AUTOMATIC SOIL PENETROMETER MEASUREMENTS AND GIS-BASED DOCUMENTATION WITH THE AUTONOMOUS FIELD ROBOT PLATFORM BONIROB

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ABSTRACT

For a sustainable agriculture, reliable measurements of soil properties and its interpretation are of highest relevance. Until today most of the measurements are carried out manually. Moreover, the number and density of measurement points is always an important aspect with respect to the statistical significance of the results. In this paper, a fully automatic measurement system has been developed and applied for the first time with free selectable measurement points.

As first measurement examples – in particular for soil compaction interpretations – a penetrometer module has been designed, where the penetration can be measured up to 80 cm below ground level. If the resistance (as for example caused by a stone) measured with a pressure sensor at the probe exceeds a certain level the measurement is automatically stopped via the vertical linear actuator control. New trials can be performed close to these measurements by programming the implemented horizontal linear motor for positioning the measuring rod perpendicular to the driving direction (within a range of 60 cm). Moreover, surface moisture and temperature are measured in parallel. The complete measurement module is attached to a multi-purpose field robot platform ("BoniRob"), which can navigate autonomously or via remote control on the field. The module can be considered as an application module ("App") of the robot with defined mechanical, energetic and digital interfaces.

A RTK-DGPS attached to the robot allows a precise positioning and GIS-based documentation of the measurement data. By combining the GPS navigation with the option of the horizontal linear positioning actuator, user-defined positioning and statistics can be predefined. For the communication between the application module and the field robot, the Robot Operating System (ROS) has been chosen as the open framework software. For validating the system, the measurement data has been compared to the data of a commercial penetrologger. The results match within the standard deviation of the data. At first the system has been tested independent of the robot. Afterwards field measurements have been performed by using the robot in two modes: a “manual mode”, where the user controls the system via a remote control panel, and an “automatic mode” where the robot acts completely automatic, however, safety is assigned to the user. As a result, GIS maps of sensor data have been generated as a basis for further interpretation and agricultural processing. The field robot-based soil sensor system has a high potential for further applications, e.g. by including additional sensors.

Keywords: soil penetrometer, field robot, Robotic Operating System ROS, Soil compaction, GIS

INTRODUCTION

In order to solve present and future economic as well as ecological global challenges of crop production for sustainable food production and energy supply, the soil is of highest relevance. The complex interaction between humans and the environment necessitates an increase in knowledge regarding soil properties for the development of robust decision models in order to minimize negative environmental impacts. Thus, the resulting need for an efficient and innovative soil mapping has come up in the past years (Hartemink and McBratney 2008).

While the general correlation between crop yield and soil properties is generally accepted (Hinck et al. 2013), the temporal and spatial resolution of soil maps is always a matter of discussion (Domsch and Schirmann, 2009). Since several measurement methods are still carried out manually (such as soil penetrometer), user/time-dependent variances of these measurements as well as the time consumption create a demand for reliable, highly automated, flexible and on-the-go measurements (Zheng et al. 2008). The corresponding temporal and spatial sampling could then be adapted to the agronomic knowledge and specific field conditions. As a consequence, field mappings may vary in their resolution range from small to large scales depending on the measurement results or previous (à priori) information. In this contribution the penetrometer technology is in focus, thereby resulting in data that can be used for soil compactness interpretation as one example. Moreover, the sensor data are combined with other on-the-go sensors (Lin et al. 2014) or off-line data. In order to fulfill the boundary conditions for automatic measurements, there is a need for automation technologies with respect to the sensor itself, the positioning of each individual measurement, as well as the mapping of the whole field. It is of highest relevance that the complete process be realized for outdoor field conditions. Thus, the following sections will focus on the sensor technology itself, the system

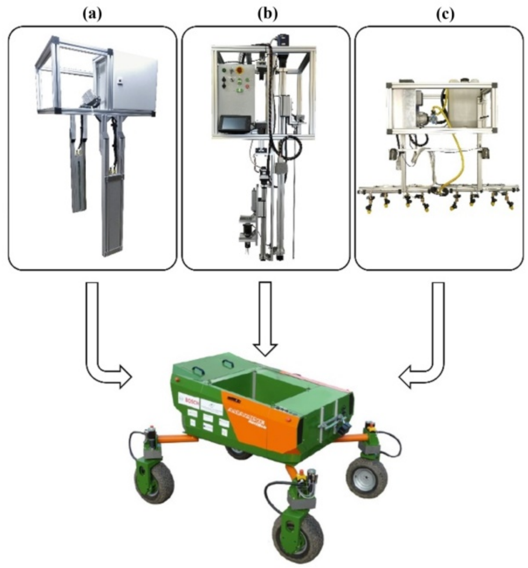

Fig. 1. Multipurpose BoniRob and different Apps. (a) Phenotyping-App: multi-sensor App for plant characteristic measurements, (b) Penetrometer-App: soil- properties like penetration data, temperature and moisture measurements, (c) Precision-Spraying-App: camera-based application for selective weed control

integration in a flexible module, the integration in a vehicle and on the measurement results carried out manually. Moreover, the number and density of measurement points are always an important aspect with respect to the statistical significance of the results. In this paper, a fully automatic measurement system has been developed and applied for the first time with free selectable measurement points.

MATERIAL AND METHODS

Field robot platform BoniRob

For this paper a multipurpose field robot platform based on the field robot BoniRob crop scout (Ruckelshausen et al., 2009) was developed. It was re-engineered with a focus on robustness and reusability. It can navigate autonomously along crop rows or by using GPS coordinates. The robot has an empty cavity within the body, which is designed as a carrier, supplier and base for multiple BoniRob modules. These modules are called “BoniRob-Apps”. The combination of BoniRob and Apps can be compared to the traditional combination of a tractor with different implements. The Apps can be integrated into the field robot platform by using defined mechanical, electrical and logical interfaces. The opportunity to install different Apps into BoniRob allows for the usage of this field robot platform over an extended time in the year and increases the usefulness of the robot throughout this time. Several Apps with different purposes have been developed (Bangert et al., 2013).

Fig. 2. BoniRob with Penetrometer App during field trails in the Netherlands

Penetrometer App

This application module ("App") integrates a mechanical actuator into BoniRob. A measurement unit consisting of a probing rod with defined cone ($1cm^2$, 60°), force sensor and vertical linear actuator is included for soil property measurements down to a depth of approximately 80 cm below ground level by measuring the resulting penetration force of the cone with the force sensor from a starting position. The penetration force of the cone is measured in MPa (Megapascal) and specified in this paper as the penetration data. If the resistance exceeds a certain level (e.g. the ground is too compacted or the probing rod hits a stone), the measurement is automatically stopped by the vertical linear actuator control. In this case the actuator returns to the starting point and positions the probing rod in a defined range perpendicular to the driving direction by the usage of the lateral shifting unit control. The maximum range of the lateral shifting within the App is about 60 cm and currently allows up to 4 repetitions of measurements transverse to the direction of travel. Furthermore, to achieve lateral shifting for the surface- moisture and temperature measurements of the soil, a second linear actuator unit is mounted on the backside of the first measurement unit. Figure 2 shows BoniRob with the Penetrometer App during field trails in the Netherlands in December 2013.

Hardware

The components of the Penetrometer App are shown in Figure 3. The App frame **(g)** consists of aluminum construction profiles and fits into the free space of BoniRob. The voltage level (230V, 24V, 12V, 5V), Ethernet communication and emergency stop are transmitted from the robot by using the custom plug **(c)** of the App. The probing rod with defined cone **(d)** is connected by a coupling to a force sensor with a measurement device **(b)**. To achieve vertical shifting a DC stepping motor **(a)** and linear bearing **(h)** are used. For lateral shifting **(i)** a DC stepping motor and linear bearing are used. The sensors for surface-soil moisture (ThetaProbe, Type ML2x) and surface temperature (thermocouple element, Type K) **(e)** are attached to the linear bearing with a DC stepping motor.

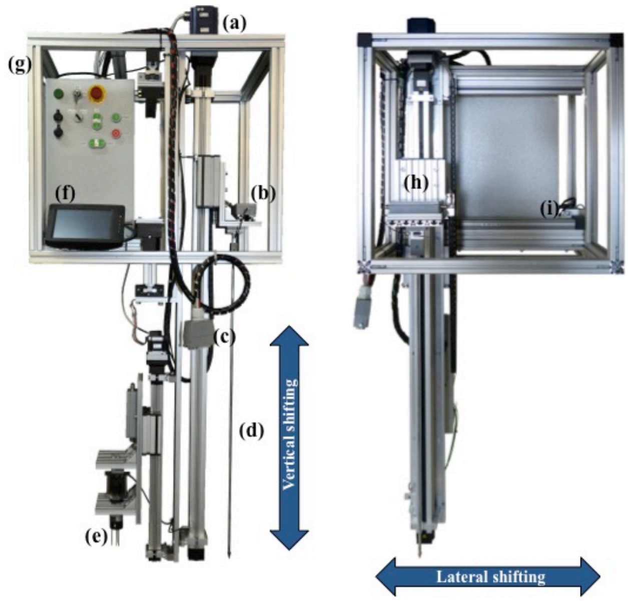

Fig. 3. Penetrometer App: (a) vertical shifting DC stepping motor, (b) force sensor and measurement device, (c) custom plug, (d) probing, (e) soil moisture sensor, (f) touch monitor, (g) App frame, (h) linear bearing, (i) lateral shifting DC stepping motor

Real Time Kinematic (RTK) receiver and geographic information system (GIS)-based documentation

To log the GPS position for the soil property measurements a RTK-GNSS receiver is used. This receiver allows highly accurate positioning. A positioning service SAPOS-HEPS (LGLN, 2014) provides correction data (RTCM format) via Networked Transport of RTCM via Internet Protocol (Ntrip), making a base station unnecessary. The open source GIS tool OpenJump (www.openjump.org) is used for detailed measurement planning (adapting the density and arrangement of the measure points), e.g. considering soil maps, yield maps, etc.

Data management

The modular system architecture of the “App” is illustrated in Fig. 4. Both motors and the force sensor are connected to an embedded system via RS232, an Arduino-MEGA (www.arduino.cc) development board. The surface moisture sensor and temperature logger also use an Arduino-MEGA board. One motor and one force sensor are connected to the board via RS232. The moisture sensor is connected to the board via analog input. The thermocouple element is connected directly via USB to an Industry PC. The embedded systems control the motors and send the sensor data via Ethernet network to the Industry PC. This PC runs a software application with an user Interface for a “manual“ and “semi-automatic” measurement of soil properties (Fig. 5).

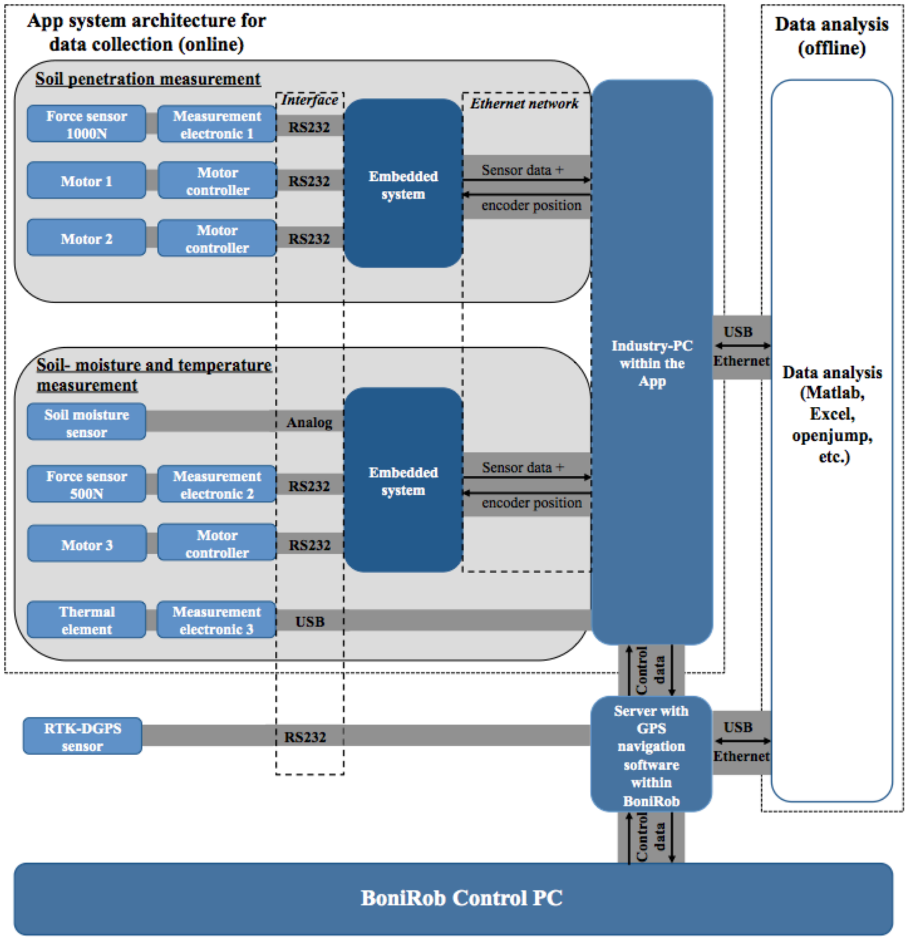

Fig. 4. System architecture of the Penetrometer App for data collection, analysis and RTK-DGPS navigation software

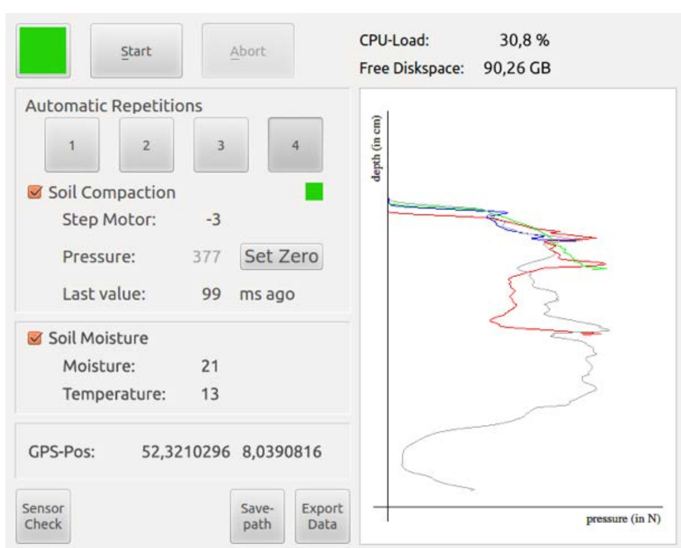

Fig. 5. Screenshot of the operating software for soil properties measurements

Robot Operating System (ROS)

The field robot platform "BoniRob" uses the open framework ROS (Robot Operating System) for control and communication (Quigley et al., 2009). ROS is also used in the soil property software described above to communicate outside the App system with the navigation server and the BoniRob Control PC (Fig. 4). Status codes and values are exchanged through this interface (e.g. next measurement can be acquired, measurement has been completed or RTK-GPS-position). This communication is essential for automatic measurements with the Penetrometer App and BoniRob.

Laboratory tests

Laboratory tests were performed to compare the penetration data (measured in MPa) of the Penetrometer App to a commercial penetrologger (www.eijkelkamp.com) using the same probing rod and cone ($1cm^2$, 60°). Figure 6 shows the measurement setup for the laboratory tests. To ensure a homogeneous measurement, three plastic tubes with a length of about 1m and an aperture of 0.30m have been used and filled with different soil textures. The used soil textures are illustrated in table 1.

Table 1. Soil textures for laboratory measurements

Soil textures	Percentages	Moisture
sand (Sa)	98% sand, 2% silt	18%
silt (Si)	86% silt, 12% clay, 2% sand	14%
loamy sand (Lo)	46% sand, 38% silt, 16% clay	11%

By using a fork lift (Fig. 6. **(a)**), the plastic tubes **(c)** are placed below the Penetrometer App **(b)** for measurement acquisition. The setup as shown in Figure 6 **(e)** is realized for the commercial penetrologger measurements. In order to reduce the effect of side moving, the penetrologger is equipped with a bearing. The tests are performed in six readings for each soil texture and sensor system with a maximum depth of 80cm. The penetration force of the probing rod has been set to 2cm/s for both systems. With this setup, the amount of determined penetration data identified by the cone of each system was the same. For any measurement 80 values are determined according to the depth information. In order to compare the data, the average of six readings from various locations was calculated. Soil moisture was also measured during the tests for all soil textures. The laboratory measurements were realized during a bachelor thesis (Scheibe, 2013).

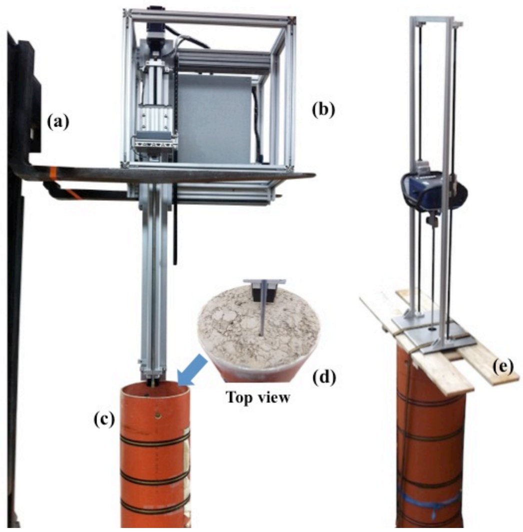

Fig. 6. Measurement setup for laboratory tests, (a) fork lift, (b) Penetrometer App, (c) plastic tube with soil type, (d) top view of plastic tube with probing rod and soil, (e) setup for commercial penetrologger with bearing

Field trials

The field trials were performed in two different parts. The first part includes the correlation measurement on the field with the commercial penetrologger and the Penetrometer App. For this measurement, the Penetrometer App was mounted into BoniRob as a carrier vehicle. BoniRob was controlled manually with a control panel. The measurements were performed automatically with the software described above. For these measurements three different locations were used. The shortcut names of the locations are **Lan** (Germany, 52°19'23.3"N 8°09'13.0"E), **Hs** (The Netherlands, 53°04'50.9"N 7°05'09.7"E) and **Hc** (The Netherlands, 53°22'14.5"N 6°19'21.1"E). At each location sixteen readings with both systems are performed next to each other. Averages of the raw data were calculated based on the readings for comparison and analysis.

The second part of the field trials includes an application measurement with Penetrometer App and BoniRob to identify a former traffic lane in a grass field (Germany, 52°19'15.8"N 8°02'20.7"E). Four readings were performed in twenty different areas in order to identify the position of the traffic lane. For the first time, BoniRob and the Penetrometer App were operated autonomously in a stop-and-go modus by using freehand RTK-GPS coordinates of the measurement areas. The user observes safety applications for this field trial. Figure 7 shows the field used for the data acquisition. The identified penetration data were then used to create a visualization of the traffic lane via the OpenJump software platform.

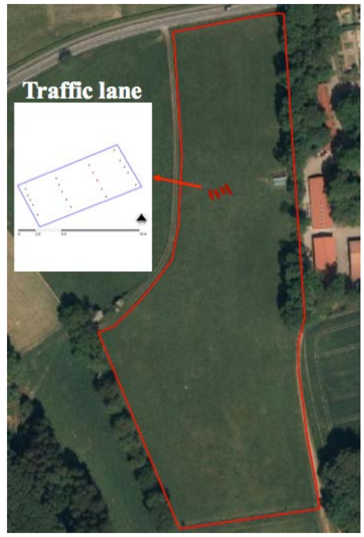

Fig. 7. Measurement locations within the used field (see Fig. 9)

RESULTS

Laboratory tests

The correlation analysis was performed by the curve-fitting tool of Matlab®.
Figure 8, left shows the correlation of the averages of the penetration data from both systems. The measured data from the Penetrometer App shows a strong correlation to the reference data of the commercial penetrologger with R_{Lo}^2 = 0.92 and RMSE = 0.185 for soil texture loamy sand (Lo), R_{Sa}^2 = 0.98 and RMSE = 0.145 for Sand (Sa) and R_{Si}^2 = 0.98 and RMSE = 0.120 for Silt (Si) as illustrated in table 2.

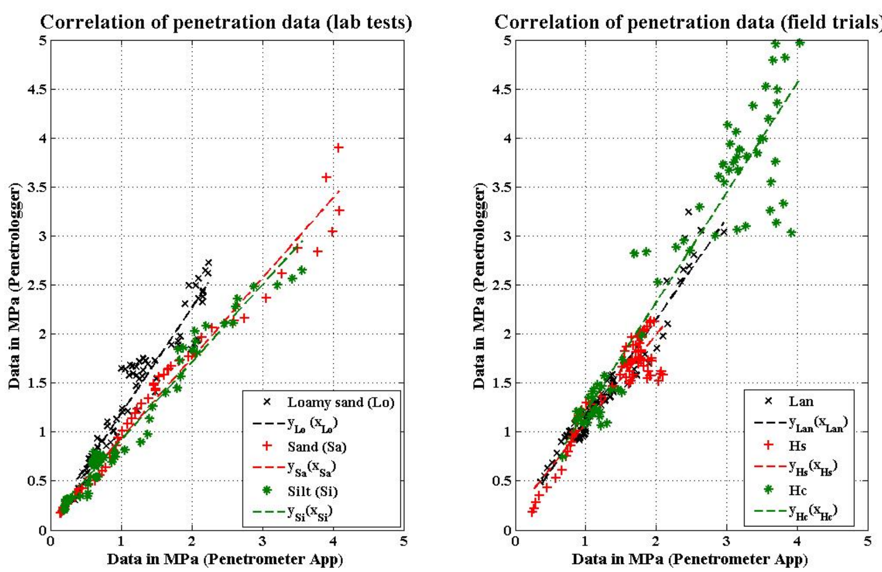

Fig. 8. Correlation of penetration data, left: lab tests with 3 different soil textures, right: field trials at 3 different locations and soil compositions

Table 2. Results of calculated data for the measurements

Parameter	Laboratory tests			First field test		
short names	Lo	Sa	Si	Lan	Hs	Hc
R^2	0.92	0.98	0.98	0.94	0.85	0.90
RMSE	0.185	0.145	0.120	0.146	0.19	0.417
y(x)	1.08*x +0.11	0.82*x +0.11	0.79*x +0.12	1.03*x +0.086	0.91*x +0.176	1.12*x +0.086

Field trails

Correlation measurement on the field

The correlation analysis was performed by the curve fitting tool of Matlab®. Figure 8, right shows the correlation of averages of the data sets from either system. The data from the Penetrometer App shows a strong correlation to the reference data of the penetrologger with $R_{Lan}{}^2 = 0.94$ and RMSE 0.146 for the first location, $R_{Hs}{}^2 = 0.85$ and RMSE = 0.19 for the second one and $R_{Hc}{}^2 = 0.90$ and RMSE = 0.417 for the third location. The correlation between the calculated data of these field measurements shows a weaker correlation to each other than the data of the laboratory tests due to the inhomogeneity of the soil (e.g. different soil textures, stones, etc.)

Traffic lane measurement

Within the selected area with a size of approximately 70m^2 four readings at twenty areas were performed. Figure 9 shows the map for this field trial in order to identify the penetration resistance of the soil. The map was created in the open source software package OpenJump. Figure 9, top shows the averages of the penetration data in a range of 0-5cm from ground level. Figure 9, bottom shows the averages of the penetration data in a range of 10-15cm at the same areas. The field trial was performed with the field robot platform BoniRob and Penetrometer App in a fully automatic modus. The investigation carried out was a first automated test on agricultural land. The variability within the small-scale area shows a large variation in the horizontal and vertical directions. In the rooting depth (0-5cm) the identified penetration data indicate a lower value in comparison with the identified values of 10-15 cm due to the plants.

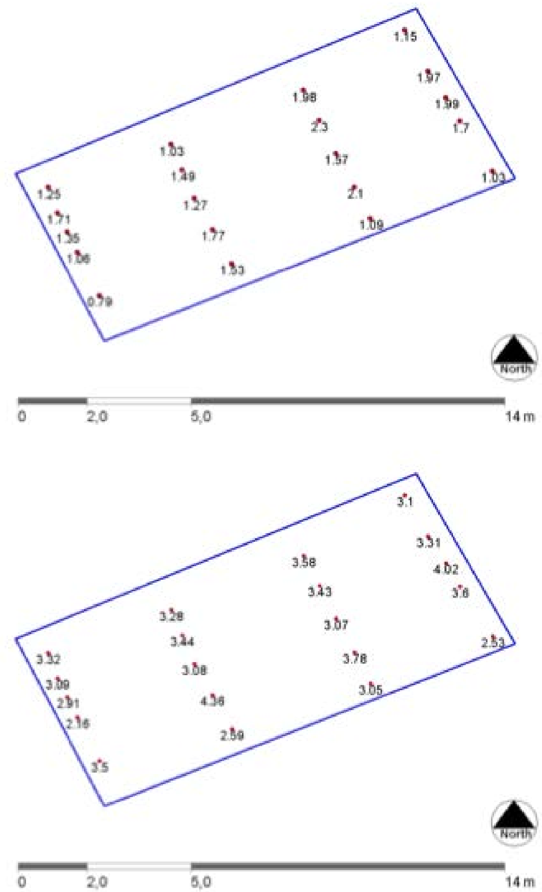

Fig. 9. Top: penetration data of the selected areas on the field in a range of 0-5cm from ground level, bottom: penetration data of the selected areas on the field in a range of 10-15cm from ground level.

DISCUSSION

In this paper an application module "App" for soil property measurement was described and validated in laboratory and field tests. The first results show the utilization of the field robot platform BoniRob in combination with the Penetrometer App in order to an automated soil property measurement. The identified values of the former traffic lane show a large variability of penetration resistance on a small scale. These results confirm similar studies (Schön and Hinck, 2005). The modular system architecture allows further applications e.g. including different sensor technologies. The next step will be more field trials with a large density of measurement points in different fields and the corresponding interpretation.

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