Trends in instrumentation, control and automation and the consequences on urban water systems

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Abstract In recent years more and more on-line sensors have been used on different structures of urban water systems (UWS, i.e. wastewater treatment plants (WWTP), waterworks (WW), sewer systems). This development is influenced and driven by numerous trends, which will be discussed in this paper. For a better understanding, the discussion is illustrated with a factual example. The new possibilities of on-line measurement and automation technologies will also change the way as UWS will be planned, built and operated.

Keywords Automation; instrumentation; on-line measuring devices; real-time control

Introduction

In recent years, an increase in the use of on-line measurements can be observed in the field of UWS. On the one hand, major reasons can be found in increasing requirements for (waste)water purification caused by higher environmental protection laws. On the other hand, technologies for instrumentation, control and automation (ICA) have become more powerful and less expensive. Modern WWTPs and WWs are complex systems with numerous actuators, sensors, status indicators etc. Consequently, ICA becomes more and more important. There are many other trends supporting the use and distribution of on-line instruments e.g. miniaturization of (electronic) components and the use of digital components resulting in lower cost of investment and operation. This report, will discuss those trends by means of a full scale WWTP: The considered WWTP is a small Sequencing Batch Reactor (SBR) plant (5,000 p.e.) in Germany and was put into operation in 2000. The plant consists of a primary treatment, one influent buffer tank, two SBRs, and one effluent buffer. This configuration is often used in Germany and/or Europe and the plant equipment is typical for some other modern SBR plants. Furthermore, the plants catchment area is typical for rural areas in Central Europe.

Trends in ICA on urban water systems

Trends in UWM supporting the use of on-line sensors etc

Higher environmental protection regulations and emission taxes. A major reason for an increased use of on-line equipment is the development of more rigorous environmental protection regulations. This is a global trend, which is caused by the fact, that clean water is an essential resource for human beings as well as our flora and fauna. Some countries (e.g., Germany) have already introduced emission taxes to create financial incentives for a reduction of environmental pollution. As a consequence of higher environmental protection regulations many sewer systems, WWTPs etc. must be built (or replaced by modern systems) all over the world in order to fulfil the standards.

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In general, modern plants are more complex, especially in case of biological nutrient removal.

Cost pressure. Many operators are under growing pressure to make their WWTP safer and more effective. The most critical processes, in terms of cost and quality of treatment, are biological and chemical nutrient removal. Continuously rising costs for energy and sludge disposal are the main driversfor the implementation of analysers and probes measuring NH_4-N, NO_3-N and PO_4-P in order to optimise and monitor those processes.

Remote monitoring of WWTPs, WWs etc. In most countries municipalities are still responsible for water and/or wastewater treatment i.e. most of the systems are operated autonomously. But, due to an increasing pressure of costs, more and more municipalities are working together or hand over the operation to specified companies. In this context the automation of (small) plants wins more and more importance. Many small plants are already operated automatically and are often unmanned. These plants are equipped with supervisory control systems, remote video cameras, numerous on-line devices; all these systems are connected to a management center. So, the staff comes only for routine work or in case of malfunction on the plant.

Integrated management. Due to an increased immission-oriented point of view, numerous monitoring stations for continuous river water quality monitoring (e.g., TN, TP, pH, DO) were installed; many other monitoring stations will follow. Many of these stations are connected to networks (e.g., river catchment area-wide). These systems can be used for only monitoring, early warning in case of pollution accidents, the observance of environmental standards etc.

Full scale example. The receiving water in the catchment area of WWTP Messel is sensitive like in many other rural areas. Consequently, despite the fact that this is a small plant, the official limits for the effluent concentrations, which are measured in a 2 hours composite sample (CS), were reduced constantly: BOD5 (until 2000: 25 mg/l, today: 9 mg/l), COD (until 2000: 110 mg/l, today: 45 mg/l), NH4-N (until 2000: none, today: 3 mg/l) etc. Therefore, it was necessary to build a new WWTP. Table 1 shows a comparison between the old (trickling filter) and the new plant, which is a complex technical system.

It is not as easy to run such a system efficiently. This particularly applies, because the plant is not permanently manned. The plant was fully automated and equipped with a modern supervisory control and data acquisition (SCADA) system and numerous sensors can be operated via remote control. As with most of the SBR plants worldwide, the plant was operated originally with a fixed time-based sequential control strategy (TSC). In order to improve the treatment efficiency and capacity, in 2003 the TSC was replaced by an integrated process-dependent sequential controller (IPSC), which is able to adapt the

Table 1 Characteristics of the old and the new WWTP Messel

	1975–2000	Since 2000
Principle	Trickling Filter	SBR
Purification efficiency	medium	very high
SCADA	none	state of the art
Actuators/Sensors, status indicators etc.	1/3	$>15/>50$
Complexity/Requirement on operators	low/low	very high/high
Control possibilities/Optimization potential	1/low	$\rightarrow \infty$/high

duration of the treatment steps to the current operating conditions (Wiese *et al.*, 2005a). Therefore, the plant was retrofitted with numerous on-line devices (Table 2). By using this IPSC the treatment capacity was increased by ca. 50%. The TN, NH_4-N and TP treatment efficiency is much better. The emission taxes could be reduced by app. 50%. IPSC is also able to reduce the total emissions from sewer system and WWTP: The number of combined sewer overflow (CSO) events per year could be reduced by 25%. The duration of CSO events could be reduced by 50%. Due to this, the county can refuse building a further CSO 550 m^3 storage tank. The results of an economic evaluation show, that the total costs of the IPSC are approx. 12,000 EUR/a cheaper than the costs of structural enlargements. This example shows, that because of the permanently and rapidly changing boundary conditions, the use of RTC can be already economically meaningful for WWTP with $<$ 10,000 p.e.

Trends in the field of on-line instrumentation for water and wastewater

More and more parameters can be measured. In recent years, instruments have been developed to measure a greater range of parameters. Today numerous chemical and physical parameters can be measured in water, wastewater and/or sludge continuously or quasi-continuously: probes and analyzers for carbon (total and/or dissolved organic carbon (TOC, DOC)), chemical and biological oxygen demand (COD, BOD), dissolved organic substances (SAC), nitrogen (NO_X-N, NH_4-N, TN), phosphorus (PO_4-P, TP), sludge characteristics (sludge level (SL), sludge volume (index) (SV/SVI), total suspended solids (TSS), turbidity, dissolved oxygen (DO), pH, Redox (ORP), temperature (T), electrical conductivity, alkalinity, chlorine, volatile fatty acids (VFA), flow rate, level meter etc. Furthermore, equipment is available to measure the biogas flow rate and composition, i.e. methane (CH_4), oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), hydrogen sulphide (H_2S); these devices are interesting for anaerobic treatment. So today almost all relevant chemical and physical parameters, which are necessary to control and monitor the treatment processes, to analyze the composition of most of the different material flows (i.e. in a WWTP: influent, effluent, excess sludge, biogas) can be measured continuously. Detailed information can be found e.g., in Spanjers and van Lier (2006), Winkler (2005) and Vanrolleghem *et al.* (2006). In contrast to this, until now it is only possible to measure few biological parameters on-line: the most important practical application is the use of on-line respiratory devices (e.g., Miksch *et al.*, 2005).

New measurement technologies and sampling methods

Dissolved oxygen. For many decades, DO was measured using electro-chemical principles. For a few years, it has been possible to determine the DO with an optical

Table 2 Investment costs (IC) and Costs for consumables (CC; i.e. parts subject to regular tear and fear, reagents etc.) in 2003 vs. 2005 for the online-monitoring equipment of WWTP Messel (each 2 devices, one device per SB reactor)

	IC 2003	IC 2005	CC 2003	CC 2005
NH_4-N photometers	23,000 €	17,600 €	4,400 €/a	2,650 €/a
Filter modules	10,200 €[1]	8,100 €	950 €/a	750 €/a
Sludge level probes	11,000 €[1]	5,900 €	200 €/a	200 €/a
TSS probes	7,200 €[1]	5,100 €	200 €/a	200 €/a
Universal controller	–	2,200 €	–	–
Total investment costs	51,400 €	38,900 €	5,750 €/a	3,800 €/a

[1]IC for controller units are included

method (e.g., Winkler, 2005). This method has several advantages (e.g., no more replacing of electrolyte → minimal maintenance; no electrode poisoning/ no dilution of the electrolyte → no drift).

pH, ORP. A superior technology for pH and ORP are differential probes. Due to a closed design, the reference system of the electrode (e.g., surrounded by a less soil-sensitive salt bridge) does not come into contact with the fluid. Consequently, no electrode poisoning can occur. The advantages of this technology are evident: minimal maintenance, longer service life, greater reliability. These electrodes can also be used for extreme applications; e.g. the authors successfully used differential electrodes for monitoring agricultural biogas plants.

TOC, COD, SAC. Measuring devices based on UV absorption (SAC) are used to determinate organic concentration calculating equivalence parameters (e.g., COD_{254}, TOC_{254}) based on defined correlations between absorbance and individual parameter. The advantage of this technology is that several parameters can be measured by a simple dip probe.

Nutrients. NO_3-N is still measured by process probes based on UV absorption. The simple handling and extremely short reaction time of these probes make them ideal sensors ("dip and measure"). For NH_4-N and PO_4-P inline and on-site analysers are increasingly displacing traditional process analysers, which require separate sample preparation and are dependent on very specific ambient temperature and humidity conditions, and therefore have to be housed in an analysis station, a container etc. These concepts provide maximum flexibility in the choice of measurement points, as analysers can be used just as flexibly as DO or pH probes, being especially important for optimisation of WWTPs.

State of the art sample preparation systems are based either on special membrane filtration or ion exchange membrane designed for use with the analysis instruments. Those membranes are integrated in the analysers so that response times have been considerably shortened. Another decisive advantage is that, thanks to short distance between sampling and analysis, errors associated with longer transportation paths (degradation processes) are eliminated.

The advent of micromechanics for exact dosage and mixing of liquid streams drastically reduced the instruments' reagent consumption. At the same time, peristaltic pumps were replaced by wear-free dispensing systems, thus reducing the frequency of maintenance.

Intelligent (smart) sensors. A measuring instrument for determining parameters like pH, DO, etc. formerly consisted of a sensor and a transducer, in which the essential signal processing took place. Due to the possibilities of digital signal processing, these traditional measuring instruments are going to be replaced by digital sensors, often referred to as smart sensors. Smart sensors contain the sensor itself together with the complete signal evaluation system, and send the higher order transducer a digital signal consisting of numerical value, unit and status signals. The advantage of this philosophy is that different sensors can be connected to a single, multi-channel controller. Thanks to interference-free digital signal transmission, the distance between sensor and controller is no longer important. Process analysers integrated into this concept are therefore regarded as straightforward sensors. The use of smart sensors can save up to 1,000 € per measurement parameter, as numerous sensors and/or process analysers can be connected to just a single controller. Moreover, a standardised controller can simplify the interchange-ability and inventory management of spare parts, thus reducing costs.

Network capability. The network capability of modern controllers enables distributed measurement points to be cost-effectively linked to each other to form a network. Each measurement point is equipped with a probe module, which is linked to the measurement point's sensors. All probe modules are connected together on a single bus cable. The whole network can be operated via a display screen connected to any one of the probe modules. The probe modules can optionally be provided with power outputs and relay contacts. The most economic arrangement, however, is to house them in a central control cabinet, i.e. where the signals are needed for control purposes. This reduces the amount of cabling needed and simplifies the start-up of all the sensors in the network. If necessary, the network can be connected to a field bus.

Data transmission/communication/service. Ethernet capability of modern controllers means that, if a WLAN is installed at a WWTP, all sensors and status signals of the network can be called up at any time from any part of the plant from a conventional mobile device or a pocket PC. By using GSM modules, measurement and status signals can be transmitted over long distances, all connected sensors can be remotely configured, and new software can be uploaded from a distance. Results can be sent by SMS or email. These far-reaching communication options create the conditions for new service and maintenance concepts, which are of special interest for smaller WWTPs.

Open systems/automation modules. Traditional controller have 0/4–20 mA current output cards for measurement signal transmission and relays that transmit high-value or low-value alerts and error messages. New-generation controllers also enable analogue and/or digital measurement and status signals to be read in. These can be mathematically linked with the measured values of the connected sensors to generate more signals or controlled variables (in much the same way as in a programmable logic controller (PLC), but more conveniently and without any programming knowledge). For example, a controller can register flow signals and quality measurements and use them to calculate the loading; if necessary, it can then trigger actuators via digital or analogue outputs. PID controllers designed specially for wastewater treatment processes are of particular importance for small plants. For example, it is now possible to parameterise a control program for intermittent denitrification, based on an oxygen sensor and a NO_3-N probe, conveniently and cost-efficiently on a controller.

Full scale example. WWTP Messel was retrofitted in 2003 with numerous on-line devices (Table 2). The on-line devices were part of a model series, which was introduced in the second half of 1990s. For almost each part of these analogous devices a separate type of controller was necessary; max. 2 measuring instruments could be connected to one controller unit. In 2005 the manufacturer introduced a new model series, which is based on digital components i.e. one universal controller can be used for all probes and photometers; max. 8 devices can now be connected to one controller. This is one of the reasons why the investment costs in 2003 were approx. 12,500 EUR (32%) higher than in 2005. The performance of the 2005 series is comparable (or in case of the NH_4-N photometer better) than that of the 2003 series. Furthermore, the costs for parts subject to regular wear and tear, reagents, maintenance etc. of the 2005 series (9,350 EUR/a; thereof approx. 3,600 EUR/a for labour costs) are significantly lower than those of the 2003 series (6,200 EUR/a; thereof approx. 2,400 EUR/a for labour costs), especially because the reagents consumption of the NH_4-N photometers was reduced by more than 50% (Table 2). This example shows impressively how significantly decreased the total costs for measuring devices during the last years. The following consequence results from this development: Less than a decade ago, the application of measuring devices for NH_4-N, NO_3-N, PO_4-P or similar parameters was only economically meaningful for larger WWTPs (>50,000 p.e.). Now, the use of this equipment is often even economically meaningful for WWTP with only 5,000–20,000 p.e. Because of the described trends it is probable that the break-even point will be further reduced.

Trends in the field of automation and drive

More powerful SCADA and PLC systems. Due to the rapid technical progress in electrical engineering modern SCADA systems and PLCs have become powerful tools. Today it is possible to implement even complex RTC strategies with hundreds or even thousands of variables. Modern systems were also designed according to the principles of PC-based automation, modularity, flexibility, scalability and openness i.e. many of these systems offer a broad range of communication channels (e.g., fieldbus, Industrial Ethernet), programming interfaces (e.g., VBA, C-Script), standard interfaces (e.g., Active-X, OLE, OPC), data-base interfaces (e.g., SQL, ODBC, OLE DB), add-ons (e.g., multi-user systems with Web clients; tools for operating and monitoring plants via Internet, a company intranet or LAN; audit trains; tools for signalling of faults by means of telecommunication) etc. i.e. the documentation and storage of measuring signals, the supervision of the measuring instruments etc. is much easier than a few years ago.

Field bus technology, Industrial Ethernet and Industrial Mobile Communication. The communication in automation is becoming increasingly direct, i.e. horizontally in all areas as well as vertically through all hierarchy and levels of automation. Due to this, field bus technologies (e.g., PROFIBUS) and Industrial Ethernet (e.g., PROFINET) will become more important in the field of ICA. The field bus and Industrial Ethernet approaches produce significant cost savings in design, installation and maintenance expenses over the old approach of point-to-point wiring. The principles of openness and standardization guarantee the supply of field devices etc. from many different vendors. Consequently, modern measuring devices are compatible to field bus and Industrial Ethernet standards i.e. project planning, commissioning and supervision of monitoring stations etc. with numerous measuring devices are simplified. Furthermore, industrial mobile communication (IMC) (e.g., based on IEEE 802.11 – Wirelesss LAN standard) becomes more and more important in different industries. Steinmetz *et al.* (2005) show that mobile information systems can also be helpful for the staff of urban water facilities e.g., with the help of these mobile devices it is possible to display all available information related to buildings and devices and/or work processes. These systems can also be helpful for maintenance etc. of measurement devices (e.g., pdf-file of operating manual, online order of spare parts via internet).

Adaptive and multivariable controller, artificial intelligence etc. Common control strategies in UWM today are still almost exclusively based on conventional controllers (e.g., two-position, P, PI and PID controllers); often manual intervention by the plant operators is also necessary. In plants with complex dynamics and structures these controllers are often overstretched. If plants should be operated close to the treatment capacity limit, while at the same time minimizing energy consumption and/or maximizing the treatment efficiency, the consideration of these boundary conditions in the controller strategy is absolutely essential. In these cases, it is necessary to use complex controllers, which are based on model predictive control, soft sensors, multivariable and/or multi-objective decisions and often artificial intelligence (AI).

Ful scale example. The plant is equipped with a modern SCADA and a powerful PLC; parts of the plant are equipped with a fieldbus. Thanks to these technical edge terms it was easily possible to realize the new RTC, which is based on more than 5,000 variables! Some years ago this would not have been possible. On a SBR-WWTP (20,000 p.e), which configuration and equipment is nearly identical to WWTP Messel, an IMC system was implemented in 2004 for less than 10,000 EUR.

Future trends

Controlling and benchmark, information society etc. Software for controlling and benchmark, which are widely used in numerous industries, are used up to now only seldom in UWM. But, in order to operate UWS economically and ecologically more efficiently, it is necessary to use these tools. Consequently, controlling and benchmark will become more and more important for UWM during the next decade. Therefore, the use of PC-based automation in combination with numerous on-line measuring devices is indispensable for the technical, economical and environmental controlling of the manufacture process “clean water”. Consequently, automation and control systems, on-line devices and IT & Business software in all areas and through all levels of UWS will be integrated according to principles of totally integrated automation (TIA) within the next two decades. This trend will benefit from another worldwide trend: the information society. In order to satisfy the rising information demand of the population, some countries and municipalities begin to develop web-based environmental information systems, where all available information from UWS, river monitoring stations are available for the public.

Transformation from information in knowledge. Approaches for optimization of UWM systems attract more and more attention, because of ecological and economic reasons. At this stage, methods and technologies from AI have been discovered to play an important role. Even though measuring and control technologies are improving, the problem of incomplete or missing data still (and will further) exists because many parameters are difficult (or expensive) to be determined or cannot be determined at all (e.g., biological parameters). Furthermore, in specific cases, the measured data might not be representative for the overall system. Therefore, it often happens that WWTP operators must control their plant or engineers must design UWS with their experience from past events rather than with sophisticated machines. When it comes to capturing and especially drawing conclusions from information, AI offers several powerful technologies, which have already proved their potentials in different industrial applications (see, e.g., Bergmann *et al.*, 1999). Nevertheless, AI methods are still not widely used in the field of UWM in practice until now. But, one can find some examples that show that the extensive use of AI in UWM could be very promising, especially in case of decision support systems (planning and operation), RTC, education etc. But, in the authors point of view two advances are necessary to reach this goal: first suitable machine learning approaches must be developed, which take the application and UWM domain specific characteristics into account. Second, the number of measured parameters must be further increased in order to improve the database and to acquire more process information, which can be converted then into knowledge.

Full scale example. In order to use the whole potential for optimization a control methodology was developed for WWTP Messel that is able to predict as early as possible the duration and composition of a cycle, which is necessary to achieve the required purification target i.e. the controller should be able to act and not only to react. The controller will work with Case-Based Reasoning (CBR), an AI method i.e. the controller bases its decisions on past events and situations captured in cases. Up to now, only a few components have been developed as technology demonstrators (e.g., prediction of the inflow flow rate, prediction of sludge settling curves). So far, this system works offline, i.e. the generated solutions are not to be returned to the PCS. Further information about this predictive controller can be found in Wiese *et al.* (2005b).

Development of biosensors. Until now it is only possible to measure few biological parameters on-line (e.g., respiratory), but many other parameters (e.g., amount of nitrifying bacteria, *E. coli* bacteria etc.) can be detected in the lab by using gene probes. But, because of the rapid progress in the area of biotechnology and bioengineering it is realistic to assume that within the next decade numerous different practical online biosensors will be developed, which can be used for monitoring (e.g., detection of a inhabitation of nitrifying bacteria) or control (e.g., filling of an emergency tank) (e.g., Okayasu *et al.*, 2006). Other biosensors can potentially be used for the estimation of kinetic parameters (e.g., yield, growth rate) of the biomass. This information could be used for example as input data for model-based predictive control.

Conclusions

Despite the fact, that the level of instrumentation, control and automation (ICA) of urban water systems was significantly improved during the last decade, the ICA level is still relatively low (especially in comparison with other industries); this particularly applies for small WWTP (e.g., in Germany 90% of the 10,000 WWTPs are smaller than 20,000 p.e.). The authors derive from the described trends that the ICA of UWS is only at the beginning and that there is a high potential for automation and online measurement in all areas and levels of urban water management. So, ICA will be one of the most important tasks in urban water management for the next two decades.

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