Concept and first results of a field-robot-based on-the-go assessment of soil nutrients with ion-sensitive field effect transistors

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Abstract

In the research project "soil2data", a mobile field laboratory will be developed. While driving/moving over a field, it collects representative mixed soil samples, conducts a soil nutrient analysis and leaves the excavated soil on the field after measurement. The results with the corresponding GPS-position are stored or sent to a data platform. Innovative ion-sensitive field-effect transistors (ISFETs) are the key component of the mobile field laboratory. A custom-specific ISFET multi-sensor module - a "lab on chip" – was specified und produced to measure the nutrients (N, P, K), pH and electrical conductivity of the soil extraction solution.

The mobile field laboratory can be used with various vehicles. Mounted on a carrier and coupled on a tractor but also on an autonomous field-robot platform. The combination of the on-the-go soil nutrient analysis method with an autonomous field robot offers considerable advantages with respect to economic and environmental requirements. The soil nutrient analysis is done fully automated directly on the field, the result is promptly available real-time and can be considered for other ongoing or shortly following processes (e.g. planned fertilization measures).

Key words: field robot**,** ion-sensitive field effect transistors (ISFET), mobile field lab, soil nutrient analysis, soil test

Introduction

Knowledge of the spatial distribution of soil nutrient status is important information for a sustainable fertilization in crop production. Up to now the process of soil sampling and analysis is time consuming and cost-intensive. The current practice of soil nutrient analysis comprises the following steps : a) creation of a sampling plan, b) soil sampling in the field, c) transportation of the soil samples to a laboratory, d) physical and chemical preparing of the soil samples, e) analysis of the sample f) creation of a documentation and sending the analysis result to the farmer as well as g) disposing soil material from the laboratory. The entire process, from soil sampling until the farmer receives the analysis results takes in general several a long time (up to 8 weeks). This means that the analysis results cannot be integrated into current fertilizing processes in a timely manner, which is very critical, especially in the spring.

The development of an on-the-go soil nutrient analysis method – a mobile field laboratory – that delivers soil parameters immediately will open ups new options. The analysis results are available in a very short time. It will be take only a short moment after finish soil sampling and analysis at the field.

By combining a mobile field-laboratory (field-lab) with an autonomous carrier platform (e.g. field robotic “BoniRob”) will proved new opportunities in soil sampling and mapping. An on-the-go verification of the actual measurement results on the field with a database is one of the options. The dynamic adaptation of the sampling line during the soil sampling will be another innovative option. If the currently processed series of measurements on a sampling line or within a sub field show a high fluctuation in the measurements, it will be possible to subdividing this sampling line. (Hinck et al. 2018)

Transportation of soil probe material from field to laboratory is not necessary. Furthermore, it will greatly enhance infield variability characterization by dividing the field in smaller sub fields than it would be possible with traditional soil sampling and mapping. With this new technique, the knowledge of the spatial distribution of soil nutrients status will be improved. Also, the repetition of the measurement, e.g. annually, weekly or even daily (at a sub field or for specific area within a field) would be possible. Also, the availability of the analysis result will be improved and the real-time linking between the actual result and an existing database will be possible.

This new approach will contribute to a sustainable and demand-driven fertilization for crop production at small-scale field level.

Materials and methods

Several researchers have been working on the implementation of an on-the-go nutrient analysis for field application. A soil preparation method for mobile field laboratories for analyzing NO_3^-, K^+ and P was developed by Kim et al. (2007). Mobile field laboratories for on-the-go measurement have been designed for analyzing NO3- in the topsoil (Sibley et al. 2010, Sibley 2008), for pH (Viscarra Rossel et al. 2004) and for multiple parameters including NO3-, K and pH (Sethuramasamyraja et al. 2008).

The interdisciplinary research project "soil2data" is about to develop a mobile field laboratory to measure the nutrients (N, P, K), pH and electrical conductivity of the soil extraction solution in on-the-go mode. Three carrier platforms are planned in the project for the use of the mobile field lab. The lab is equipped with additional systems for an automatic generation of a soil sampling plan, components for chemical and physical soil preparation, sensors for soil analysis and systems for storing the analysis results.

One of this carrier platforms is the autonomous field-robot BoniRob (Ruckelshausen et al. 2009). It includes sensor systems for autonomously navigating autonomously along the crop rows or by using GPS coordinates. The robot has an empty cavity within the body, which serves as carrier, electricity supplier for multiple application modules – App's (Scholz, et al. 2014). The standardized field robot interfaces (hardware/software) and modular construction of the App's enable a flexible integration of these application modules also in other carrier platforms (e.g. a tractor) or other field-robots.

Figure 1: Autonomous field-robot BoniRob with "soil2data" application module

The application module for soil nutrient analysis – "soil2data" mobile field lab – contains the following components:

- A soil sampler to collect the soil samples
- A collection container to create a mixed soil sample (15-20 core samples, 250-300 g. soil material)
- The measuring systems to determine the amount of collected soil material
- A transport system (chain elevator) for transporting the soil material
- A linear actuator and a mixer for homogenization / physical preparation of a mixed soil sample
- Various pumps / valves to supply the extraction agents for the chemical preparation of the soil material
- A filter station to filter the measurement solution extracted from the soil material
- An ISFET multi-sensor module including readout circuit for measuring the concentration of the nutrients (N, P, K), pH and electrical conductivity of the extracted solution.
- Transport system for the removal of extracted soil material
- Systems for cleaning of all components for preparing subsequent measurements
- An industry PC-system with real time Ethernet bus to control the components of the field lab, to communicate with readout circuit of the ISFET multi-sensor module and the carrier platform.

As soil sampler, a commercial product from the company Bodenprobetechnik Nietfeld GmbH (Germany) is used. This soil sampler (boring-type, soil auger Ø 16 mm) allows sampling at a depth of 30 cm and has been equipped with additional components for the automation of the overall soil nutrient analysis process.

After soil sampling and complete of a representative soil mix sample, the soil sample processing takes place. It should be noted, however, that the quality of soil sample processing in this on-the-go soil nutrient analysis process is fundamental and crucial for an autonomous, fully automated soil nutrient study. The flawed execution of the soil sampling process can lead to erroneous assessment of the measurement. Therefore, the results of future field trials measurements within the project will be qualitatively compared with the results of the state of the art laboratory analysis. In the context of the research project “soil2data”, the project partner LUFA Nord-West - an accredited service laboratory affiliated with the Chamber of Agriculture in Lower Saxony / Germany - developed a new soil processing method for the on-the-go soil nutrient analysis on the field (Najdenko et al. 2018).

The new soil sample processing method - referred to as the “soil2data LUFA method” - is based on the standard soil sample processing method for nutrient analysis in laboratory and includes the following steps: homogenization of a mixed soil sample, supply of the extraction agent to dissolve the nutrients from the soil, filtration of the soil sample extract. In order to reduce the soil sample processing time, a chemical and mechanical method for homogenizing the soil material in the pre-wet state with a mixer and simultaneous feed of the extraction solution is developed and tested. This method produced comparable results under labor conditions and will now be tested/used the “soil2data” mobile field lab for on-the-go soil sample preparation.

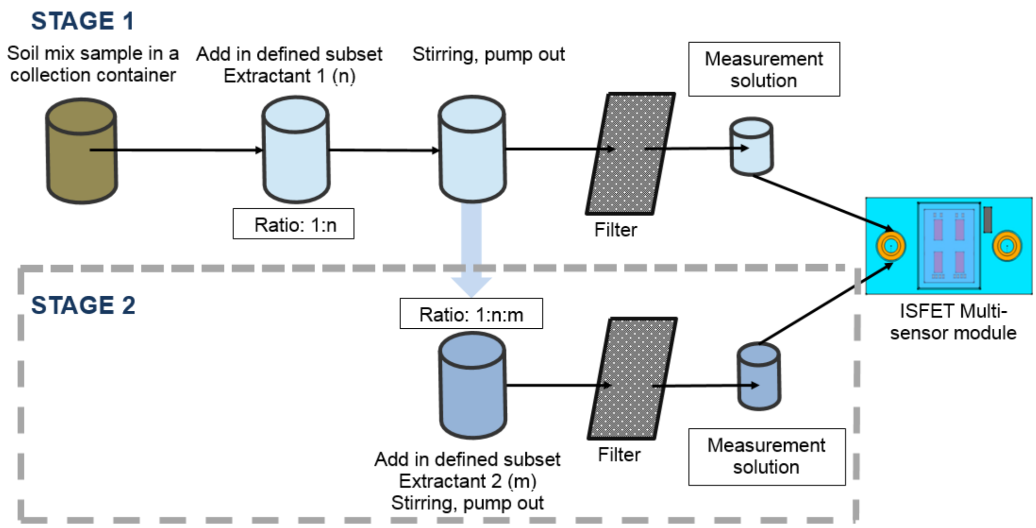

Figure 2: "soil2data" nutrient extraction procedure

In order to allow a flexibility during the testing of different extraction liquids and to cover the diversity of the extraction methods, a proposed soil sample processing method was extended. For a case, that only one extraction agent for a soil sample processing will be used, was a Stage 1 designed with the standard steps like laboratory soil sample processing procedure: homogenization of a mixed soil sample, supply of the extraction agent to dissolve the nutrients from the soil, filtration of the soil sample extract. In case, that more than one extraction agent or a mix of several extraction agents will be used, is a soil sample processing method with a Stage 2 extended.

The description of the “soil2data” nutrient extraction procedure is as follows (Fig.2):

- Stage 1 - after determining the amount of soil material in a collection container, an extraction fluid (Extractant 1) is added and stirred vigorously with a mixer for a fixed time. Afterwards, a defined quantity of the measurement solution is pumped out and passed to a filter station.
- Stage 2 – a various extraction fluid (Extractant 2) is added to the residual amount of soil material in the collection container is stirred again with a mixer. There after the measurement solution is pumped off and passed to same filter station.

These two stages were realized in the hardware of the "soil2data" mobile field lab with a chain elevator with a hydraulic drive. It contains the storage containers for mixed soil sample and has fixed reference points during operation – the so-called workstations (WS):

- Workstation 1 - transfer soil samples from soil sampler, collecting the mixed soil sample, pre-wetting with Extractant 1, determination of the quantity of the mixed soil sample
- Workstation 2 - “soil2data” soil nutrient extraction procedure (Stage 1 / Stage 2)
- Workstation 3 - removal of measured soil material from a collection container
- Workstation 4 – cleaning of collection container

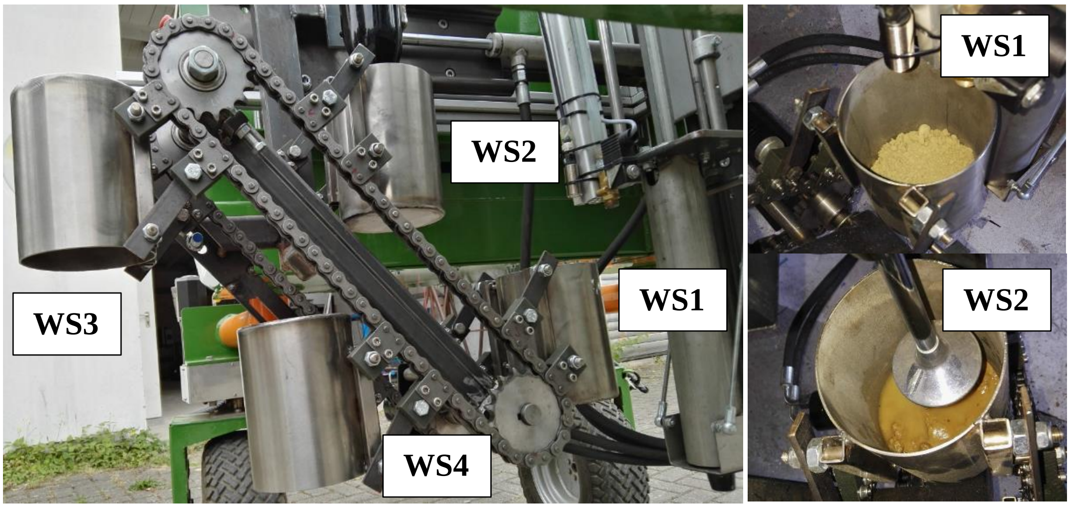

Figure 3: "soil2data" soil nutrient extraction procedure - hardware

The four workstations allow to perform the whole soil nutrient analysis process continuously without stopping - because work steps can be carried out simultaneously.

To enable the on-the-go soil nutrient analysis process directly on the field, a customer specific multi-sensor module for research project "soil2data" was produced by the company MICROSENS SA (Switzerland). This module is a key component of the mobile field laboratory. It consists of a closed LTCC (Low Temperature Cofired Ceramics) housing with an inlet / outlet tube for the influx / efflux of the prepared soil samples in liquid state (measurement solution) and contains four single ion-sensitive field-effect transistors (ISFET) to measure the nutrients (N, P, K), pH and electrical conductivity of the soil (Fig. 4).

The conventional ISFET readout circuits cannot be used to read out the electrical output signals from all four ISFET chips build into a multi-sensor module simultaneously. Such readout circuits do not provide amplification to the electrical output, and simultaneous interrogation of multiple ISFET's provides an unstable, oscillating output signal. Therefore, a new readout circuit for the ISFET multi-sensor module has been developed by the University of Applied Sciences Osnabrück and ANEDO Ltd. It eliminates the above described problem and generates a stable output signal for the multi-sensor ISFET module.

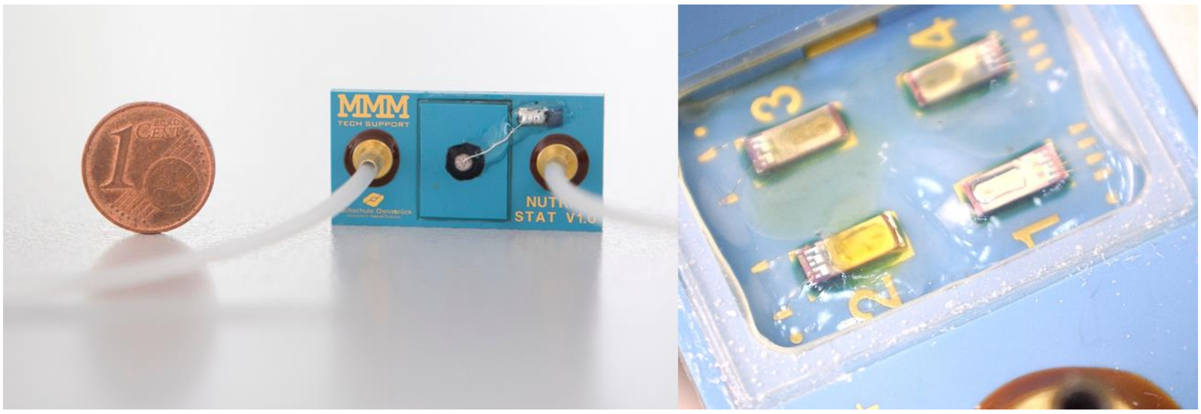

Figure 4: Multi-sensor module with four ISFET chips

Results

The multi-sensor ISFET module with the newly developed readout circuit was tested under laboratory conditions to check the stability of the readout circuit output signal and the reproducibility and quality of the measurement data output from each individual ISFET chip (Fig. 5).

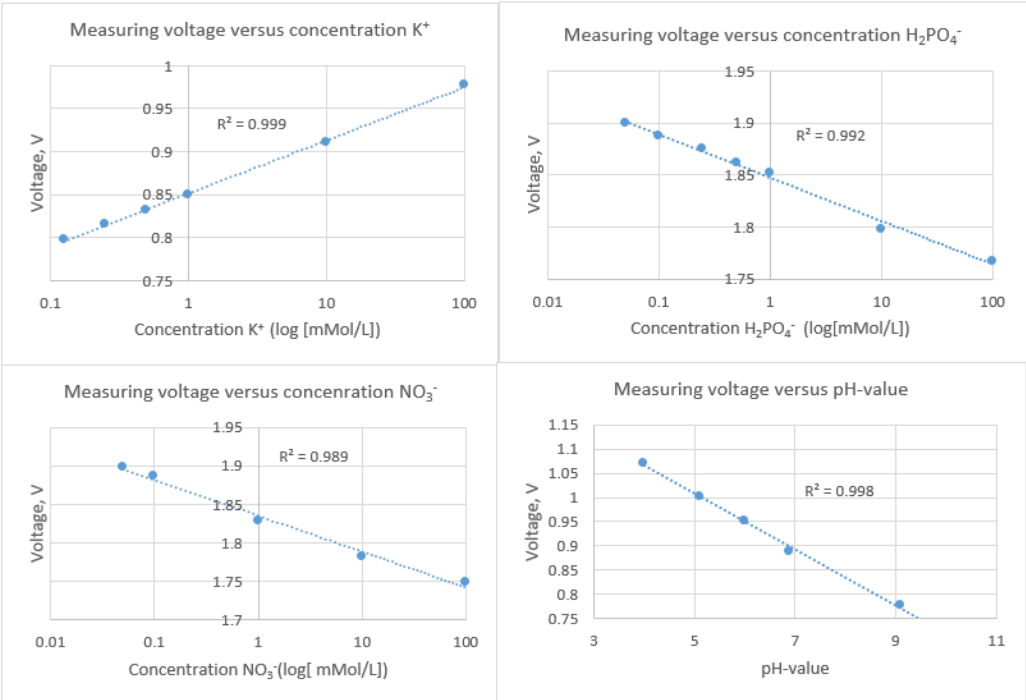

Figure 5: Results from multi-sensor ISFET measurements results of calibration solutions with different concentrations

The time required to stabilize the measurement signal was experimentally determined to 100 seconds.
The “soil2data” soil nutrient extraction procedure was tested in single steps with the use of different extraction agents. The optimum time required for liquidate/getting the nutrient extraction from a soil sample was also experimentally determined. It take approximately 15 minutes when using a two-stage soil sample preparation procedure.

Conclusion

The first functional measurements with the newly developed readout circuit were carried out with the aid of calibration solutions and showed good results. The newly developed two-stage soil sample preparation method allows simultaneous parallel execution of the necessary work steps so that the entire process sequence can be realized in non-stop mode.
The individual work steps for soil sample preparation (such as handover of a soil mix sample for preparation, extraction of the nutrients with different extraction agents, filtering procedure, etc.) were created and tested in individual work steps. The times required for the preparation processes have been determined.
Transfer, adaption and optimization of the laboratory soil sample preparation method for field conditions and also first experiment results show that the determination of the nutrient content of soil is possible by using ISFET sensors.
The next step will be integrating all required components for on-the-go nutrient analysis into a functional application module (App). Subsequently numerous field trials will be made in order to validate the entire mobile field laboratory system and compare nutrient analysis results from mobile soil laboratory to traditional laboratory results.

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