

Modular System Architecture for Individual Plant Phenotyping with an Autonomous Field Robot

Ralph Klose, Kim Möller, Carsten Vielstädte, Arno Ruckelshausen
Faculty of Engineering and Computer Science, University of Applied Sciences Osnabrück

Abstract

A concept of a modular system architecture for plant phenotyping with an autonomous robot has been developed and realized. The system takes into account the inclusion of several sensors - placed at different positions - with a broad range of data volume and data rates. The database confirms the online data storage of sensor data including position and times steps with RTK-DGPS accuracy, thereby allowing single plant analysis. Moreover the configuration of the gateways and sensors and the error handling are other tasks of the database. The human-machine interface allows a flexible setting of parameters and the inclusion of additional sensors. The data of the spectral and morphological sensor and positioning information can be accessed by standard software tools for plant phenotyping analysis. Moreover, as part of the architecture for an autonomous field robot the system has a high potential for further applications in this field.

Keywords

System architecture, autonomous field robots, plant phenotyping, sensor fusion

1 INTRODUCTION

Phenotyping is the key technology for the evaluation of plants in field trials (Montes et al. 2007). The benefit of analyzing the information is the ability to develop strategies for new procedures in order to optimize plant quality or their processing, e.g. during the harvest. Next to spectral information one important part of these phenotyping methods is the exact measurement of the plant's morphological characteristics. For example, typical parameters of interest are the plant profile, leaf sizes, leaf configuration including the angle, plant height or stem thickness.

Until now this analysis is typically executed manually by experts judging the field situation by characterizing random samples taken on the field plot. Since this analysis has to be done manually, it is very time consuming, generates high costs and has a varying reliability. Moreover, the phenotyping is performed by different experts, this may cause additional variations. Taking into account these effects it is often difficult to compare data sets or to develop new strategies for the growth process.

As a consequence, the implementation of sensors, system technologies and algorithms for automatic phenotyping are of increasing importance to overcome the disadvantages of the manual methods described above. While static measurements – typically imaging applications – can be performed under well-defined measurement conditions, online applications in the field are still a challenge for corresponding technologies (Nagasaka et al. 2004). The benefits of such methods are the comparability of data sets, the objectivity of the data and the measurement in real-time on moving vehicles. The authors have recently shown that a sensor fusion concept together with a high resolution GPS system is even able to analyze (and re-analyze) each single plant (Fender *et al.* 2006). In combination with an autonomous field robot, it should even be possible to detect all plants in their different growth stages.

2 BONIROB

This work is part of the development of such a field scout for individual plant phenotyping, named BoniRob (Ruckelshausen *et al.* 2009) (see Figure 1). The system architecture of the autonomous field

robot BoniRob includes a navigation module for the control of the robot, a speed and steering module for the control of the motors and hydraulics of the robot, a phenotyping module for the calculation of plant parameters, and a sensor module.



Figure 1: BoniRob

The sensor module contains the sensors integrated into the robots system architecture. Their measurement data can be used as a base for the calculations of the phenotyping algorithms. Besides this the data can be used as an additional data source for the navigation module. The phenotyping of plants, performed by this robot, includes the measurement of the morphological and physiological characteristics, as well as statistical overviews of the field plot. The parameters to be measured can be found in Table 1.

Table 1: Plant parameters for phenotyping with BoniRob (RUCKELSHAUSEN 2009)

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

To perform the automated phenotyping of the maize plant the robot is equipped with sensors of different types, to measure the characteristics of the plants. According to this, these sensors need to be combined in a system module, supplying the measured sensor data to a central processing unit for the calculation of the plant parameters which is placed in the mentioned phenotyping module. The sensors used for the calculation of the plant parameters can be found in Table 2.

Table 2: BoniRob sensor overview

<i>Sensor type</i>	<i>Interface</i>
3D ToF camera	Ethernet
Hyper spectral imaging system (NIR)	Ethernet
Hyper spectral imaging system (VIS)	USB
Laser distance sensor	Analogue
Light curtain	RS232
RTK GPS	RS232

Besides the different interfaces of the different sensors used for the phenotyping of plants, the sensors generate measurement data in different formats and data types with varying data rates.

To be able to develop a system structure for the plant phenotyping with an autonomous field robot it was necessary to define requirements. The system structure has to be able to handle different:

- sensor types
- positions of the sensors
- data formats
- varying data rates
- sensor settings

Besides this the system structure has to:

- be flexible
- be extensible
- guarantee data consistence
- guarantee reliable online measurements
- enable the user to perform an offline analysis of the recorded data
- be transparent for debugging purposes
- provide easy ways to interact with the system and to access the data

3 SYSTEM ARCHITECTURE

According to the described general system architecture, the system structure for the acquisition of sensor data, the data storage and data analysis was developed. This structure contains the system components of the phenotyping control system, as well as the interfaces connecting this control system to the navigation, speed and steering control system (see Figure 2). In this paper the focus will be on the phenotyping control system and the sensor system. To have a flexible system it was decided to use a modular structure. This modular system structure is built up using a decentralize preprocessing of sensor data and a central data storage. To have a structured and consistent data storage system for the huge amount of sensor data, with an easy way to query data, it was reasonable to use a database server. Besides this it was necessary to integrate a high speed bus system as a backbone, connecting the different components of the system and enabling a reliable data exchange using a standardized transfer protocol and data encapsulation for all bus members.

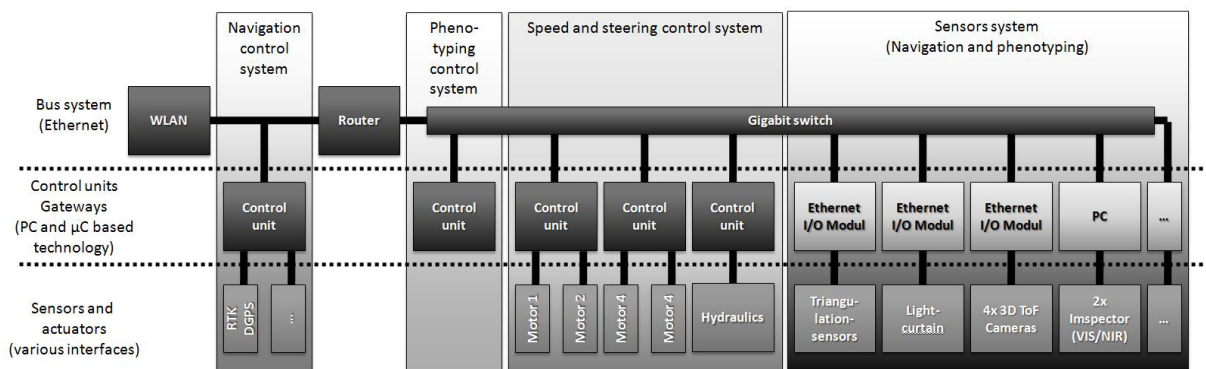


Figure 2: Complete BoniRob system structure

With the high data volume produced by some of the sensors it was decided to use a Gigabit Ethernet as a central bus system to reduce possible occurring latencies and to have a bandwidth reserve for additional sensor. The advantages of this concept are the high extensibility as a result of the modularity, transparency as a result of the standardized protocols and preprocessing of the data, and an easy accessibility of the sensor data by using only one data storage point.

Therefore the system is equipped with several embedded systems and a central PC system which is used as the central data storage using a MySQL database server. The embedded systems are based on different microcontroller boards that are equipped with different interfaces like: USB, RS232, Ethernet and AD-converters. Main tasks of these embedded systems are the configuration of the attached sensors, the collection of the sensor data and the transmission of this data to the central data storage. Since these microcontroller boards can be considered to be an interface between the sensors and the data storage they are called gateway boards. These gateways give the possibility to use different sensor types with different interfaces in the system architecture. To have a common software structure for the different hardware it was decided to use a Linux with 2.6 Kernel as an operating system.

Besides the main tasks of interfacing the sensor system to the central PC the embedded systems are used for labeling the data. Since the sensor data highly depends on the time and on the exact position of the measurement a timestamp in combination with a position stamp is used. To transmit the measurement data from the gateway boards to the data storage the client-server based XML-RPC protocol for HTTP connections is used. The benefit of this approach is the high transparency of the data packets as a result of the standardized way of transmitting the XML encoded data over the Ethernet link. Besides this, another advantage of XML-RPC is the high amount of available software implementations of this protocol for many programming languages and platforms. To transmit the data as well as the time and position stamps the standard data types of the XML-RPC protocol are used (see Table 3, Table 4).

Table 3: XML data types for sensors

<i>Sensor type</i>	<i>Data type</i>
<i>3D ToF camera</i>	<i>base64</i>
<i>Hyper spectral imaging system (NIR)</i>	<i>base64</i>
<i>Hyper spectral imaging system (VIS)</i>	<i>base64</i>
<i>Laser distance sensor</i>	<i>integer</i>
<i>Light curtain</i>	<i>string</i>
<i>RTK GPS</i>	<i>string</i>

Table 4: Data labels

<i>Stamps</i>	<i>Data type</i>
<i>Position</i>	<i>integer</i>
<i>Time</i>	<i>2x integer</i> <i>(date + time → integer, milliseconds → integer)</i>

To be able to do a performance analysis and to be able to check the time one sensor system needs for the processing of the data, the packets contain, besides the encoded data, a time stamp and a position stamp taken at the start of the measurement and a time stamp and a position stamp taken at the end of the measurement. Since it is important to know the exact timing of the measurement process, the common time stamp is extended by the milliseconds. An example of a XML-RPC packet for distance image data created by the 3D ToF cameras using the XML tag based encapsulation can be found in Figure 3.

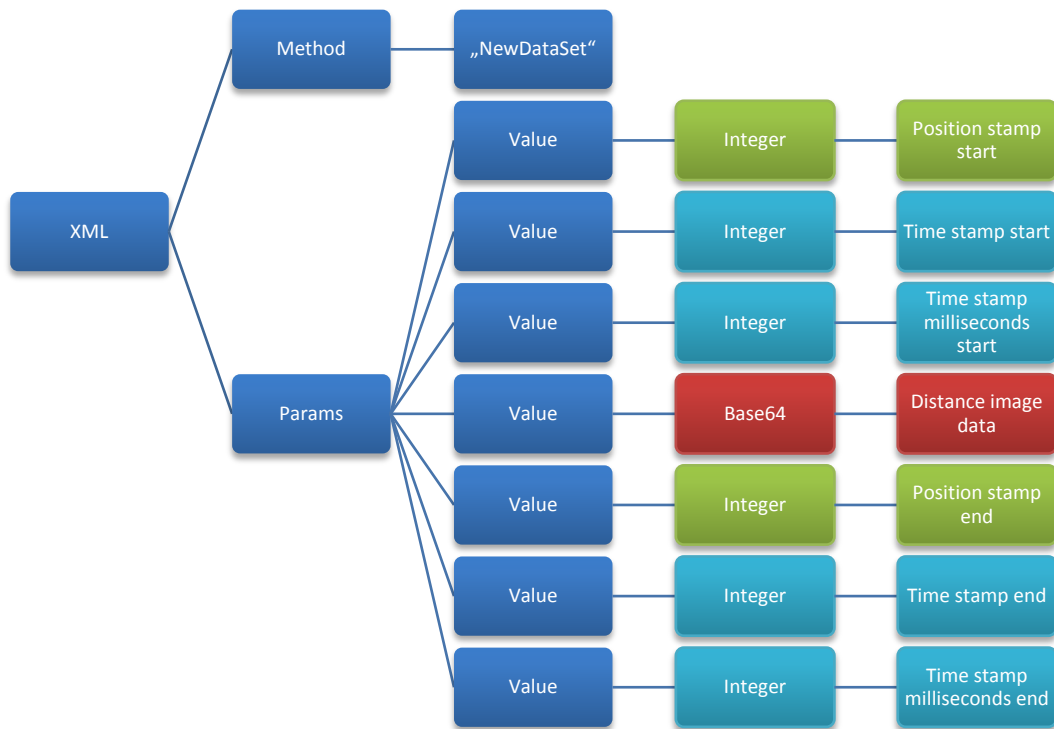


Figure 3: Example for a XML based data encapsulation for XML-RPC

To have a reliable time stamp, it was necessary to implement synchronization methods for the real time clocks of the embedded systems and the central PC system. Therefore a NTP (Network Time Protocol) server was installed on the PC which is used by the gateway board periodically for the synchronization. In contrast to this the position information is actively synchronized by a UDP broadcast over the whole subnet which is send by the speed control system. This broadcast packet contains the actual rotary encoder position of the robot. To guarantee a fast and reliable distribution of these packets, all QoS (Quality of Service) capable devices (like the switches, embedded systems and the central PC) have been set to prioritize the broadcast packets.

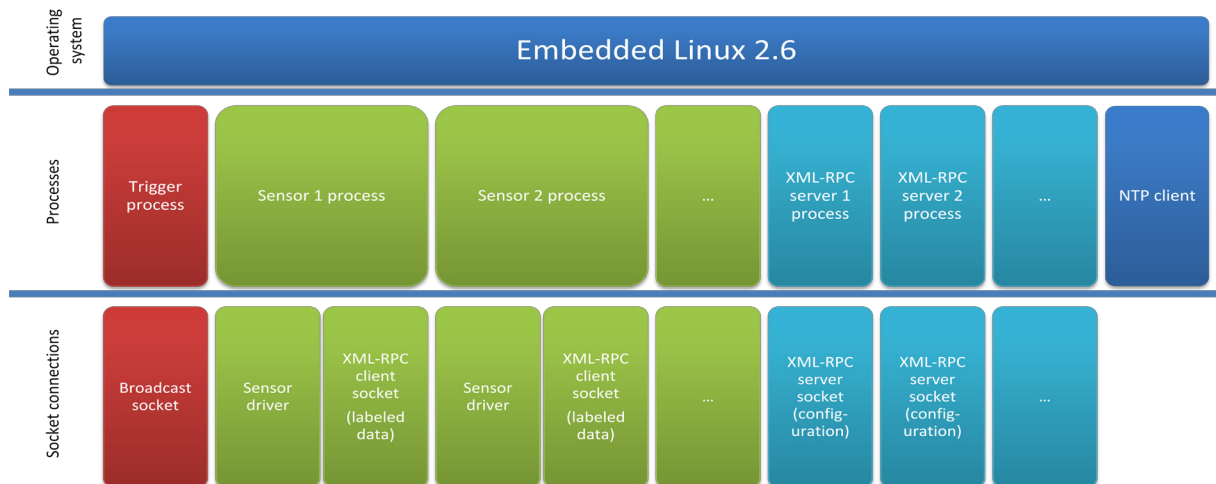


Figure 4: Process structure of the gateway boards

The software running on the embedded systems is split up into different tasks (see Figure 4). The first one of these tasks is the communication with the attached sensor systems, which contains the implementation of a device driver to enable the embedded system to change settings and to read out the data of the measurements. To be able to communicate with more than one sensor system at a time using just one gateway a new process is created for each sensor connected. This enables a parallel processing of the first task for the sensors. Moreover, a XML-RPC client was implemented into each

of the mentioned process to perform the encapsulation and transmission of the data to the central data storage as soon as a new measurement is finished. According to need to label the measurement data with a position stamp and a time stamp, the second and third important tasks are concerned with the reception of the position broadcasts and the synchronization of the system clock. Therefore a socket server, listening to on the UDP port assigned to broadcast packets, and a NTP client, performing periodical updates, are running in separate process.

To enable the user to change the settings of the sensors, as a fourth tasks, a XML-RPC server was implemented for each attached sensor system. This server is able to receive and to decode XML encoded data, send by any PC on the network. With this configuration it is possible to query all possible settings of a sensor system by sending a XML-RPC packet containing the method name "QuerySettings" to the XML-RPC server assigned to the sensor (see Figure 5).

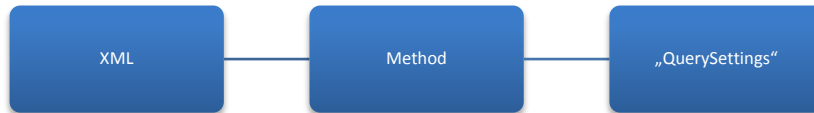


Figure 5: Query of available sensor settings using XML-RPC

The result of this query is a response made by the XML-RPC server with an attached array containing a list of the sensor parameters, data types and actual settings. To change the settings the values of this array can be changed and are sent back to the gateway board using the XML-RPC method "ChangeSettings" (see Figure 6).

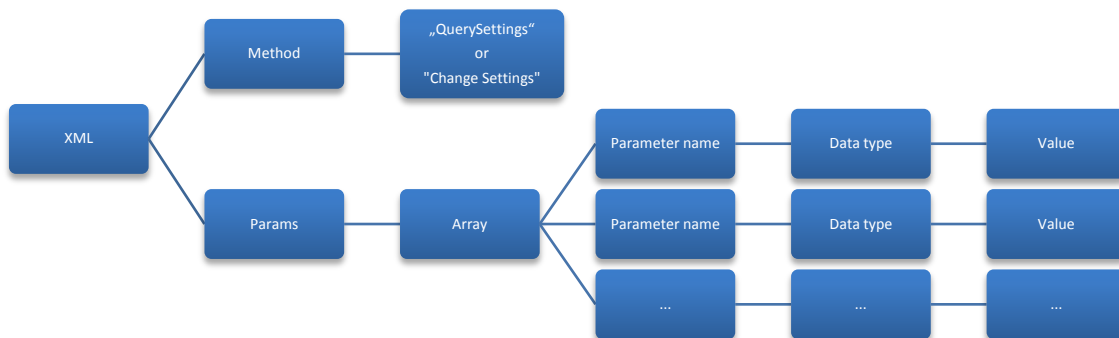


Figure 6: Response to settings query and XML-RPC structure used for changing of settings

To accept the data sent by the embedded systems, a process containing a XML-RPC server for every single sensor is implemented into the central PC. These servers are decoding the labeled sensor data and adding them into the MySQL database. Besides the sensor data the database also contains the configuration of the sensors.

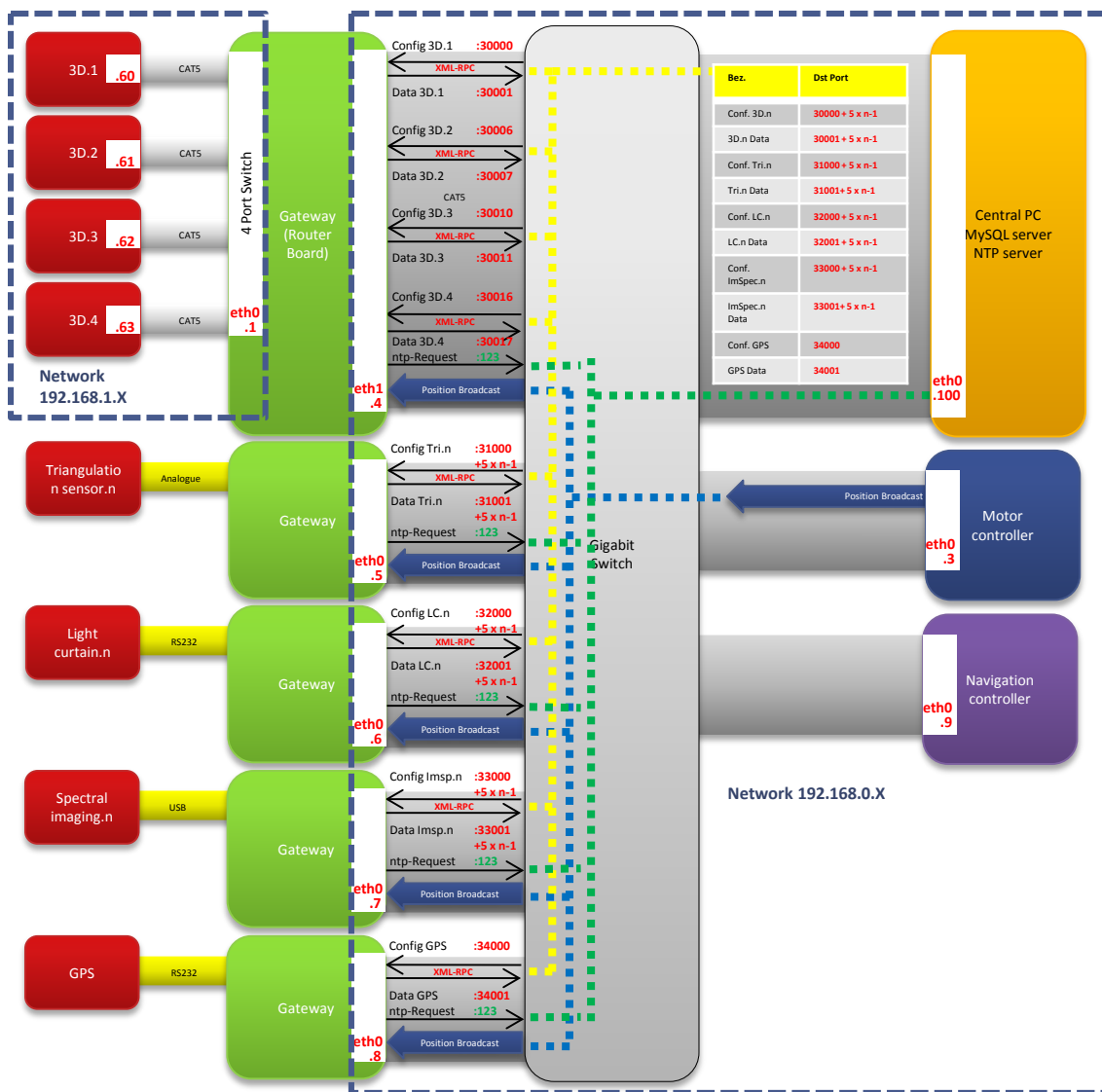


Figure 7: Example system structure

To be able to assign the sensor data to the right data table, the configuration tables include TCP port numbers that were assigned for every single connection between the XML-RPC servers of the central PC and the XML-RPC clients of the embedded systems. An example system structure for different sensor can be found in Figure 7. In this example five gateway boards were used to build up a connection between the MySQL database and the sensors as described above, including the assigned IP addresses and TCP/UDP port numbers. It is also possible to see, that for this system structure a network router board with integrated switch, which is an embedded system that can be equipped with a Linux 2.4 Kernel, was used to connect to the 3D ToF cameras. The advantage of a connection like this is that the traffic generated between the gateway and the cameras for configuration and transmission of the distance images is not disturbing the traffic of the central Gigabit Ethernet bus.

4 DATABASE

Figure 8 is showing the Entity-Relationship model of the database system. The entities of this model represent the tables of the database. As mentioned above, the database is used for the storing of measurement data and the configuration data of the gateways and sensors. Another task of the database is to save all error notifications of the processes communicating with the gateway boards over the XML-RPC connection.

The table “Sensor” of the database contains all connected sensors with their assigned configuration. Besides this, it also contain the configuration data that is needed by all sensor types, like the IP address of the gateway and the TCP ports for the XML-RPC connection assigned to the sensor.

Since several different sensor types are used for the system architecture which result in different data formats, data sizes and possible settings, it was necessary to implement another table for each of the different types. These tables, named “3D”, “Triangulation sensor”, ..., are equipped with data fields according to their additional needed settings. To be able to used different predefined settings for one sensor type, it is possible to place more than one data set in these tables. The used settings data set is saved as a reference together with the recorded measurement data to be able to connect the chosen settings to a measurement after the test run.

The table “Error” is used to hold all occurring errors of the system. With this a central point for error messages for an easy troubleshooting process was created. The table “Measurement” is the central and most important table of the database. It is used for storing the every measurement of every sensor in combination with the related time and position stamps and value called “SensorID”. With this “SensorID”, which is the primary key value of the “Sensor” table, it is possible to assign a sensor to the measurement data. Since the sensors generate a different amount of data, a generalization had to be used. Therefore, every sensor was given its own table to store its measurement data. These tables are a specialization of the table “Measurement”. Although this concept results in complex SQL queries, the advantage is that the measurement data is stored in the database which is monitored by the database system.

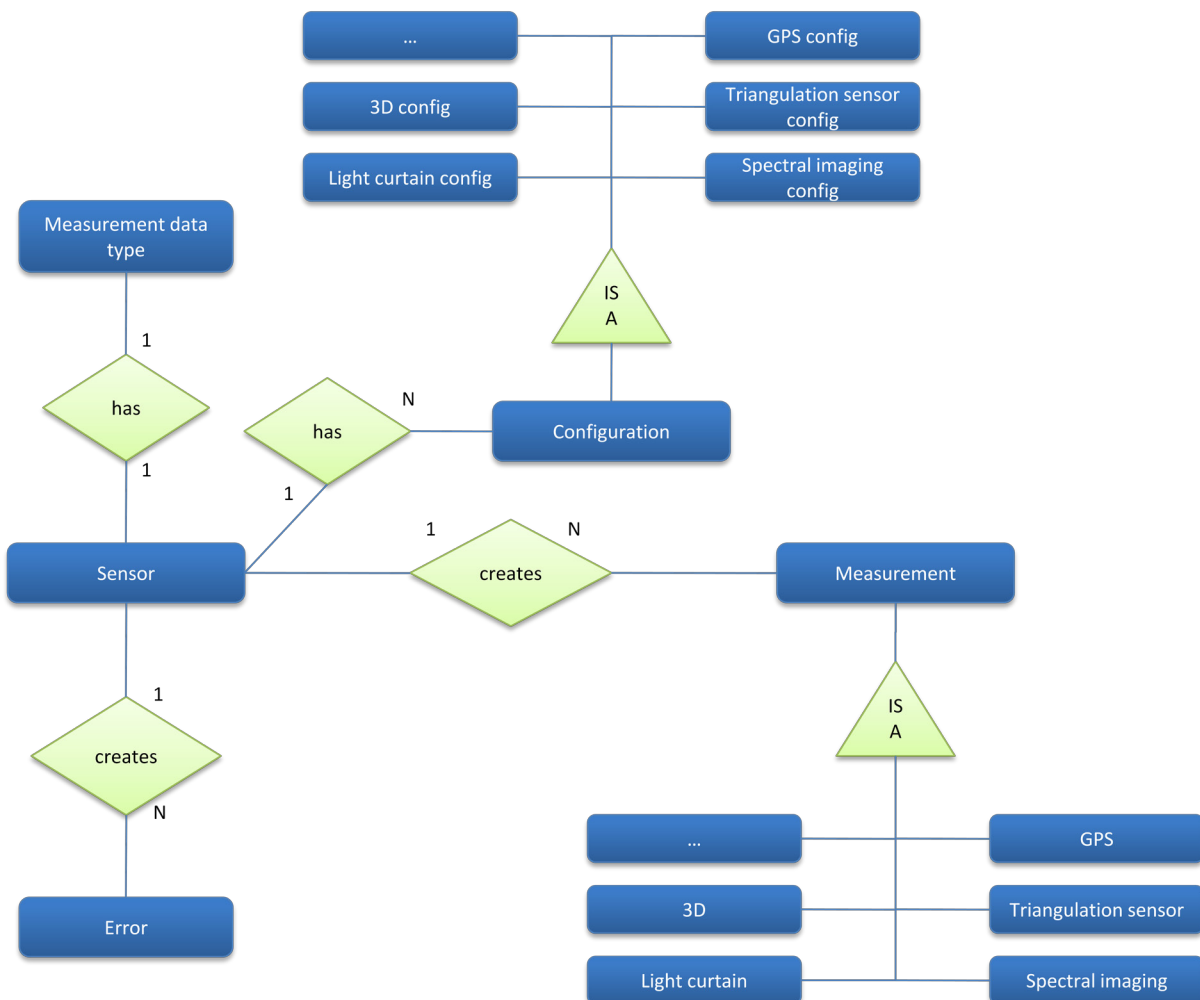


Figure 8: Entity relationship model of the database

5 CONCLUSION

A modular system structure for individual plant phenotyping with an autonomous field robot was developed. This system enables reliable online measurements using different sensor types with different interfaces, data rates, settings and data formats. The structure was implemented using decentralized embedded systems connecting the different sensors to a central database, using a central Gigabit Ethernet bus. This results in a flexible and extensible system, making it easy to include new sensors to the system, independent of its type and position, with a structured and consistent storing of the data. To have a standardized and transparent transmission of the measurement data from the embedded systems to the central data storage, an encapsulation using the XML-RPC protocol was implemented. Besides the transmission of the data, this protocol is also used to enable the user to configure the sensors attached to the system structure in a comfortable way. The synchronization of the data is performed using time and position stamps implemented into the XML data structure. With the usage of a database as a central data storage for the measurement data, the user is able to easily query the data for an offline analysis.

ACKNOWLEDGEMENTS

This work is part of projects supported by the Federal Ministry of Food, Agriculture and Consumer Protection BMELV (Germany) and the Federal Ministry of Education and Research BMBF (Germany).

REFERENCES

- Fender, F., Hanneken, M., In der Stroth, S., Kielhorn, A., Linz, A., Ruckelshausen, (2006) A.: "Sensor Fusion Meets GPS: Individual Plant Detection", Proceedings of CIGR EurAgEng/VDI-MEG, 2006.
- Montes, J.M., Melchinger, A.E., Reif, J.C. (2007): "Novel throughput phenotyping platforms in plant genetic studies", Trends in Plant Science 12
- Nagasaka Y, Zhang Q et al (2004) An autonomous field watching-dog robot for information collection in agricultural fields. Proc. ASAE Annual Meeting, no 043091.
- Ruckelshausen, A.; Biber, P.; Dorna, M., et al. (2009): "BoniRob – an autonomous field robot platform for individual plant phenotyping" JIAC 2009 Wageningen

Contact:

M.Sc. Dipl.-Ing. (FH) Ralph Klose,
Faculty of Engineering and Computer Science, University of Applied Sciences Osnabrück
Albrechtstr. 30, 49076 Osnabrück, Germany
phone: +49 (0541) 969-3164
fax: +49 (0541) 969-2235
Email: r.klose@fh-osnabrueck.de