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An ontology framework for decentralized water management and analytics using wireless sensor networks

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ABSTRACT

The implementation of decentralized water management (DWM) systems as a mainstream practice is impeded by the knowledge gaps on their actual performance in a range of development types and settings. On the other hand, wireless sensor networks (WSN) provide a capable platform for low cost, high performance and real-time monitoring. By bringing together the strengths of WSN technology and distributed, reactive, knowledge management and representation, implemented as a dual-layer ontology framework, this work provides a holistic approach to the management of DWM systems. Low-level real-time knowledge such as sensor observations (water consumption, water quality and soil quality) is represented directly in the ontology while high-level knowledge, e.g. about scheduling precision irrigation and about meeting grey water demand in the household, is inferred through low-level knowledge by means of rule-based reasoning. Ultimately, the proposed system aims to: *control* the grey water reuse process, *detect and react* to any failures and unusual events (e.g. floods, bursts, pump failures), *analyze and improve* the efficiency of water reuse, and *predict* the optimal time for maintenance, thus improving system availability.

Keywords: Sensor networks; Grey water; Smart sustainable home; Pilot; Water reuse; Real-time analytics; Ontology; Knowledge management, rule-based reasoning

1. Introduction

The current context for decentralized water management (DWM) technologies such as grey water recycling, rainwater harvesting, sustainable urban drainage systems, and their combined application offer feasible ways of rationalizing existing regimes of water usage (tap water, grey water, rain water) through the use of appropriate technologies which scale down and localize the management of water [1].

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Yet, at present, such systems hold an uncertain status and are frequently omitted from consideration, which is caused by lack of available information on their actual performance in a range of development types and settings [2]. As the widespread uptake of these approaches in modern cities is relatively new compared to centralized approaches, there is limited information available on their planning, design, implementation, reliability and robustness.

Over the past decade, advances in the semiconductor industry, wireless communication, sensor design and energy storage technologies have helped realize the concept of a truly pervasive wireless sensor network (WSN) [3]. Integrated microsensors, no more than a few millimetres in size, with onboard processing and wireless data transfer capability are the basic components of WSN nodes. WSNs organize nodes in a network topology that enables data observations to be collected, aggregated online and ultimately forwarded to a designated data sink. Topologies may also be hierarchical, in that more powerful nodes are responsible for the collection and aggregation of data, as it flows through the network. This is known as in-network processing. The main benefit of the application of WSN in the home domain is the generation of accurate, real-time information at high granularity and low cost about water uses in the home. This information can be further analysed by appropriate information systems in order to provide insights about the feasibility and effectiveness of the DWM approach.

In order to realize the above vision, a very large heterogeneity of sensor technologies are available, ranging from high-power industrial sensors, to mid-power devices such as Arduino [4] and Raspberry Pi to very low-power mote-like devices such as Waspmote and Crossbow sensors [5]. Low-power wireless communication represents by itself a major research topic for the WSN community and a great research effort has been done in the recent years. Three main proposals emerged from such an effort: IEEE 802.15.4 that is based on WiFi, 6LoWPan that is based on IPV6 and ZigBee that is proprietary. However, a number of other open and custom communication protocols are available and their support varies from vendor to vendor. The same applies to sensor and node technology that is not standardized. Furthermore, information in the distributed water management domain can be collected by *in situ* observations by reuse of geospatial or web-enabled linked data (LODC) and by the use of remote sensors. This disparate data will need to be integrated in order to be used and analysed, in order to generate decisions. Such decisions can support the match between grey or green water supply with water demand in the home or in the neighbourhood while minimizing energy consumption. Another objective that pertains to DWM is the efficient and effective use of processed grey or green water in garden irrigation systems; soil moisture and humidity measurements can be used in order to determine both the optimal time and minimal volume of water that is needed for irrigation so that only the amount of water that has evaporated is replenished automatically. This is known as precision irrigation.

Considering an analogy from the water supply chain domain, analysis is undertaken by a variety of information systems, e.g. decision support systems (DSS) [6], demand management systems (DMS), smart grid management systems and integrated water resource management systems (IWRM). Although several instances of the above systems exist already in the water supply chain domain, they are still in their infancy at the home domain. The ICT community has however developed several smart home and smart cities WSN systems and tools that can be built into useful solutions for DWM-enabled *smart sustainable homes* [5]. What is still missing is a reactive, distributed knowledge management and reasoning framework for DWM operations. This must be addressed in a systematic way taking advantage of current ICT knowledge.

The above vision is impeded by data heterogeneity that arises when trying to integrate disparate data from different resources. Data heterogeneity can be semantic or syntactic. *Syntactic heterogeneity* refers to different formats of data representation and storage, i.e. use of text files, databases, knowledge bases, data warehouses, repositories or spreadsheets. *Semantic heterogeneity* refers to difference in perception and expression of similar terminology. Semantic heterogeneity can be further classified into (1) structural—e.g. language used to describe the names of the observation attributes; and (2) contextual—e.g. the language to encode observation attributes values. Syntactic heterogeneity can be overcome using standardized languages such as WaterML [7], EML, etc. and semantic heterogeneity can be overcome by building a common knowledge base for the systems that need to be integrated. This can be achieved using ontologies, i.e. a set of representational primitives, typically classes (or sets), attributes (or properties) and relationships (or relations among class members) with which to model a domain of knowledge or discourse [8]. Several ontologies have been developed for the water supply domain; however, none of them take into consideration DWM requirements (see Section 2).

In the smart sustainable home, the primary source of information is real-time data, i.e. raw observations that can be generated as often as few times per second, depending on the application requirements. This is a significant change from the earlier technology of smart meters that are only capable, in the best case, of 15-min interval measurements. Furthermore, smart meters depend on an very expensive infrastructure of collectors and repeaters that integrate the data so that they can be used by the water managers. Last, even when communication is two-way, as is the case in the recent implementations, there are limited actions that can be taken remotely at the smart meter level (e.g. start, stop and change sample rate), which only affect the main water source in the home. On the other hand, modern sensor networks are capable of various actuations that can be applied at the appliance level [5].

Several information models exist in the ICT community for real-time data, such as event-based communication and semantic web services, i.e. service-oriented architecture (SOA) enriched with semantic information. An *event* [9] is a happening of interest that occurs instantaneously at a specific time. The authors introduced in a previous work [10] the notion of an *abstract event* as a change in a logic predicate's state from TRUE to FALSE or vice versa [11]. Events and services can be integrated programmatically by means of event or service composition, respectively. For this reason, several ontologies exist in the literature for dealing with interoperability and service composition both at the raw data and the semantic service levels. However, none of these works integrates sensor observations with events while modelling the grey water cycle in the home and its interaction with DWM components (Section 2).

On the other hand, the recent emergence of Semantic Sensor Web (SSW) has produced the Semantic Sensor Network (SSN) ontology [12] as a standard for describing the Stimulus-Sensor-Observation pattern in WSNs. However, SSN does not "understand" DWM concepts nor does it support abstractions for event-based interaction.

We propose a new ontology, DiHydro, which is appropriate for the DWM-enabled sustainable smart home. DiHydro extends the SSN ontology with concepts from the DWM domain, i.e. sources (*grey water*, *green water*, *black water*), *sinks—water uses* (*flushing, irrigation, laundry*), *transformation elements* (*treatment units*), management concepts (actuations, alerts, *suggested actions*). This enables an alignment of sensor observations with DWM parts, allowing for better understanding of the current state, for validating suggested actions that can be assigned to specialized roles and for designing new strategies. For example, by analysing all the events where the grey water tank had to be topped up with fresh water, the householder may conclude that the demand for grey water is higher than the supply, or that its quality degrades by being left too long in the tank. The householder can then think of ways to overcome this. This may not be the case for the green water tank, indicating that there is ample green water compared to grey water shortage.

DiHydro also extends SSN with real-time analytics (e.g. *real_time_water_balance*) so that high-level information that may be derived from analysis is associated with low-level observations. Furthermore, it extends SSN simulating event-based abstractions (*input*, *output*, *topic*, *publisher*, *subscriber*) and with logic rules for defining situations (abstract events) of interest, e.g. garden needs irrigation (x, y). A special case is that of representing distributed topologies of sensor networks, i.e. connecting a sensor node directly with an actuator node rather than going via the gateway, leading to savings in battery resources. Last but not least, DiHydro *extends SSN* with reactive system concepts such as *Node* and *Actuator*, with units and with temporal elements.

2. Literature survey

Section 2 reviews existing ontologies and knowledge bases related to the WM or smart home domains as well as previous related works. These works can be classified into the following categories:

(1) Ontologies which attempt to represent the knowledge of hydrologic cycles.
(2) Ontologies that represent the urban wastewater system.
(3) Ontologies for sensors.
(4) Ontologies that represent the smart home.
(5) Non-ontological resources.

2.1. Ontologies which represent the knowledge of hydrological cycles

The *Hydrologic Ontology for Discovery* was developed by CUAHSI in order to assist in their effort to compile a national water information catalogue that would incorporate information from numerous and disparate water databases. It supports the discovery of time series data collected at a fixed point, including physical, chemical and biological measurements. These time series could then be served on Water Markup Language (WaterML), the current OGC standard for water information interoperability which was developed as a continuation of WaterML.

CUAHSI is implemented in the Ontology Web Language (OWL). It is composed of around 6,500 concepts that are subdivided in three layers—Navigation, Compound and Core/Leaf. The root concept "HydroSphere" includes elements such as *land*, *atmosphere*, *surface* and *groundwater* and related resources such as *water/soil quality* that are further elaborated by concepts such as "Physical parameters" and "biological parameters".

The main weakness of the CUAHSI ontology is that it was developed only to discover data and covers only the hydrologic aspects of the water information cycle. Also the ontology does not have properties defined so it has low expressiveness and all the connections are parent-to-child such that no knowledge can be inferred.

The *Semantic Web for Earth and Environmental Terminology (SWEET) Ontology* [13] has been developed by NASA's Jet Propulsion lab for Earth system science and has been used by the MMI project to promote the exchange, integration and use of marine data by the GEON6 (GEOsciences Network) project for integrating three- and four-dimensional earth science data and by the IRI (International Research Institute for Climate and Society) in order anticipate and manage the impacts of climate.

The SWEET ontology is highly modular with 6,000 concepts in 200 separate ontologies implemented in OWL and it has been constructed over eight top-level ontologies: (i) representation; (ii) process; (iii) phenomena; (iv) realm; (v) state; (vi) matter; (vii) human activities; and (viii) quantity.

The ontology is general and is not specific to a concrete project, making it more reusable; however, in some cases, this makes it ambiguous. There is minimal detail with respect to the hydrographic cycle. The concepts or terms used in the ontology are populated with instances, which makes the ontology heavy and causes high memory consumption. Finally, the ontology cannot handle sensor observations.

2.2. Ontologies that represent the water supply distribution chain

The *Towntology & hydrOntology* [14] are two linked ontologies which have been developed by a semantic group of the Universidad Politécnica de Madrid in order to support urban civil engineers in urban design and planning. hydrOntology, developed in OWL and written in Spanish, models urban infrastructure and represents water supply, distribution and treatment elements. With regards to this aspect, environmental concepts (rivers, lakes, etc.) have been linked with artificial concepts related to water supply (piping, sewer system, etc.). hydrOntology abides by definitions of the National Spanish Institute of Geographic (IGN-E), the Defense geospatial Information Working Group (DGIWG) and the Water Framework Directive (WFD).

hydroOntology's main weakness is that it focuses on a small part of the water supply distribution chain and that it is limited to the Spanish scenario. It also needs an improvement over ontological resources such as properties, rules and axioms [15].

The *Water Management Ontology* or *WatERP ontology* has been created in order to provide interoperability between loosely coupled software applications and/or data sources, as is being proposed in the WDSS [6] and WatERP [16] projects. The novelty of the WatERP ontology over previous developments lies in its inclusion of man-made infrastructure elements (e.g. water management sources, transport, storage and transformation elements), actors, observations, actions and water uses. Doing so enables them to be linked to the natural water flow processes such that the interactions among natural and human made entities can be better understood, ultimately enabling improvements and new strategies for water resource management.

This knowledge representation is supported by a data provenance mechanism including concepts and standard terms provided by other ones, such as the NASA, CUAHSI, OGC and World Wide Web Consortium (W3C) ontologies. Moreover, the WatERP ontology is compatible with Linked Open Data Cloud (LODC) permitting resources to be accessed by a URI and linked with other elements. Linked Data is a set of best practices for publishing and connecting structured data on the Web using URIs, HTTP and RDF (a generic graph-based data model with which to structure and link data that describes things in the world).

Although these works are very significant, they have different goals to ours as they do not deal with the smart sustainable home domain but rather the urban water network.

2.3. Ontologies that represent the urban wastewater system

Waste Water Ontology (WAWO) is an ontology that models information about wastewater treatment process. It incorporates ontology-modelled microbiologic knowledge related to the treatment process into the reasoning process, which is implemented in LISP [17]. WAWO is used by the ontology-based wastewater environmental decision support system (OntoWEDSS) supporting both rule-based reasoning and case-based reasoning.

The management of urban wastewater systems (UWS) requires complex numerical models, which can be applied to predict management actions or understand failures of the system. Nevertheless, for the communication between stakeholders in the process of optimizing a UWS, these models are far too sophisticated. The European project "cost-effective development of urban wastewater system for WFD compliance" (CD4WC) has been explored using an ontological knowledge base as a conceptual model of the UWS which can be used for dissemination or as a preliminary stage to numerical models [18].

Although wastewater is one of the sources of DWM, the above works do not consider the case of the sustainable home and its neighbourhood and therefore cannot be directly applied to this domain.

2.4. Sensor ontologies

The Semantic Sensor Net (SSN) Ontology [12] is an OWL2 ontology that has been developed by the W3C Incubator Group, in order to describe (i) the capabilities and properties of sensors, (ii) the act of sensing and (iii) the results provided by observation processes. SSN has been constructed over a central node called "Stimulus-Sensor-Observation (SSO) pattern" that models sensor behaviour and information collection. "Device" and "System" represent physical sensors while "Process" and "Operating Restriction" describe more in detail the process of sensing (e.g. indicate if the process is an input/output or whether the process has some operating restriction); furthermore, "Data" categorizes observations values; "Measuring Capability" and "Constraint Block" associate a sensor with its accuracy, frequency, drift, battery lifetime, etc. as well the feature of interest observed (water, soil, etc.).

The SSN ontology integrates the DUL ontology that deals with the specification of entities that are relevant to agent-based modelling (event, goal, quality, agent etc.). Also, the SSN ontology links concepts and properties with corresponding fields in Sensor Markup Language (SensorML) language defined for exchange information with the OGC elements (Observation and Measurement Service). As another benefit, the SSN ontology permits an enrichment of the ontology during its use by allowing the specification of axioms during the population phase and the specification of restrictions over observation values at the ontology specification phase.

Earlier works do not have the same level of integration as SSN: the case of adaptive sensor networks is investigated in [19], query and inference over SensorML data is studied in [20,21], while [22,23] propose a two-tier ontology framework for hierarchical sensor networks [22]. Heterogeneous sensor networks are the focus of [24,25], while [15,26] is able to automatically select sensors for tasks based on their fitness for the task description. Data integration, search, classification and workflows are considered in [27,28], while [29] uses the OWL-S [30] Web services ontology as a basis for a sensor ontology. The above ontologies are analysed in more detail in [31].

2.5. Smart home ontologies

In the smart home domain, several ontologies have been developed. Their aims can be classified in three categories: (a) device interoperability, (b) context awareness and (c) energy efficiency. Device interoperability refers to the problem of modelling a large number of heterogeneous devices each abiding by a different home automation standard [32–36]. Some works extend the modelling to include the device hardware [37,38], device function, platform and manufacturer [39,40] and device profile [12]. The authors of [41] deal with device notification and architectural components, making this ontology the most integrated one.

Context awareness is the concept of making applications more useful for the user by making them aware of their human and physical environment, i.e. their context. Ontologies here are differentiated according to how they model context [42]. Almost all definitions include location, either as a region or as a point in space (BONSAI), and computational platform. Activity is another parameter that is considered in [41], user role and task are considered in [38], while [43] introduces the concept of event as a change in context, while [44] and BONSAI also define environmental conditions.

A specific case of contextual information is that of energy. For this class of applications, energy demand per device, energy supply, energy providers and energy tariffs are considered in [44–46], while [47] investigates the case of the smart grid.

None of these works that are analysed in detail in [39] deals with water resources management.

2.6. Non-ontological resources

All the above works deal with semantic interoperability while OGC standards, such as Sensor Observation Service (SOS) and WaterML 2.0, support syntactic interoperabiity. An SOS [48] provides an API for managing deployed sensors and retrieving sensor data in a standard way that is consistent for all sensor systems including remote, *in situ*, fixed and mobile sensors.

WaterML 2.0 is an eXtensive Markup Language (XML) for the representation of water observations data with a specific focus on time series structures, with the intent of allowing the exchange of such datasets across information systems. WaterML2 is implemented as an application schema of the GML 3.2.1, making use of the OGC Observations & Measurements standards. A detailed overview of the WaterML2 schema can be found in [7] and [49]. WaterML2 schema are encapsulated and used in the SOS schema.

DiHydro ontology is consistent with a different syntactic interoperability model, SensorML; hence, a translation is required for instances of DiHydro to be exported in the SOS service (using WaterML).

3. Ontology description

The DiHydro ontology has been designed to provide the smart sustainable household owner with sufficient knowledge to support the decision-making process that is required for distributed water resource management. The analysis of a set of use cases [5] that were captured in the requirements phase of the Hydropolis research project (Action 7: "distributed, cooperative infrastructure management") has shown that the most significant functions that are involved in distributed water resource management pertain to: *controlling* the grey water reuse process, *detecting* and *reacting* to any failures and unusual events (e.g. floods, bursts, pump failures), *analyzing* and *improving* the efficiency of water reuse and finally *predicting* the optimal time for maintenance, ahead of time, in order to reduce the risk of failure and improve system availability.

A typical DWM smart home topology was designed in the scope of a pilot application that took place in an autonomous house in Heraklion, Crete, in the fall of 2015. The topology is used as reference for the ontology and it is shown in Fig. 1. This topology has a number of important features. First, each node is responsible for a different DWM component, and moreover, there may be more than one node measuring the same physical parameter (e.g. energy consumption by means of a current sensor) in two different places. For example, they may be placed at the input of two water treatment units, in order to determine which one is more economic. This means

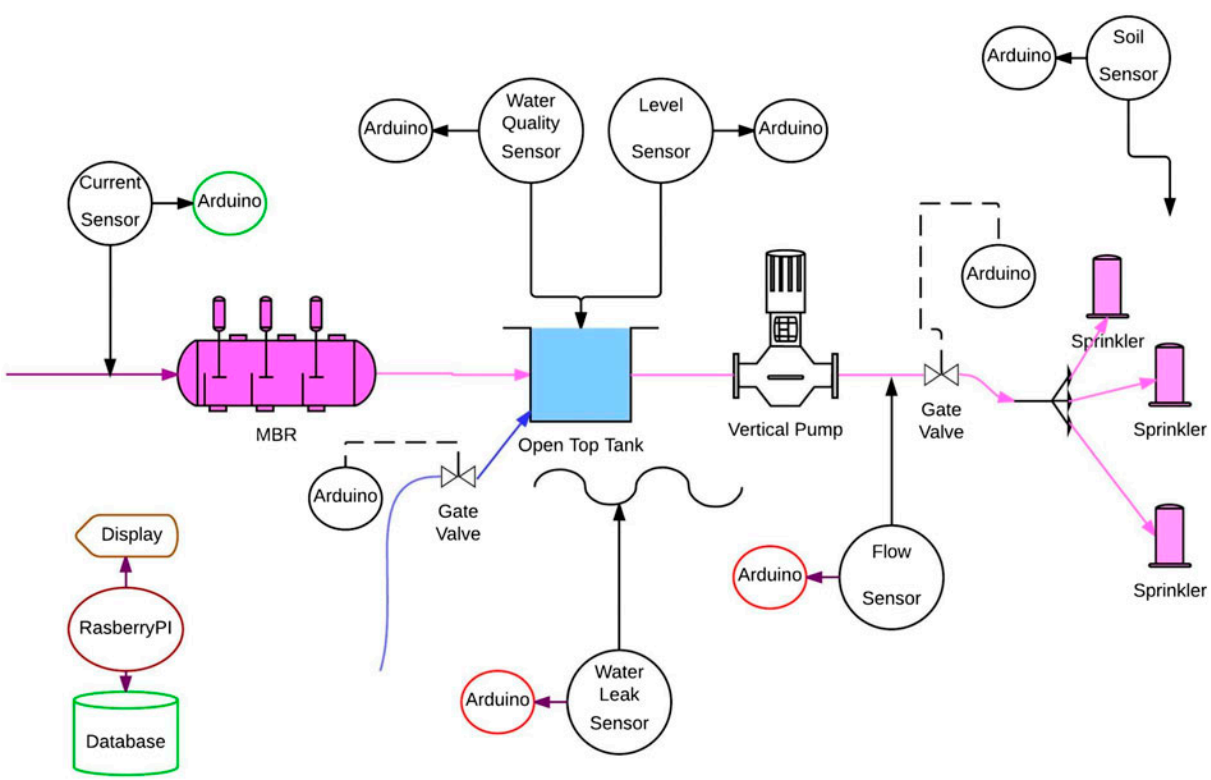

Fig. 1. Typical DWN network topology.

that the concept of a sensor must be associated with the respective DWM element, in order for this information to be exploitable by the householder. SSN is agnostic of the DWM domain; so the relevant concepts have been added in DiHydro and the linking is done through the *Feature of Interest* class (Section 3.1).

Second, a WSN node in the topology may be composite, i.e. it may have more than one sensor. For example the node that measures water quality in the grey water tank may have a pH sensor, an electro-conductivity sensor and a temperature sensor. This means that the granularity of modelling in the ontology should be at the level of the WSN node, not the sensor. SSN is agnostic of WSN nodes, and therefore the relevant concepts (Node, NodeInput, NodeOutput) and respective properties have been added in DiHydro.

Third, in order to model the network as a control system, as mentioned above, the ontology needs to support reactive concepts, such as actuations and (suggested) actions. This feature is also not supported by SSN and has been added in DiHydro through the actuator and action classes.

3.1. DiHydro

Fourth, it should be possible for the topology to operate without central control and with as little energy loss as possible. A concept known in the sensor network community as in-network processing mandates that a node pre-process data in order to make a local decision. Hoare rules were added in DiHydro so that such logic can be added. Furthermore, a sending node (e.g. the water quality sensor node) should be able to make point-to-point connections with a receiving node (e.g. the electro-valve actuator node) in order to deliver the observations that trigger an actuation in a minimal number of hops, thus saving battery. The DiHydro concepts NodeInput and NodeOutput are linked through the "=" operator to simulate such routing strategy.

The DiHydro taxonomy was developed in order to cater for the above requirements. It is presented in Section 3.2.

3.2. Taxonomy

This section presents the main terms (taxonomy) that are included in the DiHydro ontology. During the presentation of the taxonomy core, variables have been included in order to make more understandable the entity and the concept represented.

Table 1
Actors

Actor	Description
Householder	Type of actor who uses water for his own personal needs

3.2.1. Entity "actor"

An actor is defined as any kind of user that is somehow related to the smart sustainable home. The "Actor" entity has been included into the ontology with the aim of aligning actions on the smart home DWM with the roles involved. DiHydro currently supports only the householder role, while it is possible to add specializations such as garden manager, household manager, etc. (Table 1).

3.2.2. Entity "event"

The smart, sustainable home is event-driven; data are communicated in the form of events that can be low-level, e.g. *soil.temperature* > 30 °C, *soil.moisture* = 0, *or abstract* e.g. *garden_needs_irrigation*. Arbitrarily, complex user-defined abstract event types can be specified by means of simple logic rules, as explained in the next section. *Events* trigger linked actions, e.g. *open tank valve*() in order to top up processed grey water with potable water or *open irrigation valve*() *in order to water the garden*. Furthermore, real-time analytics [50] such as the *calculation of a real-time water balance* are continually triggered by event streams.

DiHydro contains the following default event types (subclasses) in Table 2.

3.2.3. Entity "node"

This entity extends the SSN:Device class in order to represent the WSN nodes (Fig. 3). A node may contain one or more sensors (sensor node) or one or more actuators (actuator node). A gateway server hosts a local database and is able to communicate data to a web server. DiHydro contains the following node types (Table 3).

3.2.4. Entity "actuator"

This entity extends the SSN:Device class in order to represent actuators. Actuators are hosted on actuator nodes and can be remotely operated (Fig. 3). DiHydro contains the following actuator types (Table 4).

Table 2
Events

Event	Description
Leak (x)	An instance of this predicate is created by a rule that is triggered by an observation with an abnormal value *x* of an instance of a WaterLeakSensor
Pump failure (x)	An instance of this predicate is created by a rule that is triggered by an observation with an abnormal value *x* of an instance of a WaterFlowSensor
Blackout (x, y)	An instance of this predicate is created by a rule that is triggered by an observation with an abnormal value *x* of an instance of a CurrentSensor combined with an AirLuminocitySensor (value *y*)
Garden needs irrigation (x, y)	An instance of this predicate is created by a rule that is triggered by an observation with an abnormal value *x* of an instance of a SoilMoistureSensor combined with an SoilHumiditySensor (value *y*)
Tank needs topping up (x)	An instance of this predicate is created by a rule that is triggered by an observation with an abnormal value *x* of an instance of a WaterLevel sensor or a WaterQualitySensor

Table 3
Nodes

Node	Description
Node	A WSN node consisting of a microprocessor/microcontroller, a communication chip and a sensor board
OpenGardenNodeArduino	A programmable WSN node consisting of an Arduino microcontroller, one or more communication devices and the Open Garden sensor board
OpenAquariumNodeArduino	A programmable WSN node consisting of an Arduino microcontroller, one or more communication devices and the open aquarium sensor board
Actuator node	A WSN node consisting of a microprocessor/microcontroller, a communication chip and one or more actuators
OpenGardenActuatorNodeArduino	A programmable WSN node consisting of an Arduino microcontroller, one or more communication devices and the Open Garden shield with one or more actuators
OpenAquariumActuatorNodeArduino	A programmable WSN node consisting of an Arduino microcontroller, one or more communication devices and the Open Aquarium shield with one or more actuators
Gateway	A programmable WSN node consisting of a Raspberry Pi or similar device with one or more communication devices

3.2.5. Entity “sensor”

This entity subclasses the SSN: “Sensing Device” in order to represent the various DWM sensors. Sensors are characterized by a *sensing function* and a *proxy* and each have one input (*stimulus*) and one output (*observation*). Sensors also have *measurement capabilities*, *measurement properties* and *energy restrictions* (Tables 5 and 6).

3.2.6. Entity “observation”

For each type of Sensor, a respective Observation type has been created, e.g. *CurrentObservation*, *SoilMoistureObservation*, *WaterFlowObservation* etc. DiHydro Observations are subclasses of SSN:Observation and each is characterized by an Observation value that is actually a range of values (SSN:Region) allowing for sensor accuracy. Each observation has apart from *value*, a *timestamp* and a *quality estimate* (Fig. 2).

3.2.7. Entity “feature of interest”

The entity Feature of Interest extends the SSN: “Feature of Interest” class, and refers to any resource that is of interest to the WSN (Table 7). For example, the observed real-world phenomenon (e.g. “Heraclion, GR” as described by [51]) is captured using the entity *Feature of Interest*, and *ObservationValue* is used to describe the measured value of a given property (e.g. water conductivity). It has been included in the ontology in order to align sensor observations with components of the DWM network (i.e. membrane bioreactor (MBR), compact disc reactor (CBR),

Table 4
Actuators

Actuator	Description
Actuator	A generic actuator
Electrovalve	A generic electro-valve
AirPump	A generic air-pump
TankValve	An electro-valve that controls the fresh water input in the grey/green water tank
TankValveOut	An electro-valve that controls the output (overflow) of the grey/green water tank so that the tank can be emptied
GardenValve	An electro-valve that controls the garden irrigation system

Table 5
Sensors

Sensor	Description
WaterSensor	A sensor for water
WaterLeakSensor	A water sensor that detects leaks
WaterFlowSensor	A water sensor that measures flow
WaterPhSensor	A water quality sensor that measures pH
WaterConductivitySensor	A water quality sensor that measures conductivity
WaterTemperatureSensor	A water quality sensor that measures temperature
WaterLevelSensor	A water sensor that measures the water level in a tank
SoilMoistureTemperatureSensor	A sensor that measures the soil moisture and soil temperature
AirHumidityTemperatureSensor	A sensor that measures air humidity and air temperature
AirLuminocitySensor	A sensor that measures luminocity
CurrentSensor	A sensor that measures current

Table 6
Sensor properties

Properties (has relation)	Variables	Description (is subclass of)
Sensing function		Text
SensorInput (stimulus)		DiHydro:Event
SensorOutput		DiHydro:Observation
MeasurementCapability	Accuracy	SSN:MeasurementCapability
	Sensitivity	
	Precision	
	Response time frequency drift	
MeasurementProperty	Measurement range	SSN:MeasurementProperty
EnergyRestriction	Battery lifetime	SSN:EnergyRestriction
	Operating range	

ultraviolet (UV), grey water tank) or with *sources* of the DWM network (grey water, green water, black water) or with *processed sources* (processed grey water, processed green water, processed black water) or with sinks of the smart home (e.g. garden soil and floor) or other environmental resources (air, power). The link is implemented though the relations *"observes"* and *"is property of"*.

<sensor> 'observes' some <property>

<property> 'is property of' some <feature of interest>

For example:

WaterConductivitySensor 'observes' some Water Conductivity

AND

WaterConductivity 'is property of' grey water tank

3.2.8. Entities "NodeInput" and "NodeOutput"

These entities have been introduced in the ontology with the aim of creating distributed WSN

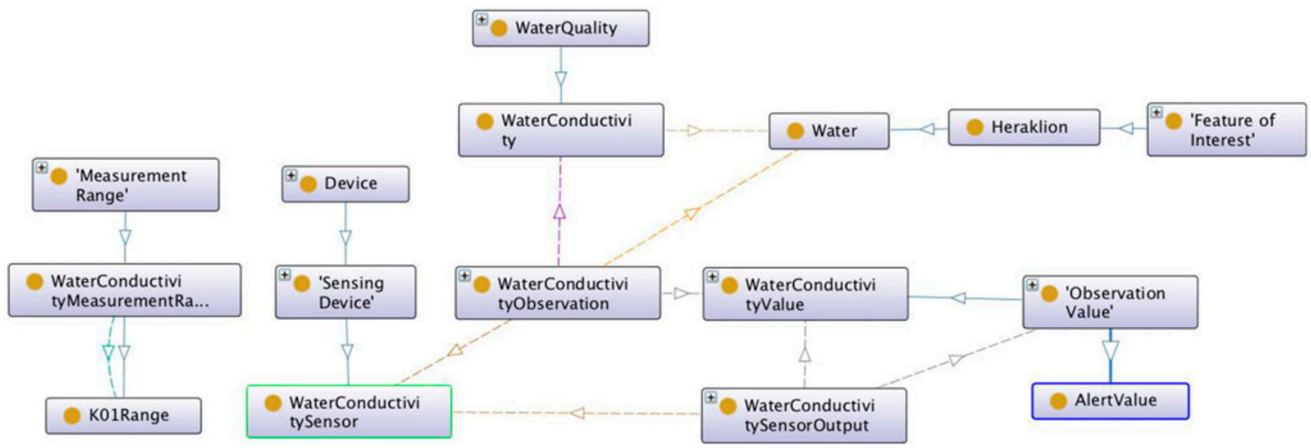

Fig. 2. Water conductivity observation.

Table 7
Features of interest

Feature of interest	Properties (has property relation)	Function (is subclass of)
Fresh water	WaterConductivity (sec^{-1})	Source/processed source
Grey water	WaterFlow (L/min)	Source/processed source
Green water	WaterpH	Source/processed source
Black water		Source/processed source
Garden soil	SoilMoisture	Sink
	SoilTemperature (°C)	
Air	AirHumidity	Resource
	AirTemperature (°C)	
Power	Current (mA)	Resource
Floor	WaterLeak	Sink
DWM component		Transformation
MBR	EnergyConsumption (Watt)	Transformation
CBR	Input flow (L/min)	Transformation
UV	Output flow (L/min)	Transformation
Grey water tank	Capacity (L)	Storage

topologies. By connecting (a) a Sensor Output to the corresponding sensor node NodeOutput and (b) the NodeOutput of a sensor node to the NodeInput of an actuator node (Fig. 4), data are routed in the physical WSN network using the shortest path between the two nodes. This eliminates the need for a central "sink" that is implemented by the gateway. As each packet transmission costs 50 times more than a processing task, by shortening the number of hops a message has to travel, battery resources are saved. NodeInput and NodeOutput subclass SSN: "information object".

3.2.9. Entity "action" (NodeOutput)

Suggested actions are in fact recommendations based on decisions that a specific actor can make with respect to an alert occurrence and/or water resources management need. They are implemented as subclasses of NodeOutput for actuator nodes only. DiHydro supports the following suggested actions that implement the use cases of [5] (Table 8).

3.2.10. Entity "alert"

Alerts are special observation values that need to be addressed by the household owner (Table 9).

4. Implementation

We define a *Core Ontology Layer* (*COL*) *that* maintains a *low-level* but *precise* view of the *current logical state* of the smart sustainable home, as produced by sensors that are distributed throughout the

Table 8
Actions

Action	NodeOutput	Description
Open/close tank valve (x)	TankValveOn/Off	Is triggered by sensor observation with value *x*. Switches on/off the potable water valve in order to top up the grey water tank with fresh water. It is required either for meeting demand or for improving grey water quality
Open/close irrigation valve (x)	GardenValveOn/Off	Is triggered by sensor observation with value *x*. Switches on/off the irrigation valve in order to water the garden with the minimum required water (precision irrigation)
Start/stop air pump (x)	AirPumpOn/Off	Is triggered by sensor observation with value *x*. Switches on/off the air pump in order to improve the quality of stored grey water

environment and continually updated through events. That is, it contains instances of the classes of Section 3.2. Equally, we define a *Deductive Ontology Layer* (DOL) that maintains an *abstract* view of the *current logical state* of the smart sustainable home, which can easily be *inferred* from the knowledge stored in the COL using Hoare *rules* [52]. For example, a Hoare logic expression for defining the abstract event garden needs irrigation (*x*, *y*) using the soil temperature and moisture values is:

$$SoilMoisture(x) = 0 \wedge SoilTemperature(y) > 30^{\circ}\text{C} \rightarrow gardenneedsirrigation(x, y)$$

The DOL contains abstract event detectors, i.e. logic rules for generating abstract events, as well as rules for linking abstract events to invoked actions. For example, the abstract event detector *tank needs topping up*(*x*) is implemented with the following rules: they cause the raising of an alert when the value of water conductivity observation at the output of the sensor node that is attached to the grey water tank is lower than 400 μS. When the alert is received by the actuator node (Fig. 3), it causes the creation of the suggested action of opening of the tank valve in order to add potable water; thus, improving water quality.

$$WaterConductivityObservation(x) < 400 \rightarrow tank\ needs\ topping\ up\,(x) \wedge alert\,(x) \wedge sensor\ node\ output(x) \tag{1}$$

$$Tank\ needs\ topping\ up\,(x) \wedge actuator\ node\ input\,(x) \rightarrow suggested\ action\,(x) \wedge open\ tank\ valve\,(x) \tag{2}$$

The DOL also contains rules for estimating the date of due maintenance of a DMW, based on the installation date, its maintenance specification (factsheet) and the current time. Reactive rules also define the optimal sampling rates whenever a situation of interest has been detected.

DiHydro is written in OWL [40], the standard language for expressing Web-accessible ontologies, as approved by the World Wide Web Consortium (W3C). DiHydro is implemented in Protégé [53] with SWRL support for rules [54], while the integration of DiHydro with Java code running on each WSN node is realized by means of the OwlAPI.

The part of DiHydro that deals with alerting is shown in Fig. 2. Boxes are instantiations of the relevant entities (classes) and arrows either show inheritance (solid line) or a relation (dotted line) between classes. For example, *WaterConductivity* is a subclass of

Table 9
Alerts

Reset MBR (x)	Is triggered by sensor observation with value *x*. It is a guideline to the householder to clean and reset the MBR component in case of under-performance. This is detected by low flow at the MBR output
Repair pump (x)	Is triggered by sensor observation with value *x*. It is a guideline to the householder to clean and reset the MBR component in case of underperformance. This is detected by low flow at the MBR output
Repair sensor (x)	Is triggered by a stream of sensor observations with values zero. It is an indication for the householder that a particular sensor may not be working
Alert (x)	Is triggered by sensor observation with value *x*. It is a generic alert

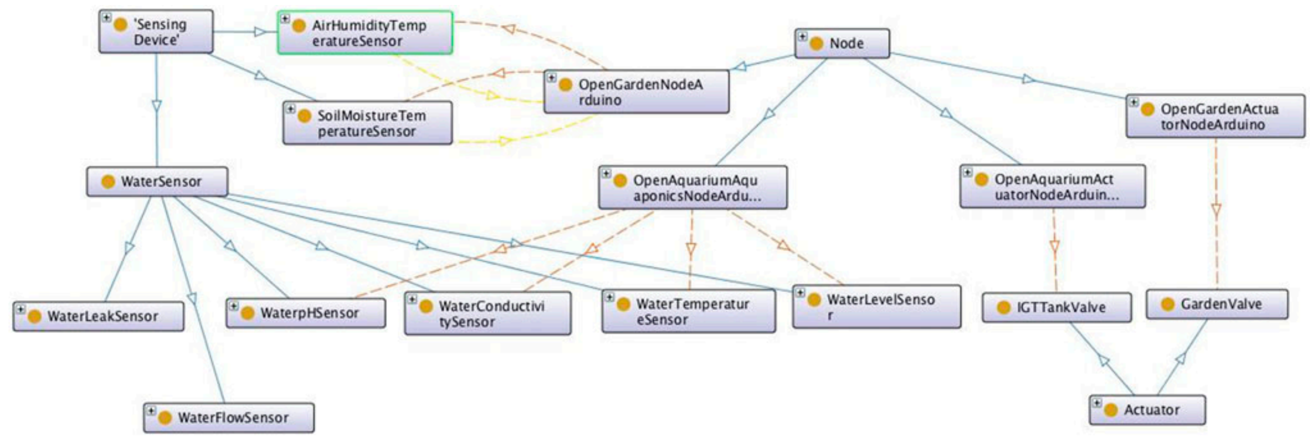

Fig. 3. System devices view.

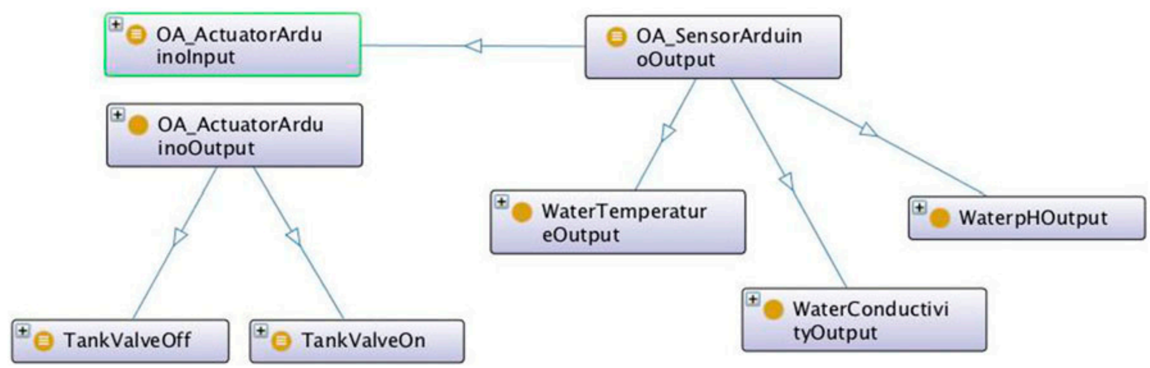

Fig. 4. The publish/subscribe view.

WaterQuality (inheritance), while *WaterConductivityObservation* "observes" some *WaterConductivity* (relation). It should be noted that *ObservationValue* is a subclass of *AlertValue*, indicating an abnormal value that has triggered an alert.

Fig. 3 shows the Devices view. It contains instantiations of the most significant Sensor, Node and Actuator classes and inter-class relationships. Fig. 4 shows the publish/subscribe view: a composite sensor node that measures three quality parameters acts as a publisher of pH, temperature and conductivity observations. It is interconnected with an actuator node that can invoke one of the two actions—open/close the tank valve, the invocation of which depends on the evaluation of the relevant rule.

5. Conclusions

Concluding, this paper presents DiHydro, a novel ontological framework that provides the base and standard for the rapid deployment and reliable management of DWM technologies. The contribution of this work is twofold: at the ontology level, we propose a new ontology, DiHydro, which is appropriate for the DWM-enabled sustainable smart home.

At the knowledge-based reasoning level, we allow applications to register inference rules that generate abstract knowledge (e.g. garden needs irrigation) from low-level, sensor-derived knowledge (e.g. *SoilMoisture* and *SoilTemperature* readings), and link high-level knowledge with actions (e.g. *open tank valve*()). In this way, a control system for DWM is implemented. The proposed system acts as a simulation reasoning tool; when linked with real-time data, it can produce as output, alerts (e.g. *leak*), suggested actions and real-time analytics. Second, it be used as a tool for driving publish—subscribe [55] communication, i.e. designing and simulating different routing strategies that may lead to savings in the battery resources in the WSN, which is a major research issue. Third, WSN nodes can outsource the rules for data aggregation to the ontology, eliminating the need for writing embedded code, which is cumbersome.

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