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A survey on the model-centered approaches to conceptual modeling of IoT systems

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Internet of Things (IoT) is a system of connected objects, entities, devices, and components which share and transfer data over a network. Many papers are published on the topic of conceptual models in the IoT context, but it is difficult to assess the current status of the conceptual modeling approaches and methods for IoT systems. This paper presents an overview of the state of the art as well as discusses fundamental concepts, challenges and current research gaps with potential future agenda for conceptual modeling of IoT. Search facilities in the selected online repositories were used to identify the most relevant papers. The primary results were scanned and papers were selected according to the inclusion/exclusion criteria. Selected papers were assessed to extract data for the defined attributes. This paper confirms that there is a large body of research related to modeling of IoT systems. However, the results show that there is a lack of commonly agreed approaches and supporting formal methods for conceptual modeling of IoT systems. On the other hand, recent studies that apply model-based or model-driven development principles that use ontology or metamodel based approaches are promising due to systematic use of models as the primary means of a development process enabling for the dissemination of the methods further to the emerging fields such as smart cities, factories, transportation, hospitals, healthcare, hospitality and tourism, etc.

KEYWORDS

conceptual modeling, Internet of Things (IoT), ontology, metamodel, model based approach

1. Introduction

Internet of Things (IoT) has gained great interest in the last decade and the range of IoT systems, which are connected objects, entities, devices and components that share and transfer data over a network, is increasing. The number of available IoT devices, sensors, and smart components are increasing rapidly due to its potential for future smart systems.

IoT consists of many small devices over a network, sometimes thousands or millions of them. Sensors, network enabled devices, mobile devices, embedded systems, etc. are in the core of IoT. Besides this, IoT has particular focus on the number of the devices, large scale application, data sharing and smart functionality of the systems. In addition, IoT devices, sensors, microprocessors, etc. are cheap when compared to computers or other hardware. Hence, IoT has gained great interest within many disciplines so not only researchers and big vendors but also small start-up companies or even interested individuals design and develop IoT solutions. However, these cheap devices are only a part of a larger IoT system. So, when we want to implement and test the whole system we will need hundreds, thousands or sometimes millions of them. As a result, it is not cost-effective to test the whole system running.

Recently research communities have started to work on the methods and tools to analyse and design IoT systems (D'Angelo et al., 2017; Kecskemeti et al., 2017). Most of the related research focuses on the modeling aspects and model-driven approaches are proposed as a potential solution for large systems modeling (Ciccozzi et al., 2017). On the other hand, there are challenges especially related to scalability and dealing with heterogeneity of IoT systems. The development of methods, tools, and procedures to analyse and design IoT systems are still in progress.

A model can be defined as a wellformed, adequate, and dependable instrument that represents a source system and functions in scenarios of use (Thalheim, 2022). Although there are many other definitions in the literature, there is a central property for model being useful. A conceptual model is a concise and purposeful consolidation of a set of concepts that are represented by means of a modeling language or method (Mayr and Thalheim, 2021). Conceptual models are early stage artifacts that represent the system of interest and provide requirements for a variety of more specialized models such as analysis and design models (Bock et al., 2017). The conceptual model must represent and specify the system sufficiently to make all stakeholders in the project are comfortable in using it as a means for understanding and discussing the system (Robinson et al., 2015).

Systems modeling and conceptual modeling in particular, provide solutions to understand and analyse systems as an effective tool. It has been widely used especially in systems engineering and has been proven to improve the communication and supports requirements engineering and further activities. Although there are existing studies that propose conceptual models in the context of IoT, research about modeling techniques specific to the conceptual modeling of the IoT systems is limited. There is still a research gap to overcome the challenges caused by the wide range of IoT devices and sensor behaviors (Markus et al., 2018). With traditional approaches, adding new devices and sensors to the modeling libraries require either programming or changing the modeling platform. However, more flexible and extendable solutions are required to configure the modeling tools and extend the libraries easily when requirements change.

Many papers are published on the topic of conceptual models in the IoT context, but it is difficult to assess the current status of the conceptual modeling approaches and methods for IoT systems. This paper presents an overview of the state of the art as well as discusses fundamental concepts, challenges, and current research gaps with potential future agenda for conceptual modeling of IoT. Search facilities in the selected online repositories were used to identify the most relevant papers. The primary results were scanned and papers were selected according to the inclusion/exclusion criteria.

This paper shows that there is a large body of research related to modeling of IoT systems. However, the results show that there is a lack of commonly agreed approaches and supporting formal methods for conceptual modeling of IoT systems. Many models or modeling approaches are alone insufficient for holistic analysis due to the high degree of heterogeneity in IoT technologies, devices, and the diverse application domains. On the other hand, recent studies that apply model-centered approaches are promising. The outline of the paper is as follows. Next section provides the background information and literature review. Section 3 presents the mapping study with the details of the process. Section 4 presents the results and discusses the threats to validity. Finally, Section 5 concludes the paper and suggests future research agenda.

2. Literature review

IoT systems connect objects, entities, devices, and components which share and transfer data over a network. In the core of IoT, there are sensors, network enabled devices, actuators, mobile devices, embedded systems, etc. Communication networks such as sensor networks or wireless *ad hoc* networks provide an underlying infrastructure for implementing IoT and various technologies such as WiFi, Bluetooth, ZigBee, cellular, etc. help to connect different devices into the network. However, it is not easy to decide which infrastructure and technology should be used due to the wide and evolving variety of options and changing requirements for many different types of systems. Moreover, IoT technologies evolve over time and new functions and devices are introduced increasingly.

Figure 1 shows an example IoT architecture to give an overview of different layers in IoT implementation. Figure 1 illustrates the elements of an IOT system on the bottom layer as things, devices or sensors. On the network and communications layer, it shows the underlying technologies and networking mechanisms that facilitates the IOT system to connect and communicate. On the top layer, the focus is on the business intelligence and data analytics. At each layer, there are applications and services that helps to implement the system. As well as security is the biggest challenge to be addressed at each layer. Besides these, other functionality and aspects can be added to this architecture such as process management, service organization, etc. (Bassi et al., 2013).

Modeling IoT systems is gaining more importance due to the recent developments in IoT related technologies and increasing usage of such systems (Van Mierlo et al., 2018). Components are equipped with ubiquitous intelligence and IoT applications are designed to effectively fulfill a purpose such as monitoring existing systems, data analytics, digital twin, predictive analysis, optimization, etc. The challenge in analysing and designing IoT systems lies in the availability of broad range of devices and the difficulty of developing a fully integrated system with both physical and digital components.

The goal of conceptual modeling is to improve our understanding of a given problem and design better systems. Conceptual models can be defined and tailored for different domains and industries. Conceptual modeling can be carried out at early stages of the development process so that there is a common understanding among the stakeholders. System components, objects, entities, etc. associated with their common properties or attributes can be included as well as any characteristic information. Actions or tasks among these system elements can be defined too. Therefore, conceptual models can cover both structural or behavioral aspects of a system. It is also important to agree on the terminology, basic terms and common language to better communicate at early stages and during the requirements engineering stage. The most important role of a conceptual model is to make all parties involved in a development project to understand the models in the same way. Proper development of

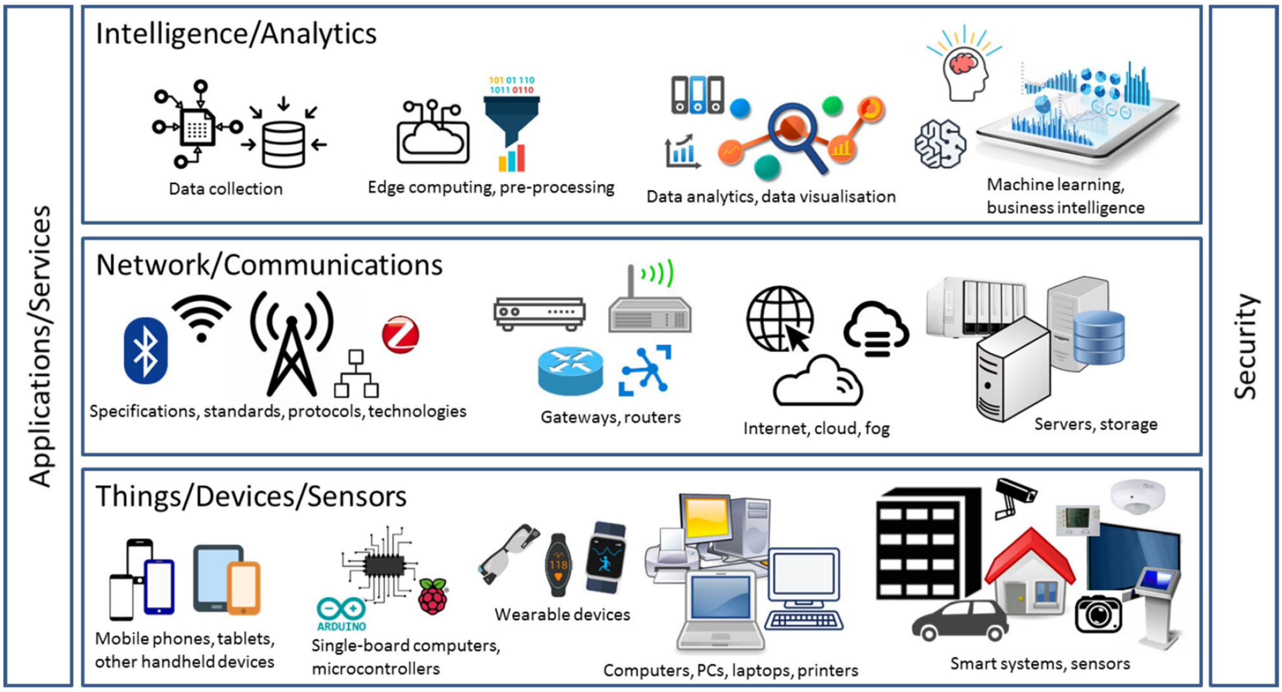

FIGURE 1
An overview of IoT architecture.

a conceptual model is critical for expressing the objectives of the system.

Modeling is used as an instrument for managing complexity in describing, analysing, and designing systems. Modeling techniques or paradigms are mostly defined by the introduction of three main elements: (1) modeling concepts (i.e., abstract syntax), (2) diagrammatic representations (i.e., concrete syntax), and (3) semantics of the concepts (Çetinkaya et al., 2015). For many years, researchers have been using and promoting model-driven and model-based approaches to improve software reusability and productivity (Ciccozzi et al., 2017). Model-based or model-centered paradigms have been introduced too to broaden and deepen the scope of model-driven system development (Costa et al., 2016).

Model-Driven Development (MDD) is a software and system development methodology that suggests the systematic use of models as the primary means of the development process. MDD introduces model transformations between the models at different abstraction levels and proposes the use of metamodels for specifying modeling languages formally. In MDD, models are transformed into other models in order to (semi)automatically generate the final source code. MDD promotes automated code generation to increase the productivity, reusability and quality during the software and system development process. For example, metamodeling, model transformations, formal language theory, systems theory, graph theory, conceptual modeling, and various methods can be used to move from the concepts into code (Çetinkaya et al., 2015).

The most common method to define modeling languages is metamodeling, which is the process of complete and precise specification of a modeling language in the form of a metamodel. Metamodeling is highly related to Domain Specific Modeling (DSM) whereas DSM raises the level of abstraction as symbols in a domain specific language map to the concepts in a specific domain. During the analysis and design of the complex systems, DSM provides better communication between stakeholders, effective representation of the concepts and consistency among development artifacts. The related work in this area defines the main concepts in IoT domain and provides an initial basis for further research (Bassi et al., 2013; Fortino et al., 2017).

UML profiles are also commonly used whereas the profiling mechanism offer a generic extension method for customizing UML models for particular domains (Thramboulidis and Christoulakis, 2016). It uses stereotypes, tagged values and constraints applied to specific model elements, such as within the class diagram. Agent based approaches have been applied to IoT modeling to model an IoT system as a multi agent system and to facilitate system modeling and development by reducing design and development time (Fortino et al., 2017). Overall, research related to conceptual modeling of IoT systems is limited but has gained interest recently. Hence, we have decided to apply a basic mapping study to review the literature which is explained in the next section.

3. Mapping process

In this study, we applied the systematic mapping process presented in Figure 2. The process is adapted from Brereton et al. (2007) and Petersen et al. (2015). The primary studies were searched, selected and evaluated according to the selected protocol. After obtaining the initial pool of papers and pre-screening of the

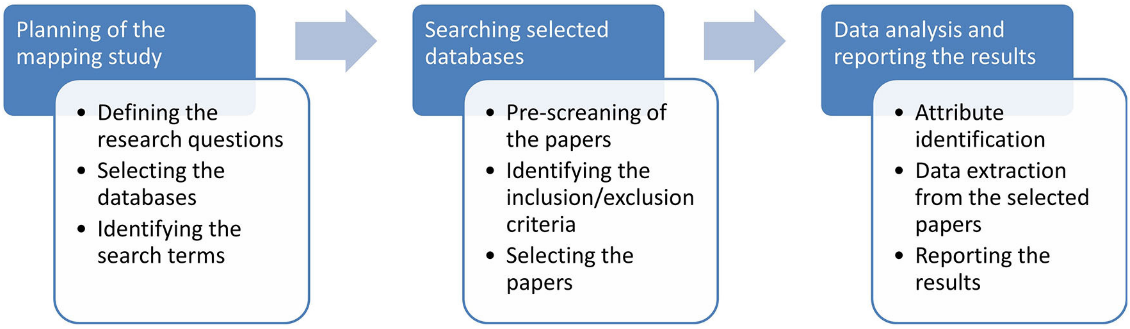

FIGURE 2
The mapping process for the review study.

papers, we refined the inclusion and exclusion criteria to select the most relevant papers. Finally, we developed our map and analyzed the extracted data. Our study mainly focuses on addressing two research questions:

- RQ1. What have been the trends of the literature within the field of conceptual modeling of IoT systems?
- RQ2. Which methods, techniques or tools are used while applying model-centered approaches to conceptual modeling of IoT systems?

3.1. Selection of the databases

Databases were selected due to selected repositories having regular content update, paper availability and accuracy of the results obtained by the search as well as being commonly used databases in our field. We performed the search in the selected databases in July 2022. Five academic publication repositories were used:

- Scopus (https://www.scopus.com/search/form.uri?display=advanced)
- ScienceDirect (https://www.sciencedirect.com/search)
- ACM (https://dl.acm.org/search/advanced)
- IEEE (https://ieeexplore.ieee.org/search/advanced)
- SpringerLink (https://link.springer.com/advanced-search)

3.2. Keywords and paper selection

To establish the search strategy based on the defined research questions, two main terms were initially identified, namely "Internet of Things" and "Conceptual Modeling". Possible variations such as abbreviations, e.g., IoT were also considered. The queries are executed with AND operator within the title, abstract and keywords.

We decided not to include "model driven" or "model based" keywords in our initial search to cover the literature about conceptual modeling in IoT whereas some papers may not apply a model driven or model based approach specifically but they could still be relevant. Selected papers were categorized according to their contribution type to further analyse the papers employing MDD or similar approaches.

Paper selection was done in two rounds. In the first round, we got the primary results by searching using the keywords and applying the inclusion criteria; and in the second round we checked and removed duplicates and irrelevant papers. Inclusion criteria is given below:

- Published as a journal paper OR conference paper OR book chapter
- Published between January 2010 and June 2022
- Language: English

Number of primary results for each database are given below:

- 327 - Scopus
- 24 - ScienceDirect
- 242 - ACM
- 104 - IEEE
- 155 - SpringerLink

After the first scan, irrelevant papers that simply have the keywords but has no relation to the aim of this study were removed according to the title and abstract as well as having a quick scan of the paper. Papers were incrementally included into the mapping dataset, i.e., if the paper is already included from another database it is not added again.

At the end of the second round, 191 papers were selected in total. Then, multiple or similar publications by the same authors in different venues were eliminated and the latest available papers were selected. A total of 177 paper were selected for further analysis and papers have been downloaded and cataloged from available online repositories. In the third round, papers were eliminated if they are not relevant based on their contribution type and do not address IoT or modeling, or the full text is not available. As a result, 148 papers were included in the analysis. The list of papers is attached to the submission and available upon request.

3.3. Attributes for data extraction

Papers were analyzed according to their application domain, methods, and research objectives. Data extraction is done according to the following attributes and questions:

- Contribution: What is the contribution of the paper?
- Methods: What is the modeling language or diagramming technique used?
- New method: Does the paper propose a new conceptual modeling language? (Yes/No/Partially)
- Application domain: What is the application domain if there is an example or case-study?
- Tools: Are there any software implementation if there is a new method proposed or any tool support? (Yes/No/Partially)
- Evaluation: Is the proposed model or method tested properly or evaluated? (Yes/No/Partially)

Regarding the contribution of the paper, there were four main categories as follows: (1) System design or overview, (2) Conceptual model or case study, (3) Review, and (4) New modeling approach. We did not exclude any aspects or certain views of modeling, however it was evident that most of the papers were covering different views but not all of the aspects. If the questions are answered as (Yes/No/Partially), further explanation has been added to identify the methods.

4. Results and discussion

4.1. Trends within the field of conceptual modeling of IoT systems

Paper details were extracted from the search databases and cross checked for any inconsistencies. In addition to the aforementioned attributes in the previous section, we had standard attributes such as title, authors, publication year, source title, etc. Looking at the number of publications by year, it is evident that the interest in conceptual modeling in the IoT context is increasing with 119 out of 148 papers were published in the last 6 years.

Regarding the publication types, there were 40 journal articles, 2 book chapters, and 106 conference papers. During our analysis it was very clear that most of the journal articles were published in the last 6 years (only 3 articles before 2017) with the highest numbers in 2021 and 2022. Although, we did not have an exclusion criteria based on the quality of the papers, we could identify that the best papers with the most relevant contributions were published in the journals. Regarding the contribution of the papers:

1. 11% (16/148) of the papers present a system design, system overview, or architectural diagrams,
2. 40.5% (60/148) of the papers present a conceptual model by using various methods,
3. 11.5% (17/148) of the papers provide a review, discussion, an approach, or state-of-the-art knowledge,
4. and 37% (55/148) of the papers propose a new modeling language or method, UML profile, ontology, or metamodel.

First and second group of the papers present models of IOT systems or case studies, focusing a specific part in many cases. We then further investigated the last group of the papers specifically to cover the model-driven approaches in depth. In the last group of papers that propose a new modeling approach, around 70% (39/55) of them proposes a new modeling language and utilizes model driven approaches. Used methods, techniques and tools are given in the next section.

According to our analysis, in the context of conceptual modeling of IoT, most commonly applied domains are smart buildings including smart homes and offices, smart agriculture, smart cities, healthcare, smart vehicles, Industry 4.0, and advanced manufacturing. There is also an increasing interest on the simulation studies in this field (Diaconescu and Wagner, 2015; Barriga et al., 2021). Some of the simulation studies emphasize the use of model-driven approaches for efficiency and productivity (Van Mierlo et al., 2018).

4.2. Methods, techniques, and tools

Although conceptual models were sometimes represented by using informal or non-standardized methods in the reviewed papers, many of them used various methods or frameworks which are listed below:

- Methods or techniques:
  - UML
  - Relational model
  - Domain model
  - Flow diagrams
  - SysML
  - Goal modeling
  - DMN (Decision Model and Notation)
  - ERD diagrams
  - BPMN
  - Colored Petri Nets
- Architectural frameworks:
  - IoT Architecture (IoT-A)
  - Unified Architecture Framework (UAF)
  - Reference Model of Open Distributed Processing (RM-ODP)
  - OSI reference model
  - Agile Modeling Method Engineering (AMME) framework
  - APPARATUS framework and metamodel
- Standards:
  - ISO/IEC 30141:2018 IoT Reference Architecture
  - ISO/PAS 19450:2015 Automation systems and integration—object-process methodology
  - ETSI Multi-access Edge Computing (MEC)

There was not any significant statistical data because each research study used various techniques. However, we can say that there is a trend toward using more semi-formal and formal methods which is promising. For completeness of this study, we have also listed the IoT solutions providers that are mentioned in the reviewed papers below:

- Amazon AWS IoT platform
- Google IoT platform
- Microsoft azure IoT Hub
- IBM Watson IoT platform
- Intel IoT platform reference model
- Cisco IoT solutions

Papers that propose a modeling language for IoT either use a metamodeling approach, ontologies, or UML. Most of the papers present a simple case study to demonstrate the use of the proposed language, while only a limited number of them discusses a formal evaluation (Fitz et al., 2019; Barriga et al., 2021; Plazas et al., 2022). A well developed modeling language is not the same as a modeling method or modeling technique. Papers that present a new modeling approach for IoT systems with a well-defined metamodel is usually complemented with prototype tool development and relevant evaluation approach (Cicirelli et al., 2018; Mavropoulos et al., 2019; Walch and Karagiannis, 2019; Escamilla-Ambrosio et al., 2021; Seiger et al., 2021; Erazo-Garzón et al., 2022). Analysis on the methods and techniques provided insight about variety of the model based tools. Popular MDD related tools are listed below:

- UML profiling mechanism and stereotypes
- Model-driven architecture (MDA) and metamodeling approach
- Eclipse modeling framework (EMF)
- Eclipse GMF (Graphical modeling framework)
- OCL (Object constraint language)
- Protégé ontology editor
- ATLAS transformation language (ATL)
- OWL Web ontology language
- Acceleo code generator

4.3. Discussion

Challenges or research gaps are highlighted in the context of the new or emerging topics such as edge or fog computing, microservices architecture, context aware systems, real-time systems, security modeling, etc. (Barriga et al., 2021; Escamilla-Ambrosio et al., 2021; Machorro-Cano et al., 2022; Valderas et al., 2022). Due to conceptual models are often not used explicitly in the further steps of the development lifecycle, a big semantic gap exists between the different models of the system. This gap causes a lack of model continuity in many cases. Main challenges with modeling IoT systems are the heterogeneity of scenarios, the variety of devices and the need for scalability (D'Angelo et al., 2017).

Regarding the issues and challenges, the security and privacy aspects in IoT and how to model these aspects were stated as potential future work in several publications (Mavropoulos et al., 2017; Maidl et al., 2019; Escamilla-Ambrosio et al., 2021). Besides these, variability modeling and model checking were also mentioned as challenging topics (D'Angelo et al., 2017). Although there is a growing interest recently in the field of IoT modeling, there is still no agreed solution to overcome the initial challenges. The summary of potential future agenda and research directions are given in the Conclusion section.

4.4. Limitations to the study

In this study we searched five online databases; there may be other relevant studies which are indexed in other databases. The validity of the results can be assessed based on the unintended human error and query results. Since not all information was obvious to answer the established research questions, some data had to be interpreted. Some studies may have been missed due to being not available or the limitations of the search engines.

5. Conclusion and future agenda

This paper presents an overview of the state of the art as well as discusses fundamental concepts, challenges and current research gaps with potential future agenda for conceptual modeling of IoT. It focuses on the model-centered approaches to contribute to the establishment of a common understanding of the concepts as well as to compile a set of tools for modeling activities in the context of conceptual modeling of IoT systems. This work can provide a basis for a more comprehensive systematic review. Based on the outcomes of this study and the trends in the literature, we prioritized the potential future work into three main groups as follows.

5.1. Formal approaches with model checking features and extension mechanisms

Model checking features and extension mechanisms for existing modeling languages and methods are only partially in place when the specifications are formally supported by metamodels or ontologies. However, in many cases these features are implemented as a proof of concept and checks only basic conditions or rules. Especially, in the context of IoT, systems designers and modelers can be supported in terms of checking component interoperability and technical requirements at modeling level. This can help to address the challenges involved in the entire IoT application lifecycle. There is a need to support the design and development of IoT systems that require modeling of reactive and reconfigurable elements with dynamic variable structures. Modelers can define the formal structural model of the system with different alternatives and future implementations can be based on this model.

5.2. Model-driven simulation of IoT systems

To the best of our knowledge, there is not an existing comprehensive metamodel for IoT in the literature. In addition, research on metamodel based and model-driven simulation of IoT is limited. Defining formal metamodel based transformation rules to generate IoT simulation models or design models from conceptual models can provide opportunities to test the IoT systems before implementing them. This approach can be very efficient and useful if you compare the cost of modeling and the cost of actual development. Future research can focus on both conceptual modeling and design of IoT systems which can provide management of different types of IoT devices and their relationships in a modular, extensible and configurable way.

5.3. Modeling security and privacy aspects in IoT

There is an increasing interest in the literature related to security aspects in IoT. However, the research on modeling the security and privacy aspects in IoT has recently gained interest. There are specific challenges in this context such as computing platforms of IoT are usually constrained in memory and processor resources. Hence, IoT devices may not support complex encryption algorithms. Moreover, embedded devices may outlive crypto algorithm lifetime. Considering the security and privacy aspects early in the modeling stage can help to understand the risks earlier and so to design the system accordingly.

As a result, there is a lack of commonly agreed approaches and supporting formal methods for conceptual modeling of IoT systems. On the other hand, recent studies that apply model-based or model-driven development principles that use ontology or metamodel based approaches are promising due to systematic use of models as the primary means of a development process.

Author contributions

DC designed and performed the research and wrote the paper. SK and LJ helped with extracting data from the selected papers and completing the mapping study. All authors agreed with the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomp.2023.1035225/full#supplementary-material

References

Barriga, J. A., Clemente, P. J., Sosa-Sánchez, E., and Prieto, A. E. (2021). SimulateIoT: domain specific language to design, code generation and execute IoT simulation environments. *IEEE Access* 9, 92531–92552. doi: 10.1109/ACCESS.2021.3092528

Bassi, A., Bauer, M., Fiedler, M., Kramp, T., Kranenburg, R. V., Lange, S., et al. (2013). *Enabling Things to Talk: Designing IoT Solutions with the IoT Architectural Reference Model*. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-40403-0

Bock, C., Dandashi, F., Friedenthal, S., Harrison, N., Jenkins, S., McGinnis, L., et al. (2017). *Conceptual Modeling*. Cham: Springer International Publishing 23–44. doi: 10.1007/978-3-319-58544-4_3

Brereton, P., Kitchenham, B. A., Budgen, D., Turner, M., and Khalil, M. (2007). Lessons from applying the systematic literature review process within the software engineering domain. *J. Syst. Softw.* 80, 571–583. doi: 10.1016/j.jss.2006.07.009

Çetinkaya, D., Verbraeck, A., and Seck, M. D. (2015). Model continuity in discrete event simulation: A framework for model-driven development of simulation models. *ACM Trans. Model. Comput. Simulat.* 25, 1–24. doi: 10.1145/2699714

Ciccozzi, F., Crnkovic, I., Di Ruscio, D., Malavolta, I., Pelliccione, P., and Spalazzese, R. (2017). Model-driven engineering for mission-critical IoT systems. *IEEE Softw.* 34, 46–53. doi: 10.1109/MS.2017.1

Cicirelli, F., Fortino, G., Guerrieri, A., Mercuri, A., Spezzano, G., and Vinci, A. (2018). "A metamodel framework for edge-based smart environments," in *2018 IEEE International Conference on Cloud Engineering (IC2E)* 286–291. doi: 10.1109/IC2E.2018.00067

Costa, B., Pires, P. F., Delicato, F. C., Li, W., and Zomaya, A. Y. (2016). "Design and analysis of IoT applications: A model-driven approach," in *IEEE 14th Interrnational Conference on Dependable, Autonomic and Secure Computing* 392–399. doi: 10.1109/DASC-PICom-DataCom-CyberSciTec.2016.81

D'Angelo, G., Ferretti, S., and Ghini, V. (2017). "Modeling the internet of things: a simulation perspective," in *2017 International Conference on High Performance Computing Simulation (HPCS)* 18–27. doi: 10.1109/HPCS.2017.13

Diaconescu, M., and Wagner, G. (2015). "Modeling and simulation of web-of-things systems part 1: Sensor nodes," in *Proceedings of the Winter Simulation Conference (WSC'15)* 3061–3072. doi: 10.1109/WSC.2015.7408409

Erazo-Garzón, L., Cedillo, P., Rossi, G., and Moyano, J. (2022). A domain-specific language for modeling IoT system architectures that support monitoring. *IEEE Access* 10, 61639–61665. doi: 10.1109/ACCESS.2022.3181166

Escamilla-Ambrosio, P. J., Robles-Ramírez, D. A., Tryfonas, T., Rodríguez-Mota, A., Gallegos-García, G., and Salinas-Rosales, M. (2021). IoTsecM: A UML/SysML extension for internet of things security modeling. *IEEE Access* 9, 154112–154135. doi: 10.1109/ACCESS.2021.3125979

Fitz, T., Theiler, M., and Smarsly, K. (2019). A metamodel for cyber-physical systems. *Adv. Eng. Inform*. 41, 100930. doi: 10.1016/j.aei.2019.100930

Fortino, G., Gravina, R., Russo, W., and Savaglio, C. (2017). Modeling and simulating internet-of-things systems: A hybrid agent-oriented approach. *Comput. Sci. Eng*. 19, 68–76. doi: 10.1109/MCSE.2017.3421541

Kecskemeti, G., Casale, G., Jha, D. N., Lyon, J., and Ranjan, R. (2017). Modelling and simulation challenges in internet of things. *IEEE Cloud Comput*. 4, 62–69. doi: 10.1109/MCC.2017.18

Machorro-Cano, I., Olmedo-Aguirre, J. O., Alor-Hernández, G., Rodríguez-Mazahua, L., Sánchez-Cervantes, J. L., and López-Chau, A. (2022). SCM-IoT: An aproach for internet of things services integration and coordination. *Appl. Sci*. 12, 3133. doi: 10.3390/app12063133

Maidl, M., Wirtz, R., Zhao, T., Heisel, M., and Wagner, M. (2019). "Pattern-based modeling of cyber-physical systems for analyzing security," in *Proceedings of the 24th European Conference on Pattern Languages of Programs, EuroPLop '19* (New York, NY, USA: Association for Computing Machinery). doi: 10.1145/3361149.3361172

Markus, A., Marques, A., Kecskeméti, G., and Kertész, A. (2018). "Efficient simulation of IoT cloud use cases," in *Autonomous Control for a Reliable Internet of Services* eds. I., Ganchev, R., van der Mei, H., van den Berg (Cham: Springer) 313–336. doi: 10.1007/978-3-319-90415-3_12

Mavropoulos, O., Mouratidis, H., Fish, A., and Panaousis, E. (2019). Apparatus: A framework for security analysis in internet of things systems. *Ad Hoc Netw*. 92, 101743. doi: 10.1016/j.adhoc.2018.08.013

Mavropoulos, O., Mouratidis, H., Fish, A., Panaousis, E., and Kalloniatis, C. (2017). A conceptual model to support security analysis in the internet of things. *Comput. Sci. Inf. Syst*. 14, 557–578. doi: 10.2298/CSIS160110016M

Mayr, H. C., and Thalheim, B. (2021). The triptych of conceptual modeling: A framework for a better understanding of conceptual modeling. *Softw. Syst. Model*. 20, 7–24. doi: 10.1007/s10270-020-00836-z

Petersen, K., Vakkalanka, S., and Kuzniarz, L. (2015). Guidelines for conducting systematic mapping studies in software engineering: An update. *Inf. Softw. Technol*. 64, 1–18. doi: 10.1016/j.infsof.2015.03.007

Plazas, J. E., Bimonte, S., Schneider, M., de Vaulx, C., Battistoni, P., Sebillo, M., et al. (2022). Sense, transform send for the internet of things (STS4IoT): UML profile for data-centric IoT applications. *Data Knowl. Eng*. 139, 101971. doi: 10.1016/j.datak.2021.101971

Robinson, S., Arbez, G., Birta, L. G., Tolk, A., and Wagner, G. (2015). "Conceptual modeling: Definition, purpose and benefits," in *Proceedings of the Winter Simulation Conference (WSC'15)* (Huntington Beach, CA), 2812–2826. doi: 10.1109/WSC.2015.7408386

Seiger, R., Kühn, R., Korzetz, M., and Aßmann, U. (2021). HoloFlows: Modelling of processes for the internet of things in mixed reality. *Softw. Syst. Model*. 20, 1465–1489. doi: 10.1007/s10270-020-00859-6

Thalheim, B. (2022). Models: The fourth dimension of computer science: Towards studies of models and modelling. *Softw. Syst. Model*. 21, 9–18. doi: 10.1007/s10270-021-00954-2

Thramboulidis, K., and Christoulakis, F. (2016). UML4IoT-A UML-based approach to exploit IoT in cyber-physical manufacturing systems. *Comput. Indust*. 82, 259–272. doi: 10.1016/j.compind.2016.05.010

Valderas, P., Torres, V., and Serral, E. (2022). Modelling and executing IoT-enhanced business processes through BPMN and microservices. *J. Syst. Softw*. 184, 111139. doi: 10.1016/j.jss.2021.111139

Van Mierlo, S., Van Tendeloo, Y., Dávid, I., Meyers, B., Gebremichael, A., and Vangheluwe, H. (2018). "A multi-paradigm approach for modelling service interactions in model-driven engineering processes," in *Proceedings of the Model-Driven Approaches for Simulation Engineering Symposium, Mod4Sim '18* (San Diego, CA, USA: Society for Computer Simulation International).

Walch, M., and Karagiannis, D. (2019). "How to connect design thinking and cyber-physical systems: the sIoT conceptual modelling approach," in *52nd Hawaii International Conference on System Sciences, HICSS 2019* (Hawaii). doi: 10.24251/HICSS.2019.870