plants. The

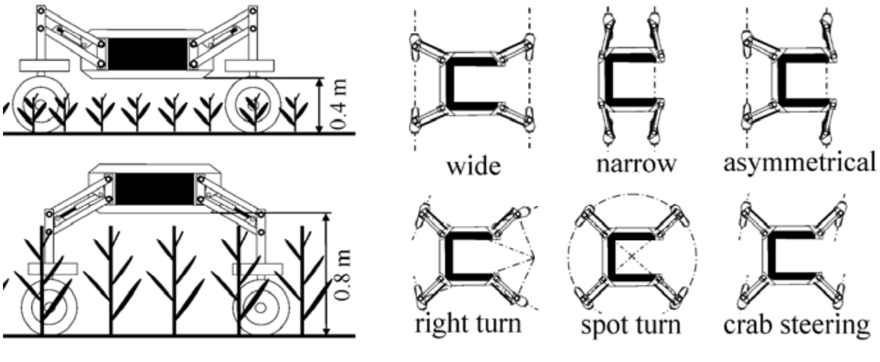


Figure 2. Concept of the autonomous vehicle platform BoniRob.

authors have started to use algorithms based on probabilistic robotics (Thrun, 2005) like particle filters for simultaneous localisation and mapping (SLAM) to fuse the sensor data and previous knowledge about the field structure.

Multi-sensor fusion

In order to increase the robustness as well as the quality of information for phenotyping, concepts of multisensor data fusion are used (Mitchell, 2007). The authors first introduced this concept in agricultural field applications already 10 years ago for online crop/weed detection as part of an intra-row weed control process (Ruckelshausen *et al.,* 1999). In continuation of this work Klose *et al.* (2008) have applied intelligent sensor systems in autonomous field robots. Cameras, spectral imaging systems, light curtains and distance sensors are used. Moreover, newly developed 3D time-of-flight cameras show a high potential for robot navigation. The sensor data for phenotyping and navigation can be used vice versa. Additional sensors are used for the safety concept (see below) and for electronic control purposes (voltage control, temperature, dust). *A priori* information as well as GPS information is used. The modular system architecture allows an extension of the number of sensors.

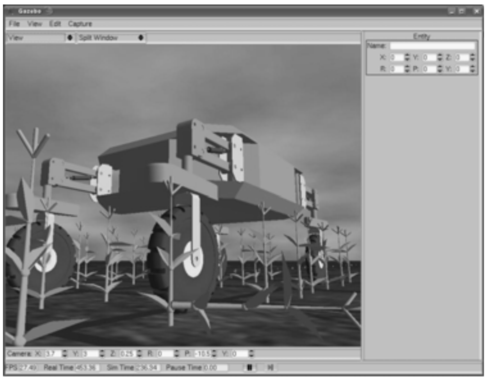
Safety concept

A safety concept has been integrated in the concept of BoniRob from the beginning in order to avoid that the robots harm humans. Each wheel system has an emergency shutdown buttom, malfunctions of the software result in a shutdown and also an external shutdown via WLAN is implemented. As realised in the experimental weeding robot WEEDY (Klose *et al.* (2008)) it is planned to detect obstacles in the surrounding area via an ultrasonic wall, however, such sensor systems have to be adapted to the flexible vehicle configuration.

Simulation

In order to perform repeatable, season independent experiments and learn how to handle the complex omnidirectional drive, the authors decided to model and simulate BoniRob in the Gazebo 3D Robotics Simulator (Gazebo, 2009), so the authors are able to get first results during the construction process of the real robot.

The open source-project Gazebo is a multi-robot simulator for both indoor and outdoor environments and relies on a number of third-party libraries, like the physics engine ODE and the graphics engine Ogre. Gazebo describes the environment, robots, sensors, light sources, user interfaces, and so



Name:
X: 0 Y: 0 Z: 0
R: 0 P: 0 Y: 0
Camera: X: 3.7 Y: 3 Z: 0.25 R: 0 P: -10.5 Y: 0
FPS 27.49 Real Time 453.36 Sim Time 236.34 Pause Time 0.00

Figure 3. Gazebo-based simulation of the BoniRob field navigation.

on in XML. It is capable of simulating a population of robots, sensors and objects and generates realistic sensor feedback, object collisions and dynamics. Like Stage, it provides an interface to the Player-framework, which allows access over TCP/IP. Also, it is utilised for developing a hardware-in-the-loop concept, able to connect the control device with the simulated or the real robot and sensors without any changes in the middleware. Figure 3 shows a screenshot illustrating the simulator with BoniRob driving over a row of maize.

Outlook

The concept of the field scout BoniRob has been developed, first parts of the system architecture, the navigation and sensors have already been realised. The mechanical construction of the first version of BoniRob is completed and first dynamic tests of the robot will be presented. Figure 4 shows the vehicle, a preliminary data sheet is given in Table 2. In the next step field tests will be performed, including first phenotyping runs. In 2011 the availability of a robust prototype for plant

Table 2. Preliminary data sheet of BoniRob.

Category	Specification
Basic data	Main body dimension (l) 1,500 × (w) 1,000 × (h) 500 mm Track gauge 750 – 2,000 mm (variable) Chassis clearance 400 – 800 mm (variable) Total weight 400 kg Vehicle speed max. 8 km/h Power consumption max. 2 kW
System technology	PC, Microcontroller, Embedded systems, Ethernet, Wireless-LAN, Middleware based communication structure
Navigation sensor technology	2D-Laserscanner, 3D-Laserscanner, Accelaration sensor, Gyroscope, RTK-GPS
Phenotyping sensor technology	Spectral Imaging, 3D-time of flight-camera, Light curtain, Laser distance sensor
Safety features	Emergency switch, Ultrasonic wall, Software monitoring

Figure 4. Autonomous vehicle BoniRob.

phenotyping is planned. The intended robustness of the autonomous field robot BoniRob will offer future options for other applications (including actuator developments) and robot swarms.

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