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An ontology-based approach for the instrumentation, control and automation infrastructure of a WWTP

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Abstract: The instrumentation, control and automation of wastewater treatment plants (WWTPs) is a key aspect to ensure good performance and lower operational costs. However, control systems are seldom interoperable and standard-compliant. In this paper, we propose a knowledge-based approach which decouples the description of the plants and their control strategies from their physical structure and instrumentation. In particular, we propose a semantic model based on ontologies, formalized using the W3C OWL2 standard. We have extended the Semantic Sensor Network and created a specialized representation of the WWTP domain, to provide a consistent description of instrumentation (sensors and probes), actuators and data acquisition systems. We show how this ontology can be used to model typical management actions, such as collecting samples or applying a control policy, and their outcomes.

Keywords: ontology; knowledge based control systems; wastewater treatment plants; IEDSS

1 INTRODUCTION

The optimal management of a wastewater treatment plant (WWTP) requires a continuous monitoring of the plant state. The biochemical processes taking place in the plant's tanks must be observed to ensure that the environment guarantees their maximum efficiency. A less than optimal process may result in the degradation of the effluent quality, possibly exceeding the limits set by the local legislation. On the other hand, preserving the ideal operating conditions does not only improve the yield of the treatment, but can also lower maintenance and energy costs [Olsson, 2012]. To achieve this goal, plant operators should collect samples from the plant regularly and analyze them to diagnose the actual plant's conditions and plan the appropriate control and maintenance actions. However, Instrumentation, Control and Automation (ICA) technologies provide the only cost and time- effective solutions Olsson et al. [2005], allowing to monitor a plant in near-real time and to act in a timely fashion. Recently, improvements in technology have lowered the costs of sensors, data acquisition systems and mechanical and electronic actuators, so that even smaller-scale plants can be instrumented with a reasonable cost/benefit ratio. Equipping the plants has allowed to implement a variety of diagnostic and control strategies, aimed at improving the process, preventing malfunctionings and reducing operational costs. These strategies are implemented within Environmental Decision Support Systems (EDSS), which combine methods from statistics [Yoo et al., 2004] and artificial intelligence [Luccarini et al., 2010] with varying degrees of success [Dürrenmatt and Gujer, 2012]. Most of the times, however, the control logic is either hardcoded into the devices that collect the data and command the actuators, or is implemented directly on top of

the interfaces provided by the devices themselves. The tight coupling between the control logic and the plant's equipment makes it difficult to port the controllers between different plants. Instead, if standards existed and were supported, the control strategies and the hardware could be deployed, replaced and upgraded independently. In fact, in a typical scenario, a manager responsible for multiple plants would like to apply policies based on the plants' class (e.g. traditional continuous flow, sequencing batch reactor, membrane bio-reactor, ...) and scale, rather than the specific type and brand of equipment installed in each plant. In this paper, we propose an initial step in the direction of the standardization of the interface between control systems and hardware. Our approach is based on semantic web technologies [Berners-Lee et al., 2001]: we have extended and combined the popular Semantic Sensor Network Ontology (SSNO) [Compton et al., 2012] and the Measurement Unit Ontology (MUO) [MUO, 2008] to create a new modular ontology, called OntoPlant. This ontology includes concepts and properties to describe the topology of a WWTP, its instrumentation and the data and policies that would be generated by the sensors and controllers. The ontology, instead, does not describe the processes themselves and the control logic. In fact, a semantic description of the former could be provided by the OntoWEDSS ontology [Ceccaroni et al., 2004], while the latter are better represented using other models such as business rules, decision trees or workflows [Sottara et al., 2012]. Our ontology, however, provides the concepts and the vocabulary which can be used both by human operators and the control systems to represent the data, the actions and the context where they are generated. In particular, we focused on four typical scenarios: i) describing the plant, ii) acquiring data automatically through the sensors, iii) acquiring manual samples to perform laboratory tests and iv) defining control interventions. We will use the scenarios to present the OntoPlant ontology and its architectural principles in Section 2, while in Section 3 will discuss how the concepts can be applied concretely to a real plant, using a pilot scale WWTP as a concrete use case.

2 MATERIALS AND METHODS

Pilot Plant The pilot plant, located inside the area of the municipal WWTP in Trebbio di Reno (Bologna), is fed with real wastewater and composed of a pre-denitrification tank (95 L), an oxidation tank (162 L), a secondary sedimentation tank (85 L). Three peristaltic pumps (for influent loading, internal and external recycle), a stirrer and a variable-flow blower are included. It is also provided with probes to measure pH, redox potential (ORP), NH_4^+-N , NO_3^--N in the anoxic tank and pH, ORP, DO, NH_4^+-N , NO_3^--N and Total Suspended Solids (TSS) in the aeration tank.

Ontologies An ontology "is a formal, explicit specification of a shared conceptualization" [Gruber, 1995]. The corpus of knowledge about WWTPs is a fitting candidate for such a conceptualization. From an operator's perspective, the concepts required to run a plant are relatively stable and well-defined, but the ability to share information is likely to be a more critical aspect. Usually, companies operating in the water treatment market manage several dozens (if not hundreds) of plants. The lack of a common framework to describe the plants and the data collected about their functioning limits a company's ability to operate and grow efficiently. In fact, multi-utilities such as Hera s.p.a. (<http://www.gruppohera.it/>) are progressively centralizing the management activities using remote control technologies, but the integration of the different local platforms often not designed for a distributed environment is currently a major issue. To create such a common ontology, we have chosen the OWL-2 DL language W3C [2012]. In addition to being a W3C standard, it has a number of other benefits. It can be consumed both by domain experts and machines, so it facilitates the development of knowledge-based software applications. It is designed for the (Semantic) Web, so it is compatible with a distributed environment. It is a formal language based on a fragment of first-order logic, which supports some types of automated reasoning such as the detection of inconsistencies or the classification of new data (in particular, the DL sublanguage provides a good compromise between expressivity and computational complexity). Finally, there exist a number of general purpose ontologies which can be reused in more specific domains such as the WWTP one. One of these "horizontal" ontologies is the SSNO, which provides the core concepts necessary to describe Sensors and Observations. All concepts are defined in a very broad sense. A Sensor is an entity which, through a Sensing process, observes the Property of some Feature of Interest in the context of an Observation. The SSN ontology, in turn, is built on top of the upper ontology DOLCE (ontologydesignpatterns.org/wiki/Ontology:DOLCE+DnS_Ultralite), which defines an even more general layer of abstraction. Among others, it defines concepts such as Agent, Event and InformationObject. The concepts in the SSN/DUL are too general to be used directly for the WWTP

domain, so we have created appropriate subclasses specifically for the description of treatment plants and their management.

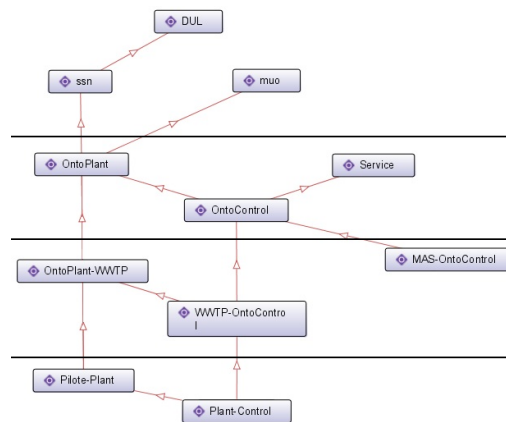


Figure 1. The OntoPlant ontology.

The OntoPlant ontology is actually given by the combination of four different modules, as shown in Figure 1. The first module, the OntoPlant core, serves two purposes. First, it imports both the SSNO and the MUO, which provides the concepts necessary to model quantities and measures. Second, it completes the SSNO, adding the notion of Actuators/Actuations and refining the model of the Devices. An Actuator is the dual counterpart of a Sensor: an entity which can influence the state of a Property: the context in which this action takes place is an Actuation. In general, even a human operator might qualify as a Sensor/Actuator: to model the hardware installed on a plant, we have defined the subclasses SensingDevice and ActuationDevice, respectively. Devices can be connected through Ports, which have Interfaces that provide the specification of their functionalities. A Port, in general, is an entity that allows the exchange of materials or information between an object and the external world. The exact nature and modality of this exchange is defined by the interface(s) exposed by the port. Notice that the OntoPlant module is still as much domain-agnostic as possible: the WWTP-specific concepts are introduced in a separate module called OntoPlantWWTP. This ontology defines the Plants and their macro-components (Tanks, Settlers, ...), the Processes that take place within the plant, such as the NitrificationProcess or the SettlingProcess and the Quantities of interest which are needed to observe the status of the processes.

3 RESULTS AND DISCUSSION

3.1 Case Studies

The OntoPlantWWTP ontology and its dependencies are intended to provide the background knowledge to create semantic models of WWTPs. Individual plants, their instrumentation, the samples acquired and the control actuations can all be represented as related individuals, instances of the classes and properties defined in the ontology. In particular, we have focused on four main use cases, which from our experience cover most of the routine requirements of a plant operator and/or an IEDSS trying to manage a WWTP, using, as a reference, the pilot plant introduced in Section 2.

UC1 : Plant Topology The main requirement is the ability to model the plant, its topology, the hydraulic pathways and the instrumentation installed on the plant itself. Using the concepts defined in the OntoPlant ontology, a Plant can have one or more PlantLine, a System with a number of Tanks. The description of individual plants can use more specific subconcepts. The Trebbo plant is actually an ActivatedSludgeWWTP with a single, traditional CASPlantLine composed by a DenitrificationPlant, a NitrificationPlant and a Settler. The sub Systems such as the Tanks are defined in terms of the

treatment Processes that take can place therein, including PrimaryTreatments, SecondaryTreatments such as Nitrification and Denitrification, Disinfection, WasteDisposal and so on.

The layout of the plant is described by the connections between the tanks. In fact, Tanks can have HydraulicPorts, a special type of Port whose Interfaces support the flow of liquids. Through the distinction between InputPorts and OutputPorts and their connections it is possible to define the complete topology of the plant. For example the NitrificationTank has three InputPorts and two OutputPorts. One of the input ports is connected to the output port of the DenitrificationTank, one is linked to the output port of the settler and the third is used to describe the internal recirculation. The two output ports model, respectively, the internal recirculation itself and the piping to the settler. Once the structure of the plant has been defined, it is possible to describe the plant's instrumentation. We distinguish several categories of Devices, but all devices are deployed in a particular System. Plants, PlantLines and Tanks are all subtypes of System, so a Device can be placed with the granularity that is appropriate, also depending on the accuracy of the knowledge about the plant. The Devices are then distinguished between mechanical devices, such as Blowers and Pumps, instrumentation devices such as Probes and electronic devices used to interface the instrumentation with the control software (including an EDSS). The notion of Port is instrumental in the definition of devices and their properties. For example, a Probe is a SensingDevice (which in turn is a Device) with a Port that exposes one or more MeasurementInterfaces. A measurement interface exposes the ability to measure some ChemicalQuantity (e.g. pH, concentration) or PhysicalQuantity (e.g. temperature, flow rate). The distinction between ports and interfaces is needed because modern probes are multi-function sensors which can measure more than a quantity at a time, and may expose the values through multiple channels in different formats. In a similar fashion, a device's port is considered an InputPort: some input ports, used to send commands to a controllable device are further classified as ControlPorts. For example, the hydraulic pump used for the internal recirculation in the plant's NitrificationTank has two input ports and one output port: the port used for the hydraulic intake, the port used for the hydraulic output and the control port used to regulate the rate. The latter, in particular, has two alternative interfaces: a manual interface, accessible through a display on the device itself, and an analogic interface that allows to set the number of revolutions per minute using an appropriate voltage. As always, ports allow to define connections, both between devices and the other (sub)systems such as the tanks or the pipes. Using these concepts, it is possible to define the instrumentation of the Trebbo plant, which is equipped with pH, redox potential (ORP) and temperature probes in the anoxic tank, and pH, ORP, dissolved oxygen concentration (DO), nitrogen (NH₄-N and NO₃-N) and suspended solids (TSS) probes in the aerobic one, three peristaltic pumps (load, internal and external recycle) and a blower. All analogic probe signals are sampled and acquired in current (4-20 mA) by a stand-alone data logger (Datataker DT80), at the rate of 1 sample/min, while all the actuators are regulated in current (4-20 mA), by an Advantech ADAM 5000 module, driven by the DT80.

UC2 : Manual Sample Collection The description of the plant enables a number of other use cases. A typical management operation is the collection of one or more samples in the plant's tanks. The samples are sent to a laboratory where routine chemical analysis are performed to check that the concentrations of the pollutants in the tanks are within the allowed limits. The OntoPlant ontology provides the concepts to describe the samples, the context in which they were acquired and the result of the analysis performed on the samples themselves.

The act of gathering a Sample is a specific type of Observation, a Situation taking place at a given TimeInstant, where a Sensor performs an act that has a result, in this case the Sample itself. A Sample is acquired in a CollectionPoint, which is located inside a (sub) system such as a Tank. The position of the collection point can be specified using the exact coordinates, or left undetermined. Using the OntoPlant ontology, the results of the analysis of the Sample can be modelled as well. In this second phase, the original sample itself is the subject of the Observation: the content of the sample is the FeatureOfInterest whose Properties are measured to obtain the desired QualityValues, expressed in terms of a quantity and a unit of measure, concepts taken from the MUO ontology.

This model is possibly redundant but accurate. Strictly speaking, the results are qualities of the sample rather than the plant. In fact, the model allows to differentiate between the time when the sample has been collected and the time the analysis have been performed, the method for the collection of the sample and the method(s) used for the analysis of each property, and the tools and actors involved in

the operations. This historical trace can be used to establish the provenance of the results and their degree of reliability, depending on the type of analysis that have been performed. For a result to reflect the state of the plant accurately, it is necessary that the sample is acquired from an appropriate location in the tank (modelled by the *CollectionPoint*), using an appropriate method (e.g. by pre-filtering the sample) and that the chemical analyses are performed in a timely fashion (modelled by the comparison of the *TimeInstants*) and suitable techniques. The automated assessment of the provenance of a sample and the validation of the result of the analysis may have technical and legal implications which will be the subject of future studies.

UC3 : Plant Equipment and Automatic Sampling Probes measuring quantities such as pH, temperature, and dissolved oxygen concentration require minimal investments, while more sophisticated sensors for quantities such as nitrates and other ammonia compounds are still more expensive, but manageable especially in large-scale plants. These sensors can potentially acquire a vast amount of data which, while useful to continuously trace the state of the processes, necessarily require some kind of automated management and large amounts of space for data storage. The advent of stable internet connectivity and, more recently, cloud-based solutions makes a centralized, remote management of the data a feasible option, especially when an organization is managing multiple plants.

However, this approach has to deal with two main challenges: the diversity of the instrumentation installed on each plant and the necessity to distinguish the source of the various data streams. The *OntoPlant* ontology has been designed to deal with both issues. First of all, it provides an abstraction layer that can be used to describe the various devices in terms of their functionality rather than the specific brand or technology. A *SensingDevice*, like other *Devices* has *Ports* that expose *Interfaces*, physical or logical, that can be connected or mapped respectively. *SensingDevices*, more specifically, are *Sensors* that can measure the *QualityValues* of one or more *Properties* directly. The measure is an instantaneous *Observation* performed by the probe using the methodology built in the probe itself. Unlike a manual sampling, there is no need to create an explicit *Sample* since the two steps (collection and analysis) usually coincide. However, probes are installed in a *CollectionPoint*, so that the provenance of the results can still be established. The values computed by the probes are accessible through at least one of their *Interfaces*, which models the endpoint of the concrete communication channel used to acquire or download the data.

From a data acquisition system's perspective, the ontology allows to describe the context where a "number" is generated, so the values can be completely qualified even in a distributed environment. If URIs are used to denote individuals, as recommended by the standard, the risk of ambiguities is removed. The linked and graph-oriented nature of the semantic data model allows to decide how much data should be shared between two endpoints so that both can share the same information. In particular, if a data acquisition system installed locally on a plant and a remote data center share the same description of the plant, as per the first use case discussed, it is merely sufficient to communicate the *QualityValues* acquired by each probe to keep the two systems synchronized, thus minimizing the amount of network traffic.

UC4 : Control and Actuation The approach used for the data acquisition can be reversed and adopted for (automated) control. Most plants allow for some form of control over time: the change of a recirculation rate or the amount of air blown in an oxidation tank are two basic and common examples. However, control policies are usually defined in terms of a target goal (e.g. the nitrogen compound or the oxygen concentration in a tank) and a manipulation variable (e.g. a pump's rpm or a blower's flow rate). A logical command such as "*set the pump speed to 20rpm*" has to be translated into a specific signal delivered to a specific channel which is normally device-specific. The *OntoPlant* ontology allows to decouple the two steps: the high-level commands can be formulated in terms of *Actuations* the dual counterpart of an *Observation*, which set the *Property* of a *Device* to the desired *QualityValue*, as always expressed by a unit/value pair. In particular, the actuation is targeted to an *Interface* exposed by a *Port* of the device. The semantic representation, as always, leverages the description of the plant and its equipment, also defined using the concepts in the ontology. The abstraction provided by the developed semantic model allows to decouple control policies from hardware configuration (Figure 2). The control system, regardless of whether it is an interface for an operator or a full EDSS, can issue the commands in a format which is independent of the specific device, but is focused on the desired functionality. The assumption is that local equipment is enhanced with a device-specific driver that can

parse the semantic request and translate it into the appropriate signals on the appropriate channels. The advantages of this approach are twofold: the original command is expressed using terms more standard and familiar to the domain experts, so the development of controllers and their logic could be simplified; moreover, the dependency on the actual devices is pushed as close as possible to the device itself, so that it is easier to replace or upgrade them.

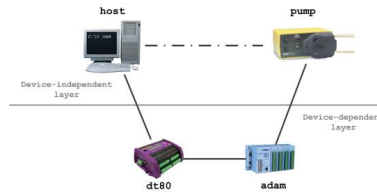


Figure 2. Semantic model.

3.2 Discussion

The current version of the OntoPlant ontology is an OWL2-DL modular theory with 234 classes, 53 object properties and 14 data properties. The ontology is still being developed, so the figures are subject to change. It leverages popular ontologies such as the SSNO, but is one of the first examples of its kind specifically targeted at the development of WWTP EDSS focused on the monitoring, control and optimization of the plant's performance. To be used effectively, plants should be modelled using the concepts defined in the ontology, creating a standard and shareable representation of their structure and equipment. This description, together with the remaining concepts in the ontology, allows to implement a variety of other use cases. First of all, it can help manage the vast amount of data that can be potentially acquire from one or more plants, allowing to explicitly define the semantics and the provenance of the values. Second, it allows to decouple the management policies from their concrete application to the specific plants. This is a critical aspect in the realization of portable EDSS, which would otherwise have to be developed for explicit combinations of plants and equipments. Instead, the policies which are usually implemented by EDSSs are likely to be expressed in general terms, such as "The value of concentration of nitrates in the effluent of a large-scale plant near a safety-critical zone must not exceed a given threshold". Using an ontology that contains the appropriate definitions, similar constraints can be implemented directly using the vocabulary provided by the ontology itself, leaving the task of performing the appropriate translations and matches to the underlying reasoning components embedded in the EDSS. In our case, a policy such as the one presented could easily be expressed in terms of the *QualityValue* of a *Property* (the concentration of nitrates) acquired in a *CollectionPoint* located downstream a *Settler* that is part of a *Plant* with a certain person-equivalent attribute value. The OntoPlant ontology can thus become an important component in the implementation of an EDSS. It provides the vocabulary to unambiguously describe a plant and its equipment, in a way that is shareable between human operators and EDSS. The semantic description can also be indexed and queried using languages such as SPARQL or SQWRL, enabling the feasibility of a plant "directory", where multiple plants are cataloged. More generally, the ontology would allow to use graph databases to store and possibly share environmental data. In such as format, the data can be queried and processed using techniques based on DL reasoning in addition to business rules, which are more traditionally adopted in knowledge-based EDSSs. A detailed discussion on the implementation of an EDSS based on the OntoPlant ontology goes beyond the scope of this work, even if a preliminary analysis can be found in Sottara et al. [2012].

The OntoPlant ontology is currently available at <https://github.com/sotty/OntoPlant>

4 CONCLUSIONS

We have proposed a new ontology, OntoPlant, that models WWTPs from the perspective of a plant operator. The ontology is modular and is built on top of preexisting upper ontologies, which facilitates

its extension and integration in other systems. The ontology serves several purposes. First, it is an asset that provides the concepts and the vocabulary to formalize a domain expert's knowledge about plants and their management policies. Second, it allows to express the knowledge in a format that is interoperable and shareable between different plants and their automated control systems. In fact, it allows to decouple the control policies from the setting-specific details, which depend on the particular devices installed on a plant at a given time. Last, as a machine-readable representation, it facilitates the development and the integration of monitoring and control softwares required by a modern plant. In particular, it is designed to model and implement the monitoring and control and policies necessary to optimize the operation of a plant. The ontology is currently being used to model a pilot-scale conventional activated sludge (CAS) plant and its agent-based Intelligent Environmental Decision Support System (IEDSS).

REFERENCES

- Berners-Lee, T., Hendler, J., and Lassila, O. (2001). The semantic web. *Scientific American*, 284(5):34–43.
- Ceccaroni, L., Cortés, U., and Sánchez-Marrè, M. (2004). Ontowedss: augmenting environmental decision-support systems with ontologies. *Environmental Modelling & Software*, 19(9):785 – 797.
- Compton, M., Barnaghi, P., Bermudez, L., Garca-Castro, R., Corcho, O., Cox, S., Graybeal, J., Hauswirth, M., Henson, C., Herzog, A., Huang, V., Janowicz, K., Kelsey, W. D., Phuoc, D. L., Lefort, L., Leggieri, M., Neuhaus, H., Nikolov, A., Page, K., Passant, A., Sheth, A., and Taylor, K. (2012). The SSN ontology of the W3C semantic sensor network incubator group. *Web Semantics: Science, Services and Agents on the World Wide Web*, 17(0):25 – 32.
- Dürrenmatt, D. and Gujer, W. (2012). Data-driven modeling approaches to support wastewater treatment plant operation. *Environment Modelling & Software*, 30:47–56.
- Gruber, T. R. (1995). Toward principles for the design of ontologies used for knowledge sharing. *Int. J. Hum.-Comput. Stud.*, 43(5-6):907–928.
- Luccarini, L., Bragadin, G., Colombini, G., Mancini, M., Mello, P., Montali, M., and Sottara, D. (2010). Formal verification of wastewater treatment processes using events detected from continuous signals by means of artificial neural networks. case study: Sbr plant. *Environmental Modelling & Software*, 25(5):648–660.
- MUO (2008). Muo ontology: <http://idi.fundacionctic.org/muo/muo-vocab.html>.
- Olsson, G. (2012). ICA and me – a subjective review. *Water Research*, 46(6):1585–624.
- Olsson, G., Nielsen, M., Yuan, Z., Lynggaard-Jensen, A., and Steyer, J. P. (2005). *Instrumentation, Control and Automation in Wastewater Systems*. IWA Publishing, London UK.
- Sottara, D., Bragaglia, S., Pulcini, D., Mello, P., Giunchi, D., and Luccarini, L. (2012). Ontologies, rules, workflow and predictive models: Knowledge assets for an EDSS. In R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.) (2012): *International Environmental Modelling and Software Society (iEMSS) 2012 International Congress on Environmental Modelling and Software. Managing Resources of a Limited Planet: Pathways and Visions under Uncertainty, Sixth Biennial Meeting, Leipzig, Germany*. <http://www.iemss.org/society/index.php/iemss-2012-proceedings>. ISBN: 978-88-9035-742-8.
- W3C (2012). W3c recommendation 11–12–2012: <http://www.w3.org/tr/owl2-overview/>.
- Yoo, C., Lee, D., and Vanrolleghem, P. (2004). Application of multiway ica for on-line process monitoring of a sequencing batch reactor. *Water Research*, 38(7):1715–1732.