International Journal of Computer Applications (0975 – 8887)
Volume 186 – No.4, January 2024

Using the Generalized World Entities (GWEs) Paradigm in a Semantic Web of Things (SWoT) Context

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ABSTRACT

The Generalized World Entities (GWEs) paradigm is a proposal for introducing a semantic/conceptual dimension into the standard IoT procedures and supporting then the creation of a real Semantic Web of Things (SWoT). It is based on a substantial extension of the kind of entities to be considered within a sensor-monitored environment, by modelling in a unified way both physical entities like objects, humans, robots, etc. and higher levels of abstraction structures like situations, events, and behaviors. The unifying element is provided by an extended conceptual representation of the world, ontology based, that is used for modelling the GWEs of both types. NKRL (Narrative Knowledge Representation Language), a high-level tool grounded on two separated but integrated ontologies, an ontology of concepts and an ontology of elementary events, is utilized in this context.

General Terms

Knowledge Representation, Ontologies, System Architecture, Automatic Reasoning.

Keywords

Semantic Web of Things (SWoT), Generalized World Entities (GWEs), Narrative Knowledge Representation Language (NKRL), ontology of standard concepts, ontology of dynamic events, inference procedures, examples of actual GWEs.

1. INTRODUCTION

The Generalized World Entities (GWEs) proposal for building-up effective SWoT (Semantic Web of Things) solutions has been the object of several publications in books, specialized journals and Computer Science conferences, raising considerable interest in a IoT context. This interest has been reinforced by the recent use of the GWEs proposal in an actual industrial in Greece, see [1]. This paper aims then to recall quickly the main principles of this approach.

The GWEs proposal originates from the remark that the development of effective SWoT applications is currently hindered by the existence of *two major shortcomings* that still affect the majority of the cognitive IoT proposals:

- The first concerns the tendency to continue to identify, in the IoT/SWoT practice, all the entities taken into account *with ordinary physical things* – surely a heritage of the first steps of IoT, when IoT was simply associated to some sort of extension of the RFID technology. This restriction to the physical domain strongly disagrees with the most evolved IoT/SWoT interpretations where the "*things*" are, in reality, *"entities" of a very general nature,* involved in the most different domains of application. To modify this situation, an innovative approach adopted in the GWEs proposal consists of making use of advanced conceptual knowledge representation tools able to denote in a *unified way* (i.e., making use of a unified representation framework) *both physical entities* like objects, humans, robots, etc. *and higher levels of abstraction structures* corresponding to actions, situations, events, behaviors, etc.
- The second shortcoming is that, even in case the requirement of using a *unified kind of representation* was really satisfied, the tools chosen for implementing this general representation *would probably be unfitting*. Looking in fact at the SWoT applications implemented so far, see next Section, we can note that they have used, essentially, *tools grounded on a Semantic Web/Linked Data approach*. However, this sort of tools is affected by *several theoretical and practical limitations*, mainly, *limited expressiveness* (see subsection 2.5 below); this makes it particularly difficult to deal with those "higher levels of abstraction structures" evoked above.

The solution proposed in this paper is centered on the use of the so-called GWEs paradigm [2, 3]. According to what stated above its aim consists, basically, in *broadening* the range of entities to be taken into account when describing a *sensor-monitored environment* by providing a *unified, coherent and seamless way* to deal with both:

- *Conceptual representations of all the observable, real world entities* like physical objects, humans, robots, sensors, actuators, low-level signals etc. – i.e., all those entities normally dealt with by the usual IoT procedures.
- *Higher level of abstraction structures* corresponding to general situations, actions, behaviors, events, involving the previous "physical" entities and their relationships, which can be described in any sort of scenarios/scripts/storyboards/narratives etc. These high-level entities are normally left aside or dealt with in a cursory way in a SWoT context, *in spite of their evident pervasiveness in any possible real-world context*.

The ability to deal with both physical and higher-level entities using a *unique, coherent set of computational tools* is provided by the use of a *single conceptual/ontological representation of the world* for modelling the GWEs of both types. The use of this unified and standardized approach implies, among many other things, the opportunity of:

- Get rid completely of the *heterogeneity/interoperability problems* that, as is well-known, affect the IoT/WoT domain – see, e.g., the "silos flaw drawback", i.e., the development of IoT applications under the form of *independent vertical systems*. The use of a *unique knowledge representation language*, ontology-based, for SWoT entities of any origin and conceptual complexity level allows the easy integration of information coming from multiple, distributed and heterogeneous sources, ensuring then *strong semantic scalability*.

- Filling *the semantic gap* between values collected at *sensor level* (i.e., at sub-symbolic level) and their *representation in conceptual format* (i.e., at symbolic level). Using a *unified representation framework* for all entities of any possible level of complexity will allow users, e.g., to *switch immediately* from the *simple instantiation* (EMERGENCY_SITUATION_1) of a concept as emergency_situation originated by the pressure on an emergency button, to the *activation of a structured scenario* where a robot moves and acts within a potentially dangerous environment.

Section 2 supplies a quick picture of the state of the art in the SWoT domain – additional information can be found, e.g., in [3]. Section 3 introduces the main notions supporting the GWEs approach and the use in this context of NKRL, the Narrative Knowledge Representation Language. NKRL concretely implements *the unique, coherent set of computational tools evoked above*. Section 4 introduces some basic information about the creation/utilization of the GWEs structures; Section 5 is a short Conclusion.

2. AN ABRIDGED STATE OF THE ART

2.1 First examples of SWoT-like systems

An early approach to the introduction of semantic elements in a standard IoT context is represented by the *Semantic Sensor Web (SSW) systems*, very popular in the first decade of 2000. These systems have been realized by implementing *a sort of merge* between the Sensor Web technology [4, 5] and the standard Semantic Web (SW) approaches. Sensor Webs were structured as *wireless-communicating, spatially distributed sensor platforms* (“pods”) able to monitor and explore environments using Web services and database tools. They operated as autonomous sensing entities capable of interpreting and reacting to the data measured, and could perform intelligent autonomous operations like responding to the change of the environmental conditions and carrying out automated diagnosis and recovery. The Sensor Web Enablement (SWE) initiative of the Open Geospatial Consortium (OGC) was created to *standardize* the basic building blocks to be used in a Sensor Web context [6].

The integration with the usual SW systems was implemented by extending the Sensor Webs’ architecture via the introduction of an *additional semantic layer*. In this, *the semantics of the sensor data* were specified by annotating them with *semantic meta-data* according to well-defined conceptual schemas (typically, ontologies). For example, in [7], the semantic layer was implemented by *annotating sensor data proper to the weather domain with spatial, temporal, and thematic semantic metadata*. To this aim, the Authors used one of the languages proposed in a SW context, RDFa, an RDF variant *often utilized for annotation purposes*. To derive, then, additional knowledge from the *semantically annotated sensor data*, the Authors employed the “antecedent → consequent” rules of SWRL, the Semantic Web Rule Language. Rather than using an existing SW language like RDFa, the Authors of [8] have developed a specific data model, stRDF, which extends RDF with the ability to represent spatial and temporal data using constraints. The corresponding query language is, in this case, stSPARQL, an extension of SPARQL. Other proposals for implementing the “*additional semantic layer”* are mentioned in [3: 111-112].

Speaking of the very first examples of SWoT-like systems, we cannot forget the so-called “sensor languages” like, e.g., the “Extended Environments Markup Language, EEML” (https://wiki.p2pfoundation.net/Extended_Environments_Markup_Language, accessed December 10, 2023) or the “Physical Markup Language, PML” (http://web.mit.edu/mecheng/pml/overview.htm, accessed December 10, 2023). An application of EEML is Pachube (https://os.mbed.com/cookbook/Pachube, accessed December 10, 2023), a still in use data brokerage platform. The most well-known sensor language is surely the “Sensor Model Language, SensorML” (http://www.opengeospatial.org/standards/sensorml, accessed December 10, 2023), an XML-based language developed by the Open Geospatial Consortium (OGC). It allows the description of the *geometric, dynamic, and observational characteristics* of a large range of sensors, from simple visual thermometers to sensors included in earth-orbiting satellites.

2.2 The SSN ontology

From the publication of important SSW papers like [7], a consensus had immediately emerged about the recognition of the use of ontologies as the *best solution* for associating semantic features to IoT data and procedures. Ontologies denote, in fact, a powerful *abstraction technology*, capable to hide the heterogeneity of the SWoT entities and to act as a mediator between providers and consumers of SWoT applications.

Two examples of general SWoT ontologies that are considered (the second in particular) as direct precursors of the *Semantic Sensor Network (SSN) ontology* [9, 10] are OntoSensor [11] and the CSIRO system [12], see again [3] for further details. With respect to SSN, a first version of this ontology was developed in 2010-2011 by a specific W3C Semantic Sensor Network Incubator group – W3C is the World Wide Web (international) Consortium. The architecture of this version *was conceived according to the principles of the Stimulus-Sensor-Observation (SSO) paradigm*, see [13]. SSO linked together sensors, what they sense, and the resulting observations. *Stimuli* represent detectable changes in the physical world that act as triggers for *sensors*, i.e., physical objects that produce *observations*. Concretely, sensors transform the incoming stimulus into *different (normally digital) forms of representation*; they implement then a *method* (an abstract description) that describes the transformation of stimuli into results. *Observations* represent the context that bring sensors and stimuli together, and represent then the *sticking items* of the SSO patterns. They define how a sensor should be realized and deployed to measure a given observable property, and are defined by procedures that determine how a certain observation must be carried out. For interoperability’s sake, the main classes of SSN have been aligned with classes of the DOLCE-UltraLite (DUL) ontology (http://ontologydesignpatterns.org/ont/dul/DUL.owl, accessed December 10, 2023).

SSN has been conceived from the beginning as a sort of *standard* for describing sensors and the different resources in the sensor networks in terms of *capabilities, measurement processes, observations and deployments processes*. In its very first version SSN was not, however, exempt from shortcomings. For example, this version did not include any modelling facilities for many features of interest in an IoT context like, e.g., units of measurement, support for the spatial and temporal association of sensor data with the resources and, mainly, *for representing contexts and domain knowledge in general*. To make an actual use of this ontology it was then necessary to associate SSN with other domain ontologies. This first version was also *a quite complex tool to use* and, given its layered structure (OWL2, DOLCE, DUL…), *a quite ineffective one* from a running/processing point of view.

An IoT-Lite ontology [14] was then created as a *lightweight instantiation of the SSN ontology*. Moreover, because IoT does not just deal with sensors and actuators, Gyrard et al. [15] proposed to extend SSN by including entities like transducer, RFIDS tag, controllers, along with other concepts like observations, phenomena, their units and domains. This has produced in practice a new sort of ontology, named M3; in a simplified form, as M3-lite, it has been used, e.g., in the EC FIESTA-IoT project, see below. A complete restructuring of the original SSN was proposed in 2017 by the W3C [16]. This new version is characterized by a *modularized architecture* that replaces the SSN's Stimulus, Sensor, Observation (SSO) focal point, and that is based on a *lightweight but self-contained core ontology* called SOSA, Sensor, Observation, Sample, and Actuator [17]. SOSA includes the SSN basic classes and properties and *can be independently used* to create basic conceptual annotations without a too important ontological commitment. A recent extension of SOSA is IoT-Stream [18].

Several ontologies have been developed after 2010 in the form of adaptations/improvements of the original SSN, see again [3]. More in general, the publication of the SSN work has stimulated the research activities in a generic SWoT domain. A very popular (and widely used) system in this context is represented, e.g., by the Smart Appliances REFerence (SAREF) OWL-based *domain ontology* [19]. SAREF is a *shared model of consensus* that facilitates the *matching of existing assets in the smart appliances' domain*. Its modular architecture makes use of pre-defined building blocks that allow separation and recombination of different parts of the ontology as a function of the specific needs. The notion of "device" is central in this system; examples of devices are *tangible objects ("appliances")* like a light switch, a temperature sensor, an energy meter, or a washing machine. The modular structure of SAREF is then used for the definition of any possible device by associating, according to its function(s) and purpose(s), *some of the pre-defined building blocks of the ontology*. An extension of SAREF for the energy domain is SAREF4EE [20].

2.3 SWoT and the European Commission

Thanks to the heavy investments of the European Commission in the IoT domain (in its *semantic/conceptual variants* in particular), several important projects developed *in a full SWoT style* have been created in Europe from the second decade of the 2000s. using both the ontologies mentioned above (SSN in particular) and new specific ontological/conceptual tools.

In this context, the IoT-A FP7 project is of a particular importance given that its goal was to create a *European architectural reference model for any sort of Future IoT*. The concrete output of IoT-A was then a proposal called ARM, Architectural Reference Model [21] consisting of four parts:

- The *vision*, explaining then the *rationale* of the architectural reference model.
- The *business scenarios*, concerning the requirements expressed by the *stakeholders*.
- The *IoT-A Reference Model*, including a top-level account of the architecture in the form of an IoT Domain Model, an IoT Information Model explaining how to shape the IoT information, an IoT Communication Model illustrating the interaction procedures between the different IoT devices and the Internet as a whole, etc.
- The *IoT-A Reference Architecture*, providing views and perspectives on different architectural aspects of possible interest for the stakeholders, focusing on *abstract sets of structures* rather than on specific application architectures.

IoT-A ARM aimed then at suggesting *best practices* to create IoT-compliant architectures in different application domains that could be seen as *instances* of the above Reference Architecture. Within this general framework, the IoT-A "things" dealt with were understood as augmented entities formed by the *association of physical entities with virtual entities* see, e.g., [23, 121]. Physical entities corresponded, obviously, to sensors, actuators and any sort of possible physical devices. The introduction of virtual entities was to be interpreted as the addition of *a new abstraction layer* capable, as in the GWEs approach (see Section 1 above), of increasing the generality level of the IoT applications. Unfortunately, in an IoT-A context, these virtual entities were *simple computer-usable counterparts of the physical ones* see, e.g., "Physical Entities are represented in the digital world by a Virtual Entity" [23, 120]. Or, even more explicitly, virtual entities are "…synchronized representations of a given set of aspects (or properties) of the Physical Entity" [23, 121). Any "Virtual Entity" of this kind has attributes like a name, a type and one or more values, to which metadata, as time and location, could also be linked [23, 128]. This vision of *virtual entities as simple computer usable, digital images of physical entities* was largely shared in an "European SWoT" context. To give only an example, see [24], where the IoT-A physical things are called "entities" and the virtual things "resources" (software components) and where the Authors state explicitly: "A resource is the core software component that represents an entity in the digital world".

Several high-level SWoT European projects have been developed on the trail of IoT-A see, e.g., iCore (Internet Connected Objects for Reconfigurable Ecosystems), COMPOSE (Collaborative Open Market to Place Objects at your Service), SENSEI (Integrating the Physical with the Digital World of the Network of the Future) and BUTLER (uBiquitous, secUre inTernet-of-things with Location and contExt-awaReness), see for additional details [3, 114-116]. A more recent European project, FIESTA-IoT (Federated Interoperable Semantic IoT/cloud Testbeds and Applications) [24], is particularly interesting because it reflects well some new trends of the SWoT European research. *Strongly based on the use of previous work done in a European context*, it aimed at realizing the *interconnection/interoperability* of all the existing IoT platforms, testbeds and of specific/isolated applications, allowing then the execution of data-intensive experiments *on top of heterogeneous sets of IoT testbeds*. Coherently, the FIESTA-IoT Ontology was *a merge of concepts* derived from various ontologies as IoT-lite, M3, SSN and DUL. FIESTA provided also a set of user-friendly interfaces for defining, implementing and deploying experiments, with minimal or even zero programming effort. The general ambition of the project was, eventually, that of proposing the FIESTA-IoT infrastructure as *the only entry point for the European researchers in the SWoT domain*.

This sub-section can be concluded by mentioning an interesting non-European project, [25], proposed by well-known figures of the SWoT/IoT world. In this, they introduce the Semantic Gateway as Service (SGS) concept. SGS is conceived as *a bridge between the physical world and the high-level layers of an IoT/WoT system*. According to the architecture of an SGS-based system, raw sensor data are transferred from external "*sink nodes*" to a central "*gateway node*" via a multi-protocol proxy. Before being forwarded, data must be *annotated* making use of SSN and domain specific ontologies. The sink nodes (or base stations) act as *low-level data collectors*: all the sensor nodes send data to the different sink nodes, which are characterized by low computational resources, stringent energy constraints and limited communication resources. The gateway nodes provide *connectivity among the sink nodes*: they have more computing resources compared to the sink nodes and are then able then to support the above annotation procedures.

2.4 Linked data and the SWoT domain

Unlike the traditional Web, where documents are crawled by following hypertext links, in the Linked Data (LD) Web they are crawled *by following RDF links to gather information stating that one piece of data has some kind of relationship to another piece.* The global results are then explored making use of SPARQL queries. An argument often utilized to justify the introduction and use of LD *in domains like IoT/SWoT* – see, e.g., [26] – is that a number of governments, corporate, and academic organizations *have collected huge amounts of data provided by environmental sensors*. However, these data are too often *strictly confined* within these organizations and, at most, *processed locally within specific application domain*. They are *strongly underutilized*, then; a correct strategy to make these data openly accessible should consist in publishing them on the Linked Open Data (LOD) Cloud.

Popular papers about the relationships between Linked Data and IoT/SWoT have been published by Payam Barnaghi and collaborators. For example, [27] is a general paper about the application of semantic technologies on various aspects of IoT. It recalls, among other things, that *interoperability* represents one of the main reasons for using LD principles in the IoT/SWoT domain. More specifically, [28] *describes Sense2Web, a linked-data platform for annotating sensors data* and i) publishing them as RDF triples, ii) associating these data to other existing RDF sensor descriptions, iii) linking existing resources on publicly available linked-data repositories, and iv) making descriptions available for linked-data consumers through SPARQL endpoints.

After a peak of popularity around 2010, the LD approach seems to have entered now a phase of stabilization. About the (many) criticisms received it can be remarked, e.g., a (particularly negative) position paper like [29] where the Authors affirm that – given the *general lack of conceptual description* of the linked datasets, the *lack of relationships between concepts* in these datasets at the schema level, the *lack of expressiveness* etc., – "Linked Data Is Merely More Data" and, then, that *this approach can only be of limited value for furthering the Semantic Web vision*. More in general, the LD approach has been objected because of the *necessity of associating all the exploitable data with HTTP URLs that point at RDF descriptions*. Taken to its extreme consequences, this could mean that *all the real-world entities should be characterized by HTTP URLs supplying RDF data when fetched*. This is not only (probably) impossible in general, but it *might be also undesirable from a general, common-sense point of view*.

2.5 Problems related to the use of SW tools

As seen previously, the SWoT domain seems to have now *resolutely embraced* a SW/W3C (Semantic Web/World Wide Web Committee) philosophy with respect to the choice of its proper implementation tools.

However, these tools are notoriously *affected by theoretical and practical limitations* – as admitted even in a specific SW context see, e.g., [30] for the theoretical aspects and [31] for the practical ones. Very in short – see, e.g., [3: 119-121] for a deeper discussion – it can be said that all these limitations derive from the *reduced expressiveness* that, *from a knowledge representation point view*, affects the totality of the SW/W3C languages. All these are, in fact, *binary languages*, which means that *their properties can only denote binary relationships used to link two individuals or an individual and a value*. However, in the real world, we frequently deal with relations that make sense only when *more than a single entity* must be taken concurrently into account see, to give only an example, an *n*-ary relationship like "purchase", Purchase (Seller, Buyer, Good, Price, Date…). We can also note that these upper-level relationships typically occur in the context of *complex, dynamic scenarios* corresponding to situations, events, actions, behaviors, etc., i.e., in the context of those *higher levels of abstraction structures particularly important from a GWEs' point of view*.

3. THE GWEs PARADIGM

GWEs are entities *proper to the digital world*, i.e., they are created using one of those Knowledge Representation Languages (KRL) that aim at *modelling in computer-usable form* large aspects of the world and at *concretely exploiting* the resulting formal representations. GWEs represent the *digital counterparts* of any possible (at least in principle) *concrete/abstract entity discernible in the real world*.

Fundamental constitutive elements of any ontological-oriented KRL are *concepts and instances*. A *concept* corresponds to a specific notion about the real world represented in digital format. These notions can correspond to very broad-spectrum concepts (like human being, event, or artefact) – proper, then, to several application domains – or to concepts specifically associated with a particular application/set of applications (like control room operator, level of temperature, valve or heat exchanger in an industrial domain context). *Instances* correspond to *particular, single examples* of the notions represented by the concepts.

We can now enhance the GWEs' definition given in the first paragraph of this Section. GWEs are, concretely, *specific instances/examples of particular notions/concepts of any possible origin* that can be recognized in the real world. Considering for example a possible, industrial/commercial company called Acme, the GWE ACME_, *digital image of the real-world entity Acme*, can be created as an *instance* of the *general concept* company_ *thanks to the insertion of an instanceOf link associating ACME_ with this concept.* Note that GWEs are *more general* than *virtual entities* as they are normally conceived in an IoT-A, iCore etc. context, i.e., *as digital images of chiefly physical entities* – see sub-sections 2.3 above. GWEs represent then, in the digital world, *all the possible abstract and concrete entities that can be identified (and then "named") in the real world*. These correspond then to physical objects, but also to humans, actions, events, (President Biden's speech in front of the Congress), scenarios (going to the restaurant), and even imaginary entities (e.g., Gandalf, or that terrible fire-breathing green-spotted dragon).

3.1 A simple example

According to a SWoT scenario concerning an Ambient Assisted Living (AAL) application, an ageing person, John, is monitored at home by a distributed control system interacting with John via a *mobile robot*. A simple fragment of this scenario reads then, "On a date corresponding to September 11, 2022, at half past seven p.m., the robot reminds John, via audio warning, of the obligation to lock the front door”.

3.1.1 Encoding the scenario in GWEs terms

Different categories of entities must be dealt with here to be translated, then, into GWEs of different levels of complexity:

- An *animate entity*, John.
- Two *physical entities*, robot and front door.
- A *modality*, the audio warning.
- *Two elementary events*, the first corresponding to the warning of the robot and identified by the surface NL verb “remind”, the second to the information about the necessity of locking the front door and identified by the surface verb “lock”.
- The *logical link* between the two above events. Being able to formally represent this link means being able to denote correctly *the global scenario fragment in GWEs terms*.

Additional information like the “date” and the “obligation” must also be represented, even if they do not give directly rise, see below, to specific GWEs.

The entities of the first three categories do not pose any problems to be represented in conceptual/digital format. They refer, in fact, to a sort of *background terminological knowledge* representing a set of stable, self-contained, *a priori* and basic *notions* that can be considered, at least in the short term, as *a-temporal and permanent*. In the specific example, these notions correspond then, in the digital world, to *simple, standard concepts* like human_being, audio_warning, front_door, denoted here according to the NKRL (Narrative Knowledge Representation Language) conventions. NKRL [32] is a KRL often used for the formal modeling of *structured and spatio-temporally denoted information*; it represents also the support for the digital representation of the GWEs. The first three GWEs to be generated are then *three specific instances,* JOHN_, AUDIO_WARNING_1, FRONT_DOOR_1, *of the above three NKRL concepts*. Note that, in NKRL, concepts (in lowercase letters) and instances (in uppercase) are formalized according to the *usual binary model* used for the standard SW, OWL-encoded, ontologies.

The situation is different when examining the characteristics of the GWEs that must represent, in the digital world, *the two elementary events included in the scenario*. In this case, the original knowledge corresponds to a particularly *complex and structured (foreground) information* designating the interpersonal, dynamic, unpredictable and strongly spatio-temporal characterized behaviors proper to the *specific domain entities (background knowledge)* like John, robot, audio warning and front door. The conceptual model used to formalize this foreground knowledge must *necessarily include*:

- *Conceptual predicates* corresponding to *surface verbs* like “remind” and “look” in the example. They are used *to specify the basic type of elementary event the particular GWEs must take into account*.
- The notion of *functional role*, see [33]. Functional roles are used to specify *the logical and semantic functions* of the background/terminological entities involved in the different elementary events. In the situation corresponding to “the robot sends a warning to John”, the GWE (instance of a concept) ROBOT_1 is the SUBJ(ect) of the action of sending, AUDIO_WARNING_1 is the corresponding OBJ(ect) and JOHN_ is the BEN(e)F(iciary) – see below, Table 1, for the full representation.
- An adequate, specific formalism to denote *the temporal and location information* and its relationships with the global representation of the elementary event.
- A way of *reifying* the global digital representations of the specific elementary events, to be able, then, to use them within larger, complex scenarios/events/narratives etc. – i.e., *within GWEs of a higher level of complexity*. As usual, reification must be understood here as *the possibility of creating new things/entities out of already existing ones* and of *saying something about them without making explicit reference to the original entities*.

The binary model used to represent in digital format the *background*, terminological/definitional knowledge, is quite ineffective for taking into account the *foreground*, dynamic/temporally-characterized knowledge. Some sort of *n*-ary representation must be utilized in this last context. This type of representation allows, in fact, *the coherent assembling within a single symbolic structure of information that is different even if conceptually related*, in particular, the arguments of the predicate introduced by the functional roles. Making use then of NKRL, the global representation in GWEs terms of the above AAL scenario is given in Table 1.

Table 1. Examples of GWEs and high-level GWEs

```
aal9.c11: MOVE:
            SUBJ: ROBOT_1
            OBJ: #aal9.c12
            BENF: JOHN_
            MODAL: AUDIO_WARNING_1
            date-1: 11/09/2022/19:30
            date-2:
```

Move:StructuredInformation (4.42)

On 11/09/2022, at 19h30, the robot reminds John through an audio message of what is described in the predicative occurrence aal9.c12**.**

```
aal9.c12: MOVE:
            SUBJ: JOHN_
            OBJ: FRONT_DOOR_1: (unlocked_, locked_)
            { oblig }
            date-1: 11/09/2022/19:30
            date-2:
```

Move:ForcedChangeOfState (4.12)

On 11/09/2022, at 19h30, John must necessarily, modulator oblig*(ation), lock the front door.*

The two halves of the fragment are then represented by *two structured GWEs*, expressed as instances of conceptual entities that, in this case, do not correspond to simple concepts but to *templates*. NKRL’s templates denote, in the real world, *classes of elementary events/states/situations* like, e.g., “several animate entities are moving”, “forced displacement of a physical object”, “production of a supporting service”, “some messages are sent or received”, “change the state of an entity”, etc. As it appears clearly from the two structured GWEs of Table 1, templates (and then their instances) are *multi-layered n-ary structures* formed of *several connected triples of the predicate – functional role – argument of the predicate form.* The triples are indissolubly associated together and *have a specific semantic predicate in common* – MOVE in Table 1, but also EXPERIENCE, EXIST, OWN, PRODUCE etc. [32, 56-68].

In the templates’ instances (i.e., in the structured or complex GWEs), the semantic labels like, e.g., move.ex1 in Table 1, *reify the global structures giving them a “name”.* This sort of reification is particularly important because these semantic labels can be used to associate together several independent GWEs, giving then rise to the *symbolic representation of complex real-world scenarios*. In Table 1, e.g., the transmission of the message to John is represented by assuming that the symbolic label aal9.c12, denoting indirectly the content of this message, is taken as the OBJ(ect) of the transmission of information represented by the aal9.c11 GWE.

This particular associative modality, which makes use of Higher Order Logic (HOL) structures, is called "*completive construction*" in NKRL [32, 87-91]. To underline its particular state, the label used as a filler (aal9.c12 in the example) is prefixed, in the external NKRL format, by a sharp, "#", code; *the format of any completive construction filler corresponds then to #symbolic_label*. Another HOL linking modality of NKRL is represented by the "*binding construction*" [32, 91-97], where several symbolic labels denoting elementary events are associated in the form of a *list of arguments of a particular binding operator* like, e.g., CAUSE, GOAL, or simply COORD(ination). In this context, important examples of HOL NKRL structures are then, e.g., (CAUSE s1 s2), meaning that the event denoted by the label s1 *finds its origin* in the event denoted by s2, and (GOAL s1 s2), meaning that the *purpose* of the event denoted by s1 is the coming about of the situation denoted by s2.

The additional elements used in Table 1 to complete the representation of the scenario's fragment are *standard NKRL features of the determiners/attributes type* [32, 70-86], used then to *supply additional information* with respect to the basic "*predicate-functional roles-arguments of the predicate*" structure of templates and their instances. The *deontic modulator* oblig(ation) has been employed, e.g., in aal9.c12 to denote the *absolute necessity* of locking the front door; the *temporal attributes date-1 and date-2* are used to introduce the *temporal information proper to the original elementary events*, see [32, 80-86, 194-201] in this context.

The list of the NKRL's knowledge representation features is, however, much larger than what introduced so far. An important NKRL's feature concerns, e.g., the possibility of creating the arguments of the predicate – like ROBOT_1, JOHN_, AUDIO_WARNING_1, etc. in Table 1 – under the form of "*structured arguments*" represented by *sets of recursive lists*. These are introduced using the four AECS operators: the *disjunctive operator* ALTERN(ative) = A, the *distributive operator* ENUM(eration) = E, the *collective operator* COORD(ination) = C and the *attributive operator* SPECIF(ication) = S. As a simple example, by assuming that MARY_ shares with JOHN_ the monitored house, the recipients of the message issued by the robot (i.e., the BENF fillers in aal9.c11) – and, at the same time, the persons who should lock the front door (the SUBJ filler in aal9.c12) – *should be denoted as (COORD MARY_ JOHN_)*. An example of use of the operator SPECIF is given in Tables 2 below. Because an unruly use of the AECS operators could give rise to *inconsistent conceptual structures,* these operators are used according to a so-called *priority rule,* see [32, 69-70]. This rule corresponds, in practice, to a suite of *cogent instructions* like, "It is impossible to use a list COORD within the scope of a list SPECIF – while the inverse is perfectly legal".

3.1.2 Dealing with more complex scenarios

Thanks, in particular, to the possibility of making use of HOL structures, *the expressiveness' level of NKRL can be considered as particularly important.* Making reference, for example, to the "robot's message" example, the representation of Table 1 can be *easily improved/enlarged* by introducing a new GWE denoted by a *binding construction* (see the previous sub-section) like (CAUSE aal9.c11 aal9.c13). In this, aal9.c11 still denotes the "message component" of the scenario of Table 1, and aal9.c13 is a new structured GWE corresponding to the robot that discovers the unlocked door.

Further information about the use of HOL structures in NKRL can be obtained by examining an interesting project recently carried out as a collaboration between the Milan Polytechnic (Italy) and the Greek Kleemann Hellas SA company, see [1]. In this work, the conceptual framework proper to the GWEs paradigm has been utilized to model both *the physical entities of the system and the associated events, situations, behaviors and relationships*. The paper describes, in particular, how the GWEs methodology has been used *to deal with two real case studies* of the Kleeman manufacturer, the first concerning the mechanization of the procedures of a bending machine and the second intra-shop floor transportation with automated guided vehicles.

Table 2 shows how the GWEs/NKRL knowledge representation tools introduced above have been utilized, with the appropriate modifications, in the context of *the second use case* mentioned in [1]. In this, the control center of the KLEEMANN's factory must provide the reload of a particular bending machine by sending an AGV (Automated Guided Vehicle) to transport a new metal sheets pallet from the warehouse to the bending workstation. A specific sensor device (such as a weight scale or a smart camera) has reported, in fact, that *the bending tray is empty*. A structured GWE in the form of NKRL's *causal binding construction,* (CAUSE kle2.1.c04 kle2.1.c03) is then used to formalize the core of the reloading operation. In this GWE (Table 2), kle2.1.c04 and #kle2.1.c05 are associated within a *completive construction*, with kle2.1.c04 representing the operator who sends a message to the automation central, and #kle2.1.c05 denoting this specific message; kle2.1.c03 is the sensor's report. The "*cause*" of the reloading request (kle2.1.c04) comes from, then, the original sensor device notification (kle2.1.c03). Note the use or the operator SPECIF(ication) in the filler of the functional role TOPIC.

Table 2. Use of high-level GWEs in an industrial context

```
(CAUSE kle2.1.c04 kle2.1.c03)
```

The cause of what represented in kle2.1.c04 *is described in* kle2.1.c03.

```
kle2.1.c04: MOVE:
              SUBJ: OPER_1
              OBJ: #kle2.1.c05
              BENF: AGV_CENTRAL
              MODAL: MESSAGE_1
              date-1: 11/03/2022/11:30
              date-2:
Move:StructuredInformation (4.42)
```

On 11/03/2022, at 11h30, an operator sends a message, detailed in #kle2.1.c05, *to the AGV central***.**

```
#kle2.1.c05: MOVE:
              SUBJ: AGV_CENTRAL
              OBJ: BENDING_TRAY_1: (empty_, loaded_)
              { oblig }
              date-1: 11/03/2022/11:30
              date-2:
Move:ForcedChangeOfState (4.12)
```

On 11/03/2022, at 11h30, the AGV must necessarily, modulator oblig*(ation), reload one of the side trays of the bending machine.*

```
kle2.1.c03: PRODUCE:
                SUBJ: SENSOR_1
                OBJ: NOTIFICATION_1
                BENF: OPERATOR_1
                TOPIC: (SPECIF BENDING_TRAY_1 empty_)
                MODAL: audio_message
                date-1: 11/09/2022/19:30
                date-2:
Move:StructuredInformation (4.42)
```

*On 11/03/2022, at 11h30, the sensor device reports to the operator that one of the side trays of the bending machine is empty – this tray is characterized by a physical state specified as "empty"***.**

4. ARCHITECTURAL ASPECTS

A typical architecture for GWEs-oriented platform, structured into *three main layers*, Front-end layer, Core layer, and Sensors/Actuators layer, is schematized in Fig. 1, see [3, 127-131] for additional information.

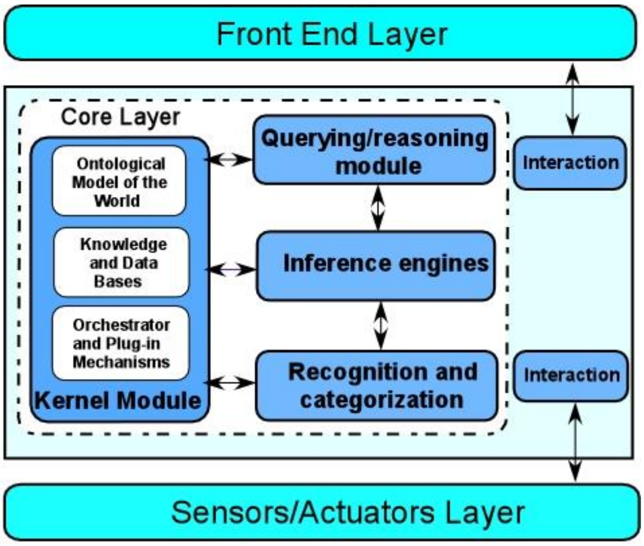

Fig 1: Schematic Architecture of a GWE-based IoT system.

The concrete generation/utilization of the GWEs entities of any possible degree of complexity is a complex process *including three main phases*, see again [3] for more details.

- *Identification/accurate characterization* of all the possible entities which enter a GWEs-based system through external data streams generated from RFIDs, contact switches, cameras, LIDARs, radars, Wireless Sensor Networks (WSNSs), etc. All these original entities must:
  - be endowed with *a (provisional) identifier* (e.g., URI-like), to be transformed into a specific instance label, like aal9.g1 or ROBOT_1 above, during the following recognition/categorization phase;
  - be provided with *a set of features/properties* to be computed in real time;
  - be equipped with *some interface* to communicate/be integrated with other entities.

  In many cases, the identification will be, at first, *partially incomplete* – e.g., “squared object” instead of “table”. Moreover, identifying the characteristics of complex entities like events, situations and circumstances corresponding in practice to structured GWEs, can require the use of *complex inference operations*.
- *Categorizing* the recognized input entities. This means *creating a correspondence* between the *real entities* (objects, events, relationships, situations, circumstances etc.) coming from the external environment and the *high level conceptual and ontological representations* proper to the specific, *NKRL-based world model* used in a GWEs context. This world model utilizes *two structurally very different but operationally fully integrated ontologies*:
  - The modelling of the *simplest*, *background GWEs*, like physical objects as tables, cars, bottles or vegetables – but also temperatures, pressures etc. – is realized in NKRL by using a *standard binary ontology* called HClass (hierarchy of classes). Simple GWEs like ROBOT_1, JOHN_, FRONT_DOOR_1, see Section 3, correspond then to *instances of HClass concepts* like robot_, individual_person, front_door etc.
  - The formalization of the *foreground knowledge* (events/situations/circumstances etc.) where the above static entities are involved, *cannot be realized using simply binary standard ontologies and RDF(S)/OWL solutions*. More complex and powerful conceptual structures, corresponding to NKRL’s *n-ary templates*, must then be used – see, e.g., the templates employed in the encoding of the 3.1.1 example. Templates are collected into a *second NKRL ontology*, *HTemp (hierarchy of templates)*; they correspond to *formal descriptions* of *classes of dynamic entities* denoting events, situations, circumstances, behaviors etc.
- *Reasoning about the full recognized situations*. When all the (*simple or structured*) GWEs have been created, we can use the general, NKRL-based, world description (HTemp + HClass) enriched with all of the new GWEs *to take decisions*. In a GWEs context, these *reasoning activities* – realized, mainly, under the form of NKRL inference procedures – can concern, e.g.:
  - *Avoiding and managing critical situations*. This type of inference refers to situations where, e.g., the goal of a given GWE-based application consists in *preventing a dependent person with vision troubles (or a robot or a baby) to collide with potentially dangerous objects*. The same type of inference can be used in contexts of homeland security, driving control, rover exploration of unknown territories, butler robots, crisis situations etc.
  - *Planning*. These activities concern, e.g., the supervision tasks of an ageing person, or the creation of a buying path within a supermarket, or the simple provision a cold drink. Planning includes prioritizing the goals, establishing when goals are complete, defining when the system is required to re-plan, etc.
  - *Monitoring*. Monitoring concerns a large class of possible applications, from those regarding an elderly person in homecare after hospitalization to the anticipation of terrorism activities, decontamination of lands/buildings, gas/oil plants control, etc.
  - *Intentions/behaviors detection*. Inferences of this type have normally *GWEs of the human type as central characters*. They can be associated with monitoring activities when, e.g., it is necessary to infer from the actions of the old person her/his (may be risky) real intentions, or when the hostile purposes of an intruder must be detected. They also concern *“sociological” applications* like detecting particular behaviors in young people, learning about the behavior of shoppers or intentions of (human and automatic) drivers, etc.

5. CONCLUSION

A consensus exists about *the need of adding more “intelligence” to the current IoT systems* to transform them into real SWoT-like solutions The description in Section 2 of the existing SWoT proposals has however shown that some of these proposals *are far from being really innovative and proficient as originally promised*. Therefore, there is still room, *in a SWoT context, for new, original efforts*.

This paper summarizes then some important characteristics of the GWEs (Generalized World Entities) paradigm. This concerns an innovative understanding of the general SWoT purposes where the possibility of: i) interpreting the environmental and context information, ii) detecting information related to human intentions/behaviors, iii) enabling human-like inferences and multi-modal interactions, and eventually iv) acting on behalf of the user purposes are *particularly important*. Moreover, GWEs *are not limited, as* *used, to physical objects*. On the contrary, this paradigm supplies a *uniform formalism* for describing objects, agents, events, situations, circumstances behaviors etc. their evolution in time, as well as the relations among these entities.

These *advanced characteristics* explain why GWEs' implementation could not be based on the use of the standard Semantic Web tools, given their limits from an *expressiveness point of view*. A tool based on an *advanced n-ary approach*, NKRL, has then been used. Interestingly, NKRL seems also to represent *one of the few existing n-ary proposals relatively close to commercial exploitation* see, e.g., the recent NKRL/GWEs-based industrial application mentioned in [1].

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