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Stratified Model of the Internet of Things Infrastructure

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Abstract: The scale and the complexity of modern network solutions built upon the promising and popular paradigm of the Internet of Things brings to the table the vital need for novel approaches to these solutions designing. To foster the further developments in this direction, the stratified model of the Internet of Things infrastructure has been proposed. There are distinguished three hierarchical layers: the lowest one is represented with web services, the intermediate one-with usage scenarios, the upper layer-with applicability domain of the Internet of Things solution. The model is based on the Temporal Logic of Actions and corresponding TLA+ formalism. To check the specification, created with respect to the proposed model, the TLC model checker has been used. Two approaches to automated TLC-verification have been utilized-model checking by way of breadth-first search and by way of depth-first search. The smart home scenario has been considered.

Key words: Internet of things, model checking, specification, verification, temporal logic of actions, scenario

INTRODUCTION

Nowadays, the rapid growth of the number of different “smart” devices and the involvement of these devices into different usage scenarios (analytics, research, data management, etc. (Ray, 2016)) brings to the table a bunch of complex problems to be resolved, e.g., the ones dealing with devices coordination, interoperability maintenance, etc. Possible solutions can be built on the basis of the Internet of Things (IoT) concept. The IoT can be considered as a network of uniquely addressable interconnected objects (Stojkoska and Trivodaliev, 2017).

There are plenty of different spheres the principles of IoT can be implemented in. The logistics is one of those where the IoT based on service-oriented architecture can be considered to be the accelerator of productivity and profitability (Tadejko, 2015). Promising technology fostering further dissemination of IoT paradigm seems to be the NB-IoT, created to reuse the LTE (Long-term Evolution) design extensively (Wang *et al*., 2017).

Apart from the numerous statements concerning the complexity of getting familiar with formal methods, especially in terms of additional overhead to be taken during the designing, more and more confirmations of these methods practical usage expediency continue to emerge, e.g., the Amazon web services design solutions checking (Newcombe *et al*., 2015). For this purpose the Temporal Logic of Actions (TLA), corresponding TLA+formalism and TLA Checker (TLC) have been successfully used (Lamport, 2002). Moreover, to strengthen the confidence in the design and to foster the potential lowering of debugging-related expenses, the TLA+formalism and TLC model checker have been used in the development of safety-critical modules of software platform for railway control applications (TAS Control Platform) (Resch and Paulitsch, 2017).

Talking about the scenarios of formal methods applicability in safety-critical solutions, the Finnish nuclear industry can be considered as a demonstrative example where the model checking technique has been

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successfully utilized since 2008 to evaluate the instrumentation and control system application logics (Pakonen *et al*., 2017).

There are many of applicability domains for the IoT. One of those is smart cities encompassing plenty of subdomains, e.g., smart home, smart grid, etc., (Khajenasiri *et al*., 2017). When considering the smart home scenarios the outcomes from bringing the IoT can potentially be quite significant-the simplification of housekeeping routines and different subsystems management and control, energy and water consumption lowering, etc. Concerning the applicability of the IoT in smart cities domain, the real time sewerage network monitoring for the purpose of flooding prediction can be considered as live scenario (Edmondson *et al*., 2018).

Taking into consideration all the aforesaid, it can be concluded that the implementations of the IoT encompass the scenarios of different scales. Dealing with the latter example, for instance, it may be assumed that, depending on the scale of sewerage network and the required level of prediction precision, the "smart" system, built upon the network of sensors can be quite complex to manage and control in particular to provide the required level of safety. To do the latter, the formal methods may be extensively used. To successfully proceed in this direction, the need for plausible concepts, models, the metamodels in particular, has to be previously fulfilled. To this end, the entities of certain applicability domain and the dependencies between them have to be properly formalized. In this context the necessity of right abstraction level of formal model(s) specification(s) choosing to be checked and subsequently detailed arises. Plausible solutions can be found by developing the metamodels based on some formalisms and temporal logics. Promising way to do that is to bring the stratification (Mesarovic *et al*., 1970). These models are required to provide the solutions for shifting the abstraction level of specification to further detail it preserving the consistency taking place in more abstract and already checked solutions. Another and complementary prompt for metamodels usage is to provide the mechanisms to safely scale the specification (formal model) alongside with the change of scale and/or complexity of system.

The research is devoted to provide the metamodel fostering the creation of scalable and easy reconfigurable solutions formal specifications of IoT-systems.

MATERIALS AND METHODS

Let us consider the IoT infrastructure as a system. The upper (application) layer of three-layer IoT architecture model has been considered as starting point (Sethi and Sarangi, 2017). All further conceptualization is built on the assumption that this layer is implemented on the basis of web services. These services will be considered as the components of system. Each such component is intended to implement certain scenario.

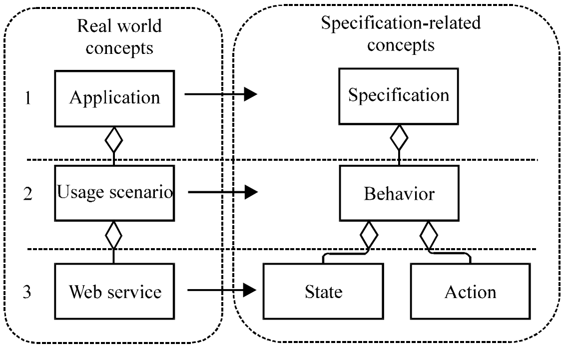

Fig. 1: Three-layered hierarchical model

The conceptualized representation of proposed metamodel is given in Fig. 1. In Fig. 1, the aggregation relation has been chosen instead of composition to highlight the reusability of concepts utilized. This means that, for instance, certain web service can potentially be accessed directly or be involved in different usage scenarios.

Let us first consider the real world-related concepts. The distributed IoT applications are assumed to be implemented on the basis of web services. These services are considered to be the building blocks of the lowest hierarchical layer. Each service is intended to perform some portion of computations to bring to life certain IoT scenario, e.g., the opening of garage door right on time, etc. Meanwhile, the whole scenario is the representative of the second hierarchical layer. It is assumed to encompass the sequence of activities to implement the desired devices functioning and intercommunication aimed, for instance, at certain routine activities simplification. Considering the aforementioned smart home scenario, the subsequent activities, following the opening of garage door, can be the choreographed light sources switching, the automated pets feeding, etc. If considering certain usage scenario, the composition of web services can be taken into consideration.

There are many other smart home scenarios though. To group these scenarios and to reason in formal models more generally and on the higher level of abstraction, the concept of "application" is brought to the use. The application is supposed to be the distributed software system intended to implement a set of scenarios associated with certain applicability domain or subdomain, e.g., the smart home domain can be considered as smart city subdomain.

The modularity of chosen TLA+ formalism provides us with the ability to create scalable and easily reconfigurable specifications in accordance with proposed conceptualization and way of stratification. Drawing the specification-related analogies, the following concepts are brought to the table.

On the lowest hierarchical level the concepts of "State" and "Action" are proposed to be used. The states are considered to be the preconditions for the actions to take place. The action is considered as the activity prompting the transition between states. Not to mention that the notion of action is one of the distinctive features of chosen Temporal Logic of Actions, considered as the main building block of specification.

The concept of behavior is intended to represent the sequence of actions (activities) taking place for certain scenario.

The specification concept should be interpreted as the resulting temporal formula encompassing all the required scenarios to be checked. Let us take a closer look at the concepts described above. To do that, the Kripke structure is used (Eq. 1) (Clarke *et al*., 2001):

$$M = \langle S, \{s_0\}, R, L \rangle \tag{1}$$

where, S-finite set of states, $s_0 \in S$-initial state to get started with during the model checking, $R \subseteq S^2$-total set of transitions between the states: $R(s) = s'$ where $s \in S$-current state, $s' \in S$-subsequent state, L: $S \to 2^{AP}$-states labeling function, AP-set of atomic prepositions. The AP set is formed as follows:

$$AP = V \times D \tag{2}$$

where, $V = \{v_0, v_1, ..., v_{m-1}\}_{m \in N}$-set of state variables: $v_i \in V$-the representation of i-th web service in specification, $0 \le i \le m-1$; $D = \{d_0, d_1\}$-set of state variable's values: $d_0 = 0$, $d_1 = 1$. The interpretation of atomic prepositions should be as follows (Shkarupylo *et al*., 2016):

a) $(v_i, 0) \in AP$-web service has not been invoked yet.
b) $(v_i, 1) \in AP$-web service has already been invoked.

The specification of initial state is used as starting point (Eq. 3):

$$Init \equiv (v_0 = 0) \wedge (v_1 = 0) \wedge, ..., \wedge (v_{m-1} = 0) \tag{3}$$

where, Init is the TLA+specification of initial state label $L(s_0)$ which means that none of the web services have been invoked yet. Init statement is intended to be the starting point $\forall b_j \in B$, where $B = \{b_0, b_1, ..., b_{n-1}\}$-set of behaviors to be specified, $0 \le j \le n-1$.

Apart from the Init the Init statement, the subsequent differentiation between the behaviors takes place because of the diversity of the events and the sequences of events (Eq. 4):

$$b_j \equiv Init \wedge X\, Act_0 \wedge X^2\, Act_1 \wedge, ..., \wedge X^p\, Act_{p-1} \tag{4}$$

where, $p \in N$, X-Next temporal operator, Act_k $(0 \le k \le p-1)$-specification of k-th action taking place at X^{k+1} priority. The actions are proposed to be analytically represented as implications:

$$Act_k \equiv (v_i = 0) \to (v_i = 1) \tag{5}$$

It can be seen that Eq. 3 and 5 expressions are the formalizations of "State" and "Action" concepts taking place at the lowest hierarchical layer (Fig. 1).

To simplify the resulting temporal formula located at the upper hierarchical layer because of the identity of behaviors specification's starting points (Init expression), the Eq. 4 expression can be rewritten as follows (Eq. 6):

$$b'_j \equiv Act_0 \wedge X^1\, Act_1 \wedge, ..., \wedge X^{p-1}\, Act_{p-1} \tag{6}$$

On the basis of Eq. 3 and 6, the resulting temporal formula to be checked in an automated manner is as follows (Eq. 7):

$$Spec \equiv Init \wedge G[b'_0 \vee b'_1 \vee, ..., \vee b'_n] \tag{7}$$

where, G is "Globally" temporal operator. Finally, the resulting temporal formula Eq. 7 has to be checked $\forall_s \in S$ of Eq. 1 structure (Eq. 8):

$$M, s \mid = Spec \tag{8}$$

RESULTS AND DISCUSSION

The smart home domain has been chosen to conduct the case study. Two alternative scenarios considered are given in Fig. 2.

In Fig. 2 it can be seen that there are three web services involved in each domain-specific scenario and there are four state variables in total: $V = \{v_0, v_1, v_2, v_3\}$. Five distinct states have been found during the verification: $|S| = 5$. No deadlocks have been faced.

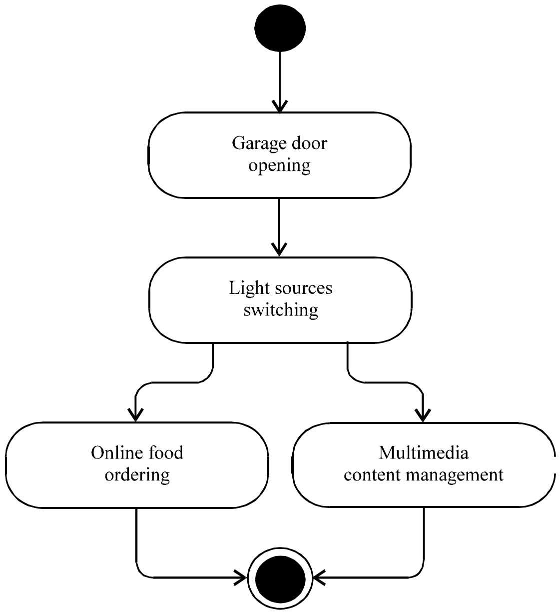

Fig. 2: The smart home scenarios

The TLA-based formal specification, created with respect to the proposed model is as follows (/* symbol is the comments delimiter):

a) VARIABLES v_0, v_1, v_2, v_3 /* define the state variables
b) Invariant = /\$v_0$\in BOOLEAN/\v1\in BOOLEAN/\$v_2$\in BOOLEAN/\$v_3$\in BOOLEAN/* specify the allowed values
c) Init = v_0 = FALSE/\$v_1$ = FALSE/\$v_2$ = FALSE/\$v_3$ = FALSE/*specify the initial state
d) Act_0 = $v_{0'}$ = IF Init THEN~v_0 ELSE v_0/*specify the actions
e) Act_1 = $v_{1'}$ = IF Act-0 THEN~1 ELSE v_1
f) Act_2 = $v_{2'}$ = IF Act-1 THEN~v2 ELSE v_2
g) Act_3 = $v_{3'}$ = IF Act-1 THEN~v_3 ELSE v_3
h) Next = \/\(Act_0/\Act_1/\Act_2)/\UNCHANGED <<v3>> \/\(Act_0/\Act_1/\Act-3)/\UNCHANGED <<v2>>/*specify the behaviors
i) Spec = Init/\[][Next]_<<v_0,v_1,v_2,v_3>>/*specify the resulting temporal formula to be checked

This specification provides the transparent representation of distinguished hierarchical layers and can easily be detailed or refined, dealing with the required level of abstraction.

To check the applicability of proposed model in terms of corresponding time costs, two approaches to TLC verification have been contemplated by way of Breadth-First Search (BFS) and by way of Depth-First Search (DFS).

The experimentation has been conducted on the following platform: CPU-Intel Core i3 M 330 (2.13 GHz); RAM-3072 MB; JRE Version-1.8.0-151; TLA Toolbox Version-1.5.6.

Measurements have been performed 10 times and then the average values have been taken: 1.354 sec for BFS-driven verification; 0.641 sec for DFS-driven verification. These values of time costs prompt the statement that proposed model can be applicable during the designing of IoT infrastructures.

Obtained results are in conformity with the ones obtained previously (Shkarupylo *et al*., 2018): DFS-driven automated TLC verification is still about two times faster in comparison with alternative BFS-driven one.

Obtained values of time costs can be characterized as acceptable in terms of design-time verification. There are plenty of options for further detailing of specifications created with respect to the proposed stratified model, e.g., by expanding V and D sets. Moreover, another hierarchical layer can be added on the top of stratified structure to generalize even further and obtain interdomain solutions.

CONCLUSION

The stratified model of IoT infrastructure has been proposed. The following conclusions have been obtained: proposed stratified model with three hierarchical layers provides the opportunity to check and reason about the consistency of IoT solutions in terms of web services, usage scenarios and applicability domains.

On the basis of smart home domain-related usage scenarios, the obtained results have shown that from corresponding time costs viewpoint, the proposed model is recommended to be applied during the designing of IoT infrastructures. The TLA+ specifications, created with respect to the proposed model, can be characterized as transparent, scalable and easily reconfigurable solutions that can be applicable in different applicability domains and/or subdomains.

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