Enriching a Situation Awareness Framework for IoT with Knowledge Base and Reasoning Components

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Abstract. The importance of system-level context- and situation awareness increases with the growth of the Internet of Things (IoT). This paper proposes an integrated approach to situation awareness by providing a semantically rich situation model together with reliable situation inference based on Context Spaces Theory and Situation Theory. The paper discusses benefits of integrating the proposed situation awareness framework with knowledge base and efficient reasoning techniques taking into account uncertainty and incomplete knowledge about situations. The paper discusses advantages and impact of proposed context adaptation in dynamic IoT environments. Practical issues of two-way mapping between O-MI/O-DF standards and Context Spaces are also discussed.

Keywords: Context Space Theory, Situation Awareness, Situation Theory, Ontology, O-MI/O-DF, Context Adaptation

1 Introduction

With the growth of the Internet of Things (IoT) more and more devices publish sensed information of the environment, promoting the development of smart services and pervasive computing systems. The key feature of these systems is called context awareness, i.e. computing systems become aware of their environment and can thus provide services of higher value to humans [1]. Existing implementations of pervasive computing systems include for example home automation, smart energy systems, decision support systems for emergency cases, environmental impact monitoring, improved efficiency of transportation systems and many more. Furthermore, the IoT – with this trend still being in its early stages – is seen as a key technology that could potentially enable the transition to a more sustainable society by providing the necessary information for a fundamental change in the way societies produce and consume. These advances are driven by large-scale problems and global challenges like resource depletion, food security and climate change, as for instance stated by the Ellen MacArthur Foundation[3]. For IoT-based systems to be deployed more vastly and in a bigger scope, particular regarding its pervasive feature, several research challenges in various disciplines still have to be solved.

In order to fully understand its environment a pervasive computing system needs to interpret acquired sensor data. Whereas *context* refers to features of entities [1], *situations* are of a more complex structure, e.g. involving relations between entities and requiring additional semantic interpretation. Situation aware applications thus rely on the integration of external knowledge to achieve an understanding of the environment on a higher level of abstraction than context [29].

This paper is concerned with challenges in knowledge representation and reasoning to achieve situation awareness in a general way. When defining the knowledge base in the form of a situation model several issues have to be dealt with. The paper is built upon prior work: A domain-independent approach combining various concepts, e.g. ontologies, Context Space Theory (CST), Situation Theory, the Open-Messaging Interface (O-MI) and the Open-Data Format (O-DF) to provide a holistic framework for situation awareness [16]. Based on this framework the following discussions cover the knowledge base integration, issues that are caused by incomplete knowledge about situations and the implications of adaptation to current context for the knowledge base.

Section 2 will present related work and background in the domain of ontologies as knowledge base for situation aware systems. Section 3 introduces the framework that is considered in this paper to achieve situation awareness. It forms the foundation for discussions in the subsequent sections. Section 4 is concerned with defining and handling the knowledge base and preprocessing it for run-time reasoning. The following Sections 5 and 6 deal with incomplete knowledge and context adaptation related to the knowledge base respectively. The paper is concluded in Section 7.

2 Ontology-based Situation Awareness

Ontologies are defined as an "explicit specification of a conceptualization" [14] and have often been applied – among other techniques like graph models, object-role modeling, markup schemes and spatial logic – to develop a general model for situation awareness. As stated in related surveys that compare underlying techniques for context models like [3], ontologies are powerful in handling the heterogeneity of sensor data, capturing relationships and dependencies between context information and its support for reasoning.

Furthermore "being understandable, shareable, and reusable by both humans and machines" [29] is another important aspect since the processes of gathering and maintaining the required domain knowledge is complex and error-prone.

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[3] Ellen MacArthur Foundation, Report on Intelligent Assets:
https://www.ellenmacarthurfoundation.org/publications/intelligent-assets

Ontologies can also be integrated into the existing infrastructures of relevant computing environments [24]. With such features the knowledge engineering effort can be significantly reduced which motivates the incorporation of ontologies into a general situation awareness framework.

Ontologies can be represented in various different ways, the most prominent being the Resource Description Format (RDF) in combination with RDF Schema (RDFS), and the Web Ontology Language (OWL). OWL [18] extends the RDFS vocabulary for RDF and thus the de-facto standard language for ontology development. Ontology reasoners, e.g. Pellet [22], are able to compute new relationships between the entities based on the given specifications of an ontology.

2.1 Situation Models and Upper Ontologies

Semantic web technologies provide a solid foundation as a knowledge base for situation awareness in IoT settings by providing a platform to share and reuse defined knowledge. The design of ontologies for this purpose need to comply with content-related requirements regarding the capabilities of representing contexts and situations in a general way.

Investigations of upper ontologies that were developed to capture domain knowledge for context awareness can be found in surveys like [2]. The authors developed an evaluation framework with context- and situation-related criteria and compared the design of four ontologies, i.e. SAWA [17], Situation Ontology [28], SOUPA [8] and CONON [27]. It is concluded that the ontologies that are primarily targeted for context awareness (SOUPA and CONON) do not comply with the criteria for a general situation model. Most of the criteria are met by the SAWA ontology, however, even this approach lacks the support of situation types, roles and representation of space and time.

Another ontology developed for the purpose of situation awareness is the Situational Context Ontology [3]. The model combines contextual information (spatial and temporal) of persons with situations these are involved in. Situation definitions are not entities of the ontology itself but formulated with SWRL rules. The approach of the Situation Theory Ontology [15] is the result of transferring the semantics of the Situation Theory [11] to ontologies. In Situation Theory facts about the world are denoted as infons, which define relations among objects (individuals, attributes, situations) and its polarity (true or false). A situation is defined by specifying which infons they support. Moreover the theory supports logical operators and parameters representing types of objects and situations for more complex statements.

2.2 Further Requirements for Reasoning

Besides the requirements for the formalism of the situation model further considerations need to be taken into account to achieve reliable reasoning results and practical applicability of the approach. These include for example mobility, timeliness as well as uncertainty (imperfection and ambiguity) [3]. Furthermore incompleteness, distributed composition of the system [24] – e.g. incorporation of sensor data from various sources and interoperability aspects – and the ability of the system to adapt current context may have implications on the model. In this paper we limit the discussion to aspects of uncertainty, incompleteness, sensor data integration and dynamic context adaptation related to ontology-based situation models.

Uncertainty aspects of a pervasive computing system, i.e. imperfect sensor data (e.g. missing values, imprecision) and incomplete knowledge about situations, are often approached with fuzzy logic. In fuzzy logic membership functions can be defined which map a set of numerical values to a fuzzy variable. The rule-based reasoning then calculates a membership degree (between 0 and 1) for each fuzzy set since the conditions for the sets may overlap. One approach that combines fuzzy logic and ontologies for situation awareness is the Fuzzy Situation Theory Ontology (FSTO) [13]. It extends the polarity of the infons of Situation Theory. Instead of assigning boolean values to the relation among objects also vague expressions like *quite true* can be formulated. Situation occurrence is then inferred trough a model which considers the membership functions for infons as well as situations (since situations can support multiple infons).

From a holistic point of view for a situation aware approach the integration of sensor data also plays an important role, both from a modelling perspective – i.e. linking sensor data from physical data to modelled context – as well as an interoperability perspective – i.e. acquiring sensor data in an IoT setting. An example and W3C standard to model a sensor setup is the Semantic Sensor Network (SSN) Ontology [9]. It allows to define information about sensing devices, the network setup and observations (sensor data readings). In an effort to provide a similar model for actuators, the SAN ontology[4] was developed. Both ontologies were applied for example in [23] to provide an *IoT Ontology*.

Smart services in the IoT are based on the access to contextual information and other services from various sources. Interoperability between these assets is thus a major concern. Messaging standards developed to address these issues are O-MI and O-DF. O-MI defines a set of possible interactions between entities, enabling a peer-to-peer data exchange to ensure interoperability in the IoT domain [26]. O-DF provides a generic structure for IoT payload information [25].

3 Framework based on Context Space Theory

This section introduces the framework on which the work of this paper is based on (originally presented in [16]). Since the exclusive use of ontologies is not sufficient to meet all requirements for a situation aware system the combination of different techniques is necessary. The approach is based on ontologies for modelling and merged with the Context Space Theory for reasoning and O-MI/O-DF for sensor data acquisition.

The Context Space Theory [20] was developed for reasoning about context based on a spatial representation. Fig. 1 visualises the main concepts of this

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[4] SAN Ontology: https://www.irit.fr/recherches/MELODI/ontologies/SAN.owl

theory. Context attributes, which are measurable properties usually provided by sensors, form the dimensions of the context or application space. Real-life situations are represented as subspaces of the application space, named situation spaces. The context state describes a point that moves through the application space depending on the current values of a corresponding set of context attribute values over time. If the context state lies in the subspace of a situation, this situation is occurring. This inference is based on a place-holder function which allows the usage of different techniques to reason about situation occurrence.

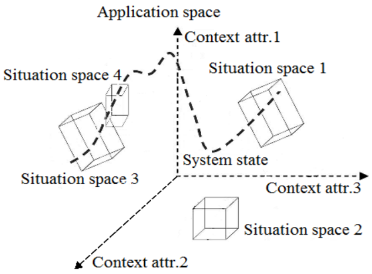

Fig. 1. Illustration of the Context Space Theory [5]

The overall architecture of the framework, which is based on ECSTRA [6], is displayed in Fig. 2.

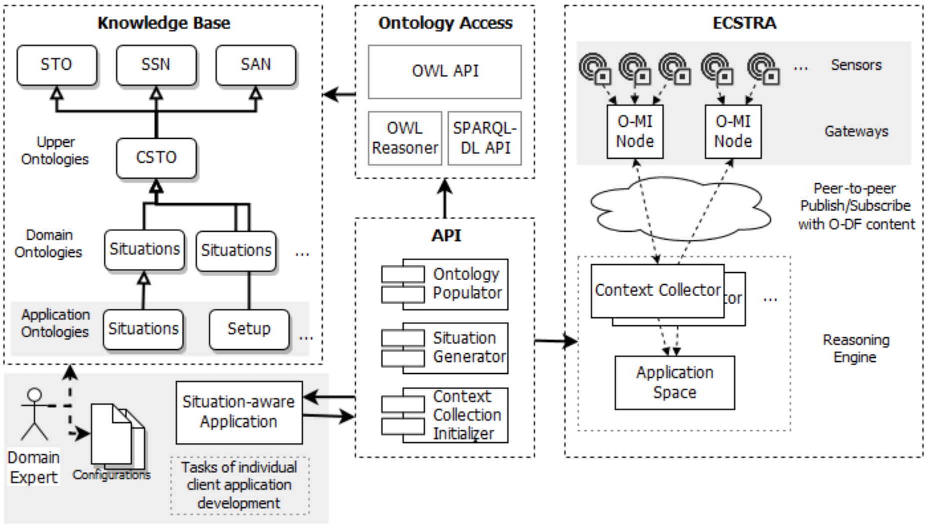

Fig. 2. Framework Architecture for Situation Awareness

The upper ontology designed for this framework is based on STO and SSN. The concepts of these different ontologies were mapped and specific CST-related aspects added to the ontology (presented in [16]). The upper ontology is used to capture domain- and application-specific knowledge about situations, individuals, attributes, sensors, actuators, their relations and their dependencies. The combined use of these ontologies allow the specification of all relevant knowledge assets for a situation aware system.

This information is extracted from the knowledge base to generate situation spaces in the context space, i.e. to initialize the application space. The following section will explain in more detail how the situation semantics from STO are transferred to situation spaces in CST. Furthermore the definitions from the ontology can be used to assign sensor data to relevant context attributes and involved individuals in situations. This approach exploits the advantages of ontologies and a sophisticated situation model and provides a flexible and efficient context reasoning foundation.

A related approach that combined CST and ontologies is presented in paper [7]. In this approach a context ontology (CONON) and a sensor ontology (SSN) are used as a foundation to develop situation formulas which are then translated to Context Space.

4 Integration of the Ontological Knowledge Base into the Reasoning System

The section presents the incorporation of a knowledge base for a CST-based approach. First, the situation models from Situation Theory and Context Space Theory have to be mapped. Further processing in the knowledge base allows a solid initialization of the application space, as presented in the second subsection.

4.1 Mapping of Situation Representations in ST and CST

In order to benefit from the advantages of both approaches, Situation Theory and Context Space Theory, situation definitions represented in ST have to be transferred to situation spaces in CST. This section presents the composition of a situation space in CST and how this knowledge can be taken from a ST definition.

According to CST $[4, 20]$ a situation space S_j is formally defined by set of acceptable regions A_i^j for each corresponding context attribute a_i. The formal definitions are given in Table 1. An acceptable region A_i^j contains the elements that satisfy a specified predicate $P(V)$. The relevance function $w_S(a_i)$ assigns a weight w_i to each context attribute a_i for a situation space S which signifies the relative importance of a particular context attribute to infer a situation occurrence. The contribution function $\eta_i^S(x_i)$ assigns a contribution degree c for each value x_i in an acceptable region for a situation space. The inference function μ_s is composed of the previous specifications. The calculated confidence value for

Table 1. Definitions related to Situation Spaces in CST [20]

Situation Space	$S_j = \left(A_1^j, A_2^j, ..., A_n^j\right)$
Acceptable Region	$A_i^j = \{V \vert P(V)\}$
Relevance Function	$w_S(a_i) = w_i; w_i \in [0,1]$ and $\sum_{i=1}^{n} w_i = 1$
Contribution Function	$\eta_i^S(x_i) = c_i^S$
Inference Function	$\mu_s = \sum_{i=1}^{n} w_S(a_i) * \eta_i^S(x_i)$

situation occurrence is compared to a confidence threshold ε_i to get a boolean output.

In ST [11], situations are defined by specifying which infons they support, i.e. $s \models \sigma$. Infons represent facts about the world and are defined as a relation r among n objects, denoted as $\sigma = \ll r, a_1, ..., a_n, i \gg$. Objects that stand in a relation can be individuals, attributes and situations. Furthermore ST considers the definition of types and parameters to make statements about a group of objects, which were extended for STO. *ATTR*, *SIT* and *VAL* for example represent the types of attributes, situations and values correspondingly.

Table 2 shows the mapping of concepts of CST and ST. It lists all parts of a situation space definition as presented before and links them to assets of situation definitions in ST. As it can be observed the basic composition of a situation space can be extracted from the situation definition in ST. Information required for CST-based reasoning cannot be extracted based on the definitions. Thus, the situation specification in STO requires extensions to allow the integration of all required assets in the knowledge base.

4.2 On Involved Individuals and Type Definitions

Situation reasoning is not only dependent on the context attributes, but also on *individuals* – items, persons, objects, etc. – that are involved in the situation. In CST, multiple involved individuals for one situation definition can be handled in two ways. Either by updating context states simultaneously and by reasoning about a general situation space, or by updating a single context state and to reason over dedicated situation spaces and context states. The second case needs to be considered for example if situation spaces of a type definition differ depending on the involved individual or if the situation space changes over time depending on reasoning results. As discussed before, the data from physical sources is linked to individuals and situation definitions by extending the model with the SSN ontology.

The support of type abstraction is an important feature in order to keep the complexity of the modelling process low. ST facilitates such general specifications trough the use of (abstraction) parameters in situation type definitions. As defined in [11], situation types are formally denoted as $[\dot{s} \vert \dot{s} \models \sigma]$. The transformation

Table 2. Mapping of CST and ST concepts

CST concept		**ST/STO concept**
Name of situation space S_j	$\Leftrightarrow$	Situation definition s
Name of context attribute a_i	$\Leftrightarrow$	Attribute definition a_n of type $ATTR$
Composition (attributes) a_i relevant for S_j	$\Leftrightarrow$	Attributes in supported infons a_n of type $ATTR$ in $s \models \sigma$
Composition (subspace) S_i relevant for S_j	$\Leftrightarrow$	Situations in supported infons a_n of type SIT in $s \models \sigma$
Acceptable region A_n^j	$\Leftrightarrow$	Attribute values a_n of type VAL
Relevance w_i	$\Leftrightarrow$	-
Contribution c	$\Leftrightarrow$	-
Confidence Threshold ε_i	$\Leftrightarrow$	-

from a situation definition to a situation space differs if the situation definition is based on types, as it will be explained in the following.

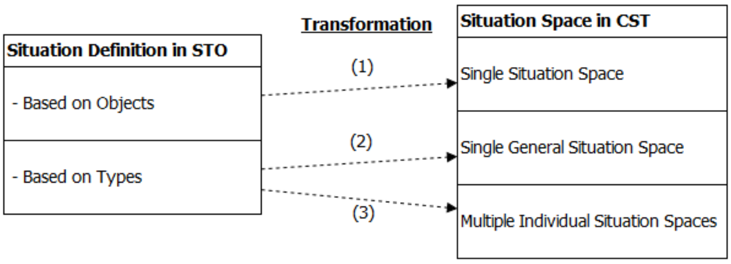

Fig. 3. Transformation from Situation Definition to Situation Space

Given a particular situation definition in this situation model and different requirements for the reasoning process, the situation space generation has to be handled in different ways. Fig. 3 shows a classification of the transformation types from situation representation in ST to CST.

If a situation definition is solely based on objects it can be transformed to a corresponding single situation space in a straight-forward manner. The transformation is formally denoted in Eq. (1).

$$s \models \sigma \Rightarrow S_j \tag{1}$$

If a situation definition in STO includes type abstraction two approaches for situation generation can be differentiated, based on the considerations in the beginning of this section. The first option, denoted in Eq. (2), represents the generation of a general situation space for a set of involved individuals.

$$[\dot{s} | \dot{s} \models \sigma] \Rightarrow S_j \tag{2}$$

The second option for a type-based transformation, formally given in Eq. (3) generates multiple situation spaces. First, all possible situations based on objects are derived from the type definition. To achieve this the n-fold Cartesian product over the objects of the n type definitions involved in the situation definition is calculated. The definitions based on objects can then be transformed to corresponding situation spaces.

$$[\dot{s} | \dot{s} \models \sigma] \Rightarrow \{s \models \sigma\} \Rightarrow \{S_j\} \tag{3}$$

The decision on how situations should be defined and how the application space should be initialized application-specific. The framework presented in Section 3 thus allows corresponding configurations.

5 Incompleteness and Ambiguity in the Situation Model

The approach for situation inference of CST that was used in ECSTRA is based on the evidential Dempster-Shafer approach [21] to calculate confidence levels [6]. Furthermore, with the use of contribution functions it also incorporates fuzzy logic. Due to the context-centric design of this theory, other well-known reasoning techniques can be applied, as for example shown with the Bayesian approach [19]. Different techniques for reasoning have different strengths in covering uncertain aspects. The application of both, evidence theory and fuzzy logic, for example is capable of handling incomplete, imprecise and out of date contextual information [29].

The utilized inference technique does have an impact on the knowledge base and the information assets that have to be provided. Based on the inference function presented in Section 4 the situation definitions in the knowledge base need to be extended to provide all required assets to allow situation reasoning. This includes the confidence thresholds, which have to be specified for situations, relevance functions, which need to be attached to attributes, and contribution functions, which are required for attribute values, as presented in [16]. The incorporation of the relevance function into the infon definition, for example, can be formally denoted as $\sigma = \ll r, (a_1, w_1), ..., (a_n, w_n), i \gg$.

For specification-based approaches the availability of knowledge is a major concern. Domain experts need to be able to define the situations beforehand. The contribution function and the relevance function already allow modelling of situations with imprecise knowledge. With STO as an underlying situation model this aspect can be even further improved. The integration of the earlier introduced Fuzzy STO [13] for example allows a non-numerical specification in case of vague knowledge about a situation. In FSTO the polarity i is replaced with τ which is element of a grammar that allows statements like *quite*, *less*, *really* true or false. Even though the weight w_n and the extended polarity τ both form a part of the infon definition they are semantically not equal. Whereas the weight assigns a relative importance to the attributes, τ makes a statement about the truth of the overall infon. This increases the imprecise modelling capabilities for domain experts. In order to incorporate this extension of the situation model for the reasoning process the transformation process needs to take the new value into account and the CST inference function needs to be adjusted. The corresponding inference function is shown in Eq. (4) in which $\mu_{\tau_\sigma}(a_i)$ represents the confidence in the infon truth of the supported infon in which the attribute a_i is involved.

$$\mu_s = \sum_{i=1}^{n} w_S(a_i) * \eta_i^S(x_i) * \mu_{\tau_\sigma}(a_i) \tag{4}$$

Another problem situation aware systems encounter is the absence of knowledge. This is a major concern for any specification- or learning-based approach, either in the form of missing situation definitions or incompleteness in the training data. It is a difficult challenge to react properly to an unknown situation, i.e. when the contextual circumstances cannot be interpret with the provided knowledge. In CST this occurs when the context state reaches a point in the application space which is not inside of any situation space. The following measures can be considered to address these issues.

Verifying completeness of the knowledge base. The knowledge base could be analysed before the deployment of the system to identify gaps. For the presented framework this could be done by looking for gaps in acceptable regions for context attributes. If no situation definition covers values within a reasonable range of that attribute, it is likely that a situation definition is missing.

Reasoning-supported completion by the domain expert. If unknown situations are encountered during run-time the system could provide additional information to the domain expert and even make suggestions about the unknown situation. For example previous and following situations, situations with same context attributes and situations near the context state can give a semantic indication of the unknown situation.

Accessing remote repositories with situation definitions. Assumed situation definitions will be specified by various domain experts in a standardized way, the possibility to look up general situations stored in remote repositories might allow to automatically close the gaps for undefined situations.

To summarize, handling uncertainty in the knowledge base of a situation aware system is a necessary step to enable reliable reasoning and to provide a practical approach to represent domain knowledge. Identifying and resolving gaps in that knowledge is necessary in order to avoid encounters with unknown situations during run-time which may lead to malfunction of the overall system.

6 IoT Interoperability and Context Adaptation

This sections aims to discuss in more detail practical issues for IoT interoperability and adaptation to dynamic environments. The impacts on the framework and the knowledge base will be investigated.

6.1 IoT Interoperability with O-MI/O-DF Integration

Interoperability is a major concern for the IoT. *Vertical silos* prevent the communication between different domains on several levels [10]. Two IoT messaging standards are applied for the framework to bypass interoperability issues on both messaging protocol and data annotation level. O-MI provides a messaging interface which can be used on top of session protocols. Sensor data is eventually published by O-MI gateways providing an abstraction from the underlying messaging protocol of the sensor networks (e.g. CoAP, MQTT, XMPP). For data annotation interoperability the framework considers O-DF which provides a generic content description model for Things in the IoT [12].

Based on a standardized communication setup and a knowledge base the implementation effort for context collection of the reasoning engine can be significantly reduced. Solely configuration files are required in order to map the O-DF annotations to objects (sensors, attributes, etc.) that are defined in the ontology. Upon initialization of the system not only the application space but also the context collectors will be generated. After creation the context collectors start the subscription of the O-MI gateways based on the provided configuration. During run-time the O-DF annotated data will be resolved via the knowledge base which allows to update the context state (following the situation inference etc.) without custom modules.

This enables automated reasoning with minimal implementation effort for client applications, taking into account a standardized IoT embedment.

6.2 Adaptation of the Knowledge Base to Current Context in a Dynamic Environment

Situation aware systems are often deployed in dynamic environments. In order to be able to provide situation awareness with dynamic aspects the knowledge base needs to adapt to current context to stay up-to-date. The following dynamic aspects that have a direct impact on the knowledge base are considered.

- Involved individuals entering or leaving the system's scope.
- Sensors entering or leaving the system's scope.

Adapting to these changing does not only imply maintaining the knowledge base – e.g. adding and removing involved individuals and sensors – but also maintaining the application space – e.g. adding and removing situation spaces.

Since the framework already provides situation awareness, the adaptation mechanism can be integrated on top of the existing functionalities in a straightforward manner. Individuals or sensors entering or leaving the system can be seen as a contextual information which is provided by sensors.

Recognising involved individuals requires additional sensing, e.g. information provided by video cameras or smartphone locations could be used to track the presence of persons. Tracking sensors can achieved by detecting new or missing data published by the O-MI gateway.

The different events of tracking individuals and sensors can be modelled as situations. Upon the occurrence of such a situation the framework automatically takes all necessary steps (regarding knowledge base and application space) to adapt the system to the new circumstances.

7 Conclusion and Future Work

Based on previous work this paper discussed the incorporation of an ontology as a knowledge base for a situation aware framework. Detailed explanation of the mapping of Situation Theory and Context Space Theory showed how a reasoning framework based on CST can be advanced with a situation model like ST and the ontology STO. It can be concluded that the combination of these theories provides both a foundation for knowledge sharing and reuse as well as a flexible reasoning technique.

The discussions related to the knowledge base included further:

- The required knowledge assets that have to be provided to allow reasoning.
- Modelling incomplete knowledge.
- Handling unknown situations.
- Interoperability related issues in IoT.
- Adaptation to current context.

In conclusion, the situation model could be extended to accommodate all relevant assets and to enhance the run-time reasoning. Moreover, the knowledge base allows modelling with imprecise knowledge and also allows the tracking of semantic changes of the system's environment and to provide situation awareness in a dynamic environment.

Future work includes the development of use cases to compare different approaches to uncertainty modelling and resolving unknown situations.

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