Engineering Challenges and Approaches in Water Quality Monitoring Networks

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Abstract: Observed engineering challenges of developing water quality monitoring networks are presented in this paper and appropriate solution approaches are proposed. Water quality monitoring stations are important tools in the area of environmental water science that are used to collect measurement values. Because of missing plug-and-play support in prevalent field bus systems and lack of semantic information available in sensor devices, the installation and maintenance of monitoring stations requires much more effort than desirable form the perspective of engineers and users. An approach is proposed to reduce this effort by providing a catalog of predefined devices that contains all necessary semantic information. Finally, requirements for advanced field bus systems in the domain of monitoring automation are derived in order to encourage future improvements that minimize engineering effort.

Keywords: Monitoring Networks, Maintenance Engineering, Fieldbus, Profibus, On-line Sensors, Parameterization, Quality Control

1. INTRODUCTION

Water quality monitoring stations are important tools in the area of environmental water science. They are commonly used in practise to observe and record various properties of the water in rivers and sewage. The aim of these activities is to create a rich data base that can be used to derive knowledge and develop models of the dynamics of chemical and ecological water qualities.

The complexity of monitoring systems results in substantial development efforts for selecting the appropriate hardware as well as designing and implementing the station software. Care must be taken to minimize costs for installing, operating, and maintaining monitoring stations. When starting the realization of monitoring station concepts, several engineering challenges emerge inevitably, e.g. concerning the commissioning and parameterisation of field bus and sensor devices. These challenges are discussed in this paper in order to identify their reasons and present pragmatic solution approaches that have been developed to resolve these challenges. Finally, requirements for advanced field bus systems in the domain of monitoring automation are derived in order to encourage future improvements.

2. THE mon*EAU* PLATFORM

Initiated by immission-based legislation, (e.g. WFD in the EU or the TMDL approach in the USA) monitoring networks will be essential tools to monitor pollutants, to (better) understand the ongoing processes and finally improve the water quality of our water courses. Whereas the state-of-the-art is still stand-alone monitoring stations, ongoing research is focussing on the development of monitoring networks that integrate the information from different locations into knowledge about whole river basins (Strobl *et al.*, 2006). The development of monitoring networks instead of individual stations leads to new demands on bidirectional data exchange, i.e. various telemetry options, safety issues and accessibility.

Three major reasons limit the use of monitoring stations: a) the lack of standardization, b) data quality problems, which lead to data graveyards that do not provide the required information, c) insufficient flexibility of the stations being evaluated leading to problems when new sensors should be connected or when the focus of the project changes.

Our vision of the next generation of water quality monitoring networks is the mon*EAU* concept (monitoring of water, “eau” in French). Besides the focus on new data evaluation methods, this monitoring network concept combines state-of-the-art technology with the highest possible flexibility in terms of connectable sensors, measuring locations and monitoring goals (Rieger and Vanrolleghem, 2008). The mon*EAU* system will provide a high-level platform for all kinds of monitoring tasks, and eliminate the same design errors numerous other attempts have gone through. The flexibility of this new monitoring network concept enables different monitoring tasks and measurement locations.

However, the most important step forward is the advanced data quality evaluation concept helping to relate the measurements to the processes under evaluation and not to guesswork about data meaning. Most importantly, this evaluation concept will eliminate the danger of building more data graveyards.

2.1 Software

The heart of the mon*EAU* system is a robust software framework serving as the backbone of the stations and server network allowing the simple connection of various modules through a specified API (Application Programming Interface). Some modules provide basic functionality like data input or output but the main reason for this framework structure is the ability to integrate new developments or to connect third party modules. In this way, robust operation (the framework is not open to the end-users) is combined with the required flexibility. Fig. 1 shows the mon*EAU* concept.

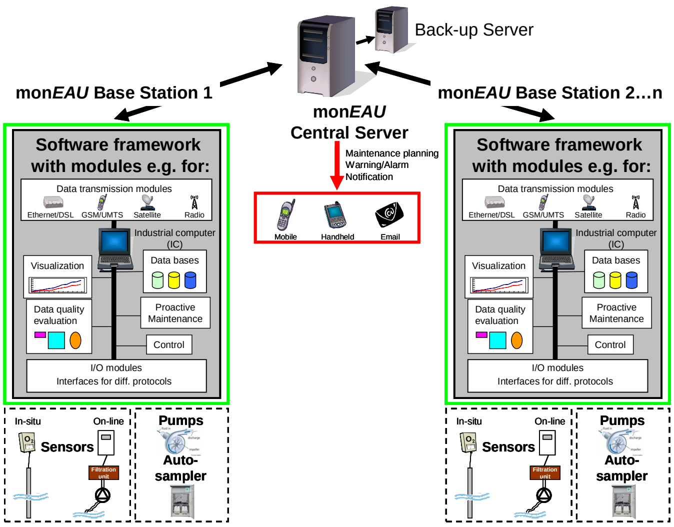

Fig. 1. Set-up of the mon*EAU* water quality monitoring network

2.2 Hardware

In the first step of the project, specifications were developed using the highest standards in terms of durability, robustness and data safety. As the mon*EAU* platform should be the same for all measuring locations, the set-up must consider all demands concerning space, energy, and environmental conditions. That is the basic unit (a box with computer and I/O units) will be the same, but the power supply, data transmission, and climate control options will vary so the station itself could be housed in a trailer or delivered as a stand-alone box, to be used directly with in-situ probes.

Sensors and actuators are not seen as part of the mon*EAU* system. The concept is to build the station flexible enough that all types of sensors and protocols can be connected. The base stations and also the central server are designed in a way that the connection of a new sensor triggers a procedure to provide storage capacity and standard visualization. Where possible, meta-data from the sensor (sensor configuration, dimension, measuring range…) is used to limit the required effort for the installation of new measuring devices. As plug-and-play is not feasible (due to standardization problems as discussed below), a list with pre-configured sensors will be made available to facilitate the connection of new devices.

As the most commonly used data transmission protocols (between sensor and base station) are provided, the user can select the best suited sensor for the application at hand, independent of specific monitoring station capabilities.

3. CHALLENGES AND ACHIEVABLE SOLUTIONS

In the current stage of the project the hardware setup of the monitoring station necessary for gathering the measurement values of the on-line sensors is solely based on PROFIBUS technology (IEC61158, 2007). This design decision is justified by the fact that many sensor manufacturers support this field bus in their products. But as PROFIBUS connectivity is not available for all sensors, the design of the monitoring station concept allows for the integration of any required communication option by means of software modules. The PROFIBUS related hardware inside of the monitoring station PC consists of a PCI card that acts as the PROFIBUS DP network master. The slave members of this network are specific transmitter devices that collect and refine the measurement values from their associated on-line sensors. Some transmitter devices are part of a PA sub-network (PI, 2004) that is transparently integrated into the main network with the help of a DP/PA coupler.

3.1 Fieldbus and Sensor Commissioning

From the perspective of the installation and maintenance engineer only a single field bus with plug-and-play support should be used for the monitoring station. The scenario of adding a new sensor transmitter to the bus should be very simple and in the best case involve just one step: The transmitter is physically connected to the bus by cable. Afterwards the new device is automatically available in the monitoring station software and all of its sensor measurement channels can be queried and read together with their associated quality and unit indicators. No prior device-specific configuration information is necessary for this as all required semantic information is available on the bus.

In reality there is no single communication technology that is supported by all important sensor manufacturers. Even worse some manufacturers do not provide any standardized connection or field bus integration for their devices but instead enforce proprietary methods that require tailored engineering solutions. The approach taken in the monitoring station software to cope with this kind of problem consists of abstracting various device access technologies and defining an interface that is used in the station software. This approach negates the need to use a particular access method (e.g. PROFIBUS) directly. For each access technology required by any supported sensor device a separate implementation of this interface must be created. These implementations are provided in the form of separate software modules (e.g. plug-ins) that can be dynamically loaded by the monitoring station on demand without rebuilding the entire software.

One particular implementation of the abstract device access interface currently available realizes PROFIBUS support. This field bus was chosen to be the primary communication technology for the monitoring station because it is supported by many sensor manufacturers and has gained wide acceptance in the automation industry. Based on experience from the first stage of the project, the integration and commissioning of new PROFIBUS devices requires much more engineering effort than would be desirable and possible compared to the ideal scenario outlined at the beginning of this section. Whenever the installation engineer wants to add a new PROFIBUS sensor transmitter to the bus, he first has to select a numeric identifier (the bus address) and assign it to the device, e.g. by adjusting a DIP switch or configuration menu inside the device. The engineer has to make sure that this identifier is unique across the entire network of PROFIBUS DP and PA devices either by maintaining a list of assigned identifiers or by checking the identifier setting of each device in the network. Depending on the sensor transmitter type an additional engineering step might be necessary that involves configuring the cyclic telegram, i.e. specifying which measurement values together with their state and quality indicators are placed in what order into the fixed-size data structure that is sent to the PROFIBUS master. On the PC side of the monitoring station further commissioning steps have to be taken. The newly added transmitter device must be included in the PROFIBUS configuration using a device-specific GSD file (Generic Station Description, PI 2003) that is provided by the manufacturer and contains the communication characteristics. Additionally, the unique bus address of the new device that has been previously assigned must be entered into the PROFIBUS configuration. If the transmitter device can provide multiple measurement values and therefore requires configuration of the cyclic telegram then the same structure (essentially the same number of bytes) must be repeated in the PROFIBUS configuration. This is because the syntactical information of the telegram can not be imported from the device but must be duplicated.

In the actual mon*EAU* station software the measurement data of PROFIBUS transmitters is eventually retrieved by using the standardized OPC DA (OLE for Process Control Data Access, OPC 1999) interface. The corresponding OPC server is made available by the vendor of the PCI card (PROFIBUS master). According to OPC DA the process values of devices, i.e. the measurements of the sensor transmitters, are referenced by a plain string that encodes the specific data location using a protocol-specific syntax. In the case of PROFIBUS and the selected PCI card, the numeric identifier (bus address) of the device and the byte offset relative to the start of the cyclic telegram are used to form the identifying string. The meaning and description of the accessible data items cannot be retrieved using this or any other interface because no such information is transmitted in the case of cyclic PROFIBUS communication. This lack of self-descriptive data access results in a semantic gap which in turn creates the need for additional configuration steps to be performed when using the station software. In order to bridge this gap the mon*EAU* station software is complemented by a *device catalog* that provides the necessary semantic information.

The device catalog is an XML file that describes the set of available devices that can be used to assemble the measuring part of a monitoring station. In this context the term “device” means a well-defined combination of transmitter (e.g. a PROFIBUS slave) and connected sensors. The relationship between the station configuration and the entities of the device catalog is shown using the simplified UML diagram in Fig. 2. The main part of the device catalog is the list of available device descriptions. Each of these descriptions references a device accessor that specifies the file and class name of the plug-in which contains the particular implementation (e.g. PROFIBUS via OPC DA) of the abstract device access interface described earlier in this section. The most important part of the device description is the set of measurement slots that it provides. In this context a slot refers to a named data item that consists of an address, data type and data dimension (size of data vector, usually one). The implementation of the corresponding device accessor is able to read the current value of a given slot using this information. In the case of PROFIBUS devices the address component is just a number that specifies the offset of the intended data inside of the cyclic telegram. Usually, the measurement values are associated with a certain unit. Therefore the set of all available units is specified in the device catalog in the unit group section. A unit group (e.g. “temperature”) defines a non-empty set of units that can be converted into each other. A single measurement slot may support several different unit groups, e.g. oxygen concentration and oxygen saturation, and may also support only a subset of all available units for these groups. Because of this each measurement slot contains a set of references to the supported unit groups together with the corresponding subset of supported units.

The part of the station configuration relevant for data acquisition is displayed on the right side of Fig. 2. The station configuration describes all variable aspects of the setup of a particular monitoring station, most importantly the installed transmitter devices and measurement channels. A measurement channel defines what sensor data shall be collected and how this collection is performed. When adding a new measurement channel, the input slot and device, that will be used to read the data, must be specified. The configuration of the devices used in a monitoring station is very simple and intuitive because the installation engineer only needs to select the appropriate device description from the device catalog and specify the address. In case of PROFIBUS the address is the unique numeric identifier (bus address) that has been determined during device installation. Additionally, it might be necessary to specify the configured unit and unit group of each input slot if the corresponding measurement slot supports more than one unit and unit group. The device catalog concept provides the missing semantic information for feasible composition and modification of monitoring stations by attaching meaning and structure to otherwise anonymous data items and thereby reduces configuration effort.

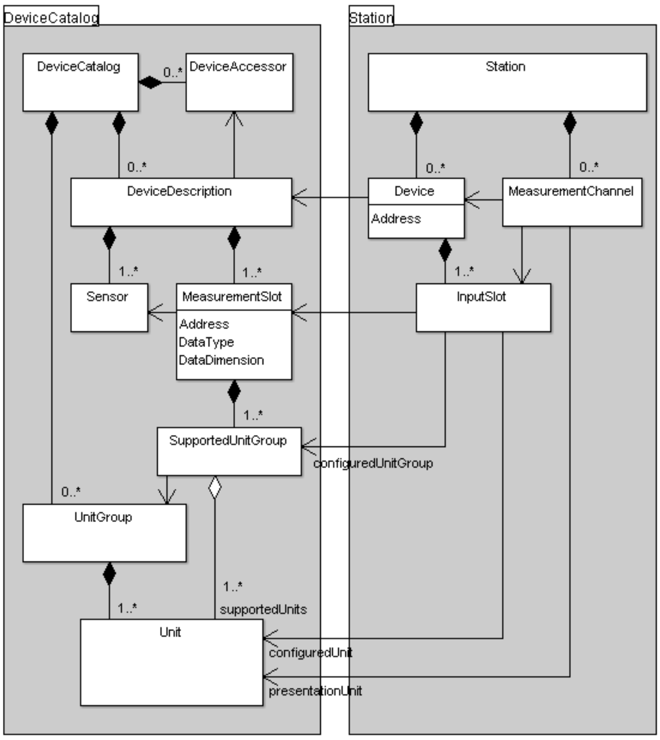

Fig. 2. Simplified UML diagram of station configuration and device catalog

3.2 Local and Remote Sensor Parameterisation

Apart from settings concerning the communication between devices and monitoring station there are many other parameters for sensors and transmitters that influence the measurements, e.g. slope and offset of linear correction functions and physical conditions like salinity of the water or altitude of the measurement location. For this reason the installation engineer must be able to perform parameterisation of the devices during commissioning and maintenance operations. Most sensor transmitters, which have been investigated for the monitoring station project, can be directly configured and parameterised using a control panel with display. However, there is still a need for a simple and uniform parameterisation facility on the station PC to minimize effort. In the best case all parameterisation can be done just by using the monitoring station software relying on standardized and automatable procedures. This would enable a simple and efficient implementation of remote parameterisation, e.g. from the central server. Another requirement for the station software in the context of parameterisation is that all modifications of the parameter values must be detected and saved to a log database. This is necessary for later data quality evaluation, since the sensor parameters potentially influence the measurement values.

So far there is no uniform parameterisation approach available for all kinds of field bus devices in general and sensor transmitters in particular. Even for PROFIBUS there are several competing parameterisation approaches with varying support amongst vendors. The most commonly used are FDT (Field Device Tool, FDT JIG 2009) and EDDL (Electronic Device Description Language, IEC61804 2006). Some vendors even employ proprietary alternatives for parameterisation, e.g. by providing a web frontend via local Ethernet connection. In case of PROFIBUS both the FDT and the EDDL approach are based on the acyclic data access using the slot/index addressing that has been introduced with the DPV1 standard extension. Because of this, any client software (e.g. monitoring station) is technically able to read and write single parameter values of any DPV1 compatible PROFIBUS device. However, some devices exhibit complex interdependencies between parameters and may require a certain write order. Moreover, semantic information needs to be attached to parameters as the meaning of values is not always self-evident. This is especially true for enumeration-typed parameters that are encoded using an arbitrary integer mapping. If all these difficulties were taken into account, a custom solution would essentially resemble major parts of the EDDL approach. Therefore, a fully integrated device parameterisation feature is not feasible for the monitoring station concept.

The consequence of these findings is that external tools have to be used for parameterisation. For convenience, these tools can be launched from within the station application. In order to meet the requirement of logging parameter changes, the current parameter values of all configured devices are read (if possible) and compared to the last known value after parameterisation has been performed and directly before measurements are started. For reading device parameters, detailed knowledge of parameters (e.g. address and data type) must be available. The actual meaning of the address depends on the device access technology being used for a particular device. In case of PROFIBUS reading parameters is realized using the acyclic services. Hence, the parameter address consists of four numbers: the slot and index information that refers to a certain data block and the length of this block as well as the offset of the value inside of the block.

Testing this approach revealed problems when reading acyclic data on different PROFIBUS sensor transmitters using the OPC DA interface: A DPV1-certified device rejected valid read requests if the queried data length was bigger than the length of the available data. The OPC server, which was provided by the vendor of the PCI card, always requested the maximum possible data length (240 bytes) ignoring the device restrictions given in the GSD file during configuration. This compatibility issue could be solved by avoiding the OPC approach for parameter reading and using a low-level interface of the PCI card. However, this workaround is vendor-specific and substantially increased implementation complexity. Another observed disadvantage of the vendor-specific OPC server is that device-level error messages are not moved up to the surface of the OPC DA interface. Therefore, special hardware equipment (e.g. bus monitor) and expert knowledge is necessary to investigate field bus problems.

The desirable remote parameterisation feature of the monitoring station can not easily be realized because device parameterisation is performed using external tools that usually do not consider remote parameterisation. A very simple but not always feasible approach is the use of VNC (Virtual Network Computing) tools for PC remote control or the Windows built-in Remote Desktop Services. The tools for parameterisation running on the station can then be started and operated from any PC. This is only possible if a TCP/IP connection with enough bandwidth is available for the station, which is not always the case. Another idea is based on the manual import and export facility that some parameterisation tools provide: The actual parameterisation can be done on any PC without the need of the physical devices. The parameters are then exported to a file and transferred to the monitoring station, e.g. by using the measurement transport channel. On the station side the file is imported by the corresponding tool, which writes the parameter values to the respective device. In practise, this approach is difficult to implement, since the parameterisation tools usually do not provide an automatable import interface that is required on the monitoring station side.

3.3 Measurement Quality Representation

Besides the raw measurement values, sensor transmitters typically offer additional quality and state information that need to be obtained and considered by the monitoring station for data evaluation purposes. Currently, there is no common standard for measurement quality representation applied by all sensor transmitters available on the market. When using the OPC DA interface (e.g. for accessing PROFIBUS devices), a simple quality indicator is returned together with a time stamp and the measurement value. But this quality only refers to the measurement value transportation from the sensor transmitter to the station and does not consider dedicated quality information offered by the sensor transmitter. For PROFIBUS PA devices the dedicated quality information is very similar to OPC DA and is commonly defined as part of the PA standard. The data type is essentially an enumeration of all possible values, each of which belongs to one of three main categories (Good, Uncertain, and Bad). Some PROFIBUS DP transmitters provide a different quality representation that is vendor-specific. It consists of a set of independent Boolean flags that indicate certain error or quality states. Therefore, several different indications can be given at the same time, e.g. “sensor error” and “calibration in progress”.

In the monitoring station concept a custom measurement quality representation is defined and appropriate mappings for the device-specific quality representations are included in the device catalog. The custom quality representation is an ordered enumeration of 49 distinct values forming a superset of the values specified in the PROFIBUS PA standard. Each of these values belongs to either the Good, Uncertain or Bad category in order to simplify evaluation. A quality mapping in the device catalog consists of a unique name, e.g. “PA”, the size of the source representation values and an ordered set of mapping entries. Every measurement slot in the device catalog contains a reference to the appropriate quality mapping and the address of the source quality representation. Each mapping entry is a triple consisting of a bit mask, an expected result signature, and the assigned value of the destination representation (see Fig. 3). The process of mapping a source value to a destination value is performed as follows: The list of mapping entries is run through and for each entry the bit mask is applied to the source value using the binary AND operation. If the result equals the corresponding result signature then the assigned value of the destination representation is returned, otherwise the next mapping entry is processed. This procedure ensures that multivalued quality indications are always mapped to a single value of the custom quality representation.

```
<QualityMapping name="PA" sourceValueSize="1">
  <MappingEntry
      mask="F0"
      signature="10"
      value="Bad_SensorError"
  />
  <MappingEntry
      mask="0F"
      signature="02"
      value="Uncertain_CalibrationInProgress"
  />
  ...
</QualityMapping>
```

Fig. 3. Example of quality mapping in device catalog

4. DERIVED REQUIREMENTS FOR ADVANCED FIELD BUS SYSTEMS

According to the experience gained during design and realization of the mon*EAU* station concept, the established field bus technology is associated with high engineering costs that appear unnecessary and disappointing from the user’s perspective. This section outlines requirements that advanced field bus concepts and devices should meet in order to improve the situation.

The most obvious requirement is the support of true plug-and-play and hot plug-in when connecting field bus devices. This involves automatic assignment of bus addresses to devices, similar to DHCP (Dynamic Host Configuration Protocol, NWG 1997) used in IP based networks. No device-specific configuration and no description files (e.g. GSD files) are necessary at the root of the network. Instead, all connected devices can be queried and provide a human-readable display name together with further attributes like meaningful description and vendor name.

The core requirement for reduced engineering effort is the availability of comprehensive semantic information. Every device connected to the field bus must provide all information that is required for its operation and control by the network root. In case of a sensor transmitter, the station can query the existing measurement slots and necessary details to process the values. All available data items (for input and output) are self-descriptive by containing various metadata like display name, description, data type, valid range, measuring unit, and quality indicator similar to PROFIBUS PA. The data items can be organised in a tree structure to reflect hierarchical relations, e.g. sensors and corresponding measurements. The realization of this requirement results in introspection and reflection features, as provided e.g. by the DOME approach for distributed software environments (Riedl, 2005).

The availability of comprehensive semantic information directly in devices eliminates the need for device catalog approaches and consequently minimizes engineering effort.

Semantic information is especially important for the parameterisation requirement: Similar to data items, all information about parameters (e.g. name, description, data type, and range of values) is provided by the device itself. Parameters are hierarchical organised to simplify navigation. Additionally, a formalized description of interdependencies between parameters is offered using a set of Boolean expressions (e.g. *Mode = 'Saturation' implies Unit = '%'*) that yield true only if the parameter assignment is valid. With the help of these expressions a parameterisation tool can automatically infer all valid modifications for a given parameter assignment. The consequence of providing all parameterisation information directly by devices is that no device-specific drivers (e.g. DTM in FDT) or external device descriptions (e.g. EDDL files) are necessary to perform any parameterisation. This is the last step to accomplish true plug-and-play functionality and also simplifies the realization of remote parameterisation.

In Table 1 the support of the six most important requirements by five established fieldbus systems are assessed. According to this comparison both PROFINET (IEC61158, 2007) as well as IO-Link (IO-Link, 2009) have better support for the desired features than PROFIBUS. Nevertheless, it was not possible to use these options for the mon*EAU* system because the important manufacturers of water quality sensors do not (yet) provide them for their devices. Apparently, none of the compared fieldbus systems have a decent support for the desired features. The reason for this is that the concepts of these fieldbus systems have been developed back in the 80s of the last century, when memory and computational power was very expensive. Therefore, very limited capabilities of the fieldbus devices were assumed, which in turn motivated simple protocols.

Table 1. Support of requirements by different fieldbus systems

	PROFIBUS	PROFINET	IO-Link	FOUNDATION Fieldbus	HART
Hot plug-in of new field devices	–	○	○	–	–
Automatic address assignment to devices	–	+	○	–	–
No need for device-specific config files	–	–	–	–	–
Semantic information for process values	○	○	○	○	○
Semantic information for parameters	○	○	○	○	○
Description of parameter interdependencies	○	○	○	○	○

5. CONCLUSIONS

In this paper the experience gained by designing and realizing the mon*EAU* system of water quality networks was presented. Several engineering challenges related to field bus commissioning and device parameterisation were identified and feasible solution approaches were presented: No single communication technology supported by all sensor manufacturers is available and field bus based solutions like PROFIBUS require much more engineering effort than necessary. This is caused by missing plug-and-play support and lack of semantic information offered, which also complicates device parameterisation. The presented approach introduced a device catalog that allows integrating new device access technologies via plug-ins and that adds all necessary semantic information for reading measurement values and parameters of specific predefined devices. The evaluation of measurements is enabled by defining mappings of device-specific quality indications to a common quality representation in the device catalog. Finally, derived requirements for advanced field bus systems with minimum engineering effort were outlined including true plug-and-play support and comprehensive semantic information available in devices, eliminating the need for separate configuration files.

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REFERENCES

FDT JIG (2009). FDT Interface Specification, Version 1.2.1

IEC 61158 (2007). Industrial communication networks - Fieldbus specifications - Communication Profile Family 3: PROFIBUS PROFINET

IEC 61804-3 (2006). Function blocks (FB) for process control - Part 3: Electronic Device Description Language (EDDL), Ed. 1.0

IO-Link (2009). IO-Link Communication, Specification, Version 1.0, Order No. 10.002

Network Working Group (1997). Request for Comments: 2131 - Dynamic Host Configuration Protocol

OPC Foundation (1999). OLE for Process Control - Data Access Automation Interface Standard, Version 2.02

PROFIBUS INTERNATIONAL (2003). Technical Guideline - Specification for PROFIBUS Device Description and Device Integration, Volume 1: GSD V5.0, Order No. 2.122

PROFIBUS INTERNATIONAL (2004). Profile for Process Control Devices, Version 3.01, Order No. 3.042

Riedl M. (2005). Distributed Object Model Environment. Ph.D. Dissertation, Otto-von-Guericke-Universität Magdeburg

Rieger L. and Vanrolleghem P. A. (2008). monEAU: A platform for water quality monitoring networks. *Water Sci. & Technol.*, 57(7), 1079-1086

Strobl, R. O., Robillard, P. D., Shannon, R. D., Day. R. L., and McDonnell, A. J. (2006). A water quality monitoring network design methodology for the selection of critical sampling points: Part I. *Environ. Monit. Ass.*, 112, 137-158