Context-Awareness in Internet of Mobile Things

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Abstract. A new cognitive paradigm in internet of mobile things (IOMT) is currently on spot: Context-Awareness (CA), which is inspired by the activity of the human autonomous nervous system. The comprehensive target of CA is to realize IOMT, that can self-govern without direct human interventions. To solve this enormous challenge of CA requires a basic solution for CA concept. For this purpose, in this paper, the categorical approach is used to establish a strong formal basis for modeling CA in order to achieve the formal aspects of CA.

Keywords: Context-Awareness (CA) · IOMT · DIOMT · NIOMT · Formal aspects · Categorical language

1 Introduction

CA is an important property of IOMT and implies an increased complexity of IOMT behavior management. CA is the primary way for OMT to be manageable [8]. Indeed, a difficulty is that IOMT cannot be centrally managed. For instance, the information needs to make decisions cannot be centralized in IOMT. In such the IOMT, CA is only possible when processing entities in IOMT respond and harmonize with each other autonomously to enable to continue correctly the required processing in IOMT. Therefore, in the context of IOMT, CA is specified as cognitive paradigm in IOMT. In other words, when CA mechanism is implemented in the IOMT then the cognitive paradigm is determined. The intrinsic nature of CA is to allow autonomous networked processing entities in IOMT to self-manage the set of services and resources distributed at any given time while interacting and coordinating with each other. Therefore, for IOMT, one of the main challenges is how to support CA in the face of changes in computational goals, user needs and environmental conditions. In other words,

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how does the IOMT make sense of the involved contextual data, change with it, and tailor the services and resources it provides, in line with the target-driven processing mechanisms?

Responding to this major IOMT challenge requires a well-founded model and in-depth analysis of the CA concept. With this goal in mind, we develop a solid formal approach in which autonomous networked processing entities in IOMT can detect, diagnose, and repair failures, as well as adjust configurations and optimize their performance as environmental conditions and user needs change. All the things here must be completed while self-protecting and self-healing in the face of natural difficulties and malevolent assaults.

In view of this, we find that a rigorous approach to CA requires fundamental study of all aspects of CA. As a new development for CA, aspects of CA are formalized using categorical language [18], the content of which is reported in the paper.

2 Outline

The content of the paper is useful for readers who already have a basic knowledge of IOMT and are now looking to learn a new approach to formalizing CA in IOMT using a categorical language.

The content of the paper related to formalization is presented in a straightforward manner with a detailed approach to the required components and a brief expansion of the more advanced components. A number of corollaries explaining the use of formal aspects, including the arguments necessary to achieve a specific result, are presented.

We try to make the presentation as self-contained as possible, despite the fact that assuming you are familiar with the concept of CA in IOMT. Familiarity with algebra and related concepts in the categorical language [9] is helpful for realizing the consequences, but is not absolutely necessary most places.

The rest of this paper is organized as follows: Sects. 3 and 4 present the notions of CA and IOMT, respectively. Section 5 presents models of CA in IOMT. Finally, a short summary is given in Sect. 6.

3 Notion of CA

In IOMT, CA mentions the idea that processing entities can perceive and respond based on their environment. The entities can have information about the circumstances under which they can take action and respond accordingly based on rules. The general term of the entities' context perception in pervasive networks is introduced in [4,15] where context-aware entities can also attempt to make suppositions about the user's current situation. In [11] context is defined as "any information that can be used to describe an entity's situation."

While the IOMT community initially viewed context as a user location matter, as discussed in [11] over the past few years, the concept has come to be regarded not only as a state, but as part of the process in which the user participates; therefore, generic and complex context models have been proposed [10] to support context-aware applications that use them to

– tune the interface,
– modify the application-related data set,
– augment the accuracy of information retrieval,
– find services,
– make user interaction invisible, or
– establish intelligent environment

For instance, a context-aware mobile phone can recognize if the user is currently in the gathering room and that the user is standing up or sitting down. The context-aware mobile phone can induce if the user is currently in a gathering and dismiss any insignificant calls [10].

Context-aware systems involve [2]

– acquiring context (e.g., using sensors to perceive a situation),
– abstracting, and understanding context (e.g. matching a perceived sensory stimulus with a context) and
– perceived context-based application behavior (e.g. triggering a context-based action)

Since user activity and location are so important to many applications, context awareness has received more attention in the research areas of location perception and activity awareness.

Context awareness is considered a technology that enables pervasive networks. Context awareness is used to design innovative user interfaces and is often used as part of ubiquitous and wearable computing. It also began to be felt on the internet with the advent of hybrid search engines. [25] identifies the human factor and the physical environment as two significant characteristics related to computer science. Recently, much work has also been completed to easily distribute context information; [23] investigated a number of middleware solutions arranged to apply straightforward context administration and supplying in mobile systems. Several context-aware location-based service systems were evaluated [14] using data by analyzing developer practice and method choices. Their development occurs during the major stages of context perception (i.e. context acquisition, context representation, reasoning, and context adjustment). [6] conducted a general overview of context-aware computing from the point of view of the Internet of Things, reviewed more than 50 leading projects in the field. Furthermore, [7] also examined a large number of industrial products currently on the IoT market from a context-aware computing standpoint. Their overview aims to serve as a guide and a conceptual structure for contextual product research and development in the IoT model. Evaluation was performed using framework theory developed by [1] over a decade ago. The composition of emerging technologies and the Internet turns everyday objects into intelligent objects that can be aware of and respond to their context [13].

Context related to human factors is constructed into the following three types:

- the user's social environment (location of others, social interactions, group dynamics),
- user tasks (spontaneous activity, engaged tasks, shared goals) and
- information about the user (knowledge of habits, emotional state, biophysical conditions).

Context related to the physical environment is organized into the following three classes [3,5]:

- infrastructure (the surrounding resources to computing, communication, task performance),
- physical conditions (noise, light, pressure, air quality) and
- location (absolute location, relative location, co-location).

In many practical situations, it is essential to use wearable sensors, embedded in mobile devices such as smart phones and smart watches, to measure the emotional state of the user [21]. This will help to understand how emotions affect processes such as decision making and reasoning [19]. Moreover, emotion recognition is still a complex and challenging task, mainly related to the following aspects:

- mode of sensing [21] –that is, what to sense and what kind of sensor can be used? Physical sensors in mobile devices or biosensors in wearables and pervasive sensors (e.g. RF sensors) are now available.
- data analysis [16] – that is, different approaches to emotional recognition are based on different types of collected data.
- application in real life [12,20,24] – that is, effective use of emotional information in pervasive computing and context-aware applications.

4 Internet of Mobile Things (IOMT)

Recently, the idea of connecting all mobile things (MT) has given rise to the emergence of the "Internet of Mobile Things" (IOMT), which can be used as a mobile device to collect data from remotely deployed IOMT devices or can act as a communication bridge [17]. In other words, the IOMT is fundamentally changing the world by allowing multiple mobile devices to communicate and exchange data with each other. Alternatively, persons equipped with their wearable can be considered as another type of movable object providing/receiving services to/from IOMT [22]. A set of MT can form a special mobile wireless network and provide services. Such networks can cover a larger area while devices connected to the network collaborate with each other to perform complex tasks [27].

However, there are several issues that need to be addressed in order to use multiple MT for IOMT applications [17,22,27] efficiently, including:

– dynamic and intelligent management of sensors and devices terrestrial IOMT devices,
– limited power of IOMT and MT,
– privacy and security in IOMT and
– communication between IOMT devices and MT, communication between MT, connectivity of MT

Due to the dynamic nature of the aforementioned issues, supporting these stakeholders becomes a challenging task. Therefore, it is necessary to develop new techniques to manage and optimize the real-time operation of these communication platforms [26].

5 CA in IOMT

As known that CA is attained when IOMT is built. In this way, for shaping IOMT, we begin to observe *deterministic internet of mobile things* (DIOMT) and then extend to *nondeterministic internet of mobile things* (NIOMT) by an approach using categorical language in this section.

5.1 CA in DIOMT

CA in DIOMT we want abstraction to be multiple partial morphism applications in intuition, such as

$$\phi_0 \xrightarrow{\gamma_0} \phi_1 \xrightarrow{\gamma_1} \phi_2 \xrightarrow{\gamma_2} \phi_3 \cdots \tag{1}$$

in which

– All indexes $i \in T$ $(= \mathbb{N} \cup \{0\})$ mention to times,
– ϕ is a state of DIOMT in the set, denoted by *IOMT*, of states. ϕ_i indicates the state ϕ at the time i,
– γ is a contextual data in the set, denoted by *Context*, of contextual data. γ_i indicates the contextual data γ at the time i, which makes change of the state ϕ_i to begin to be ϕ_{i+1}.

The adaptation process in (1) is meant by

$$\ldots\ \phi_2(\phi_1(\phi_0())) = \ldots\ \phi_2(\phi_1(\gamma_0)) = \ldots\ \phi_2(\gamma_1) = \ldots\ \gamma_2 \tag{2}$$

The meaning of (1) can also be descriptively understood as

$$\phi_0()\ \gamma_0\ \gamma_1\ \gamma_2\ \cdots \longmapsto \phi_1(\gamma_0)\ \gamma_1\ \gamma_2\ \cdots \longmapsto \gamma_0\ \phi_2(\gamma_1)\ \gamma_2\ \cdots \tag{3}$$

or, in another representation

$$\xrightarrow{\phi_0} \gamma_0\ \gamma_1\ \gamma_2\ \cdots \longmapsto \gamma_0 \xrightarrow{\phi_1} \gamma_1\ \gamma_2\ \cdots \longmapsto \gamma_0\ \gamma_1 \xrightarrow{\phi_2} \gamma_2\ \cdots \tag{4}$$

Note that in (3) and (4), we want to represent the above-mentioned adjustment process of DIOMT based on context where each step of the process is an application of unary partial morphism $1 \xrightarrow{\phi_i} IOMT$ on $1 \xrightarrow{\gamma_{i-1}} Context$, for all i in T.

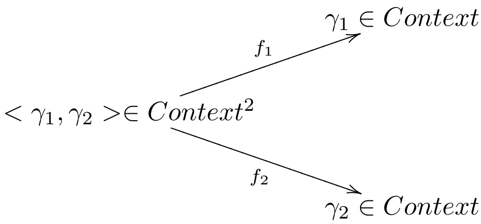
The tuning process, in (3) and (4), describes the CA concept in DIOMT including the adjustment steps to change the *configurations* of the DIOMT.

Definition 1 (Configuration of DIOMT). *A configuration of* DIOMT *at an adjustment step is defined as an element of the set* $IOMT \times Context^{i \in T}$*, in which* $Context^{i\in T}$ *stands for*

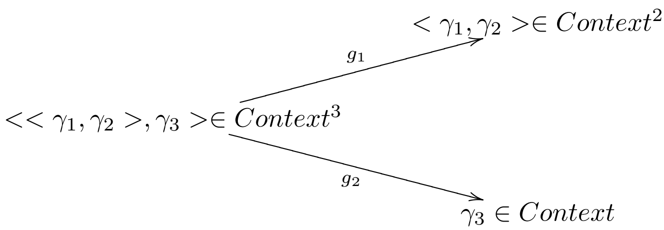
$$Context^{i\in T} = \underbrace{Context \times Context \times \ldots \times Context}_{i\ times} \tag{5}$$

As we know, when we combine sets by multiplication, each set is *factor* and the resulting set is *product*. Therefore, each set $Context$ is a factor of the result set $Context^{i\in T}$, $IOMT$ and $Context^{i\in T}$ are two factors of the set $IOMT \times Context^{i\in T}$. The multiplication of sets is defined very naturally. Just recall that a product is not just a set, but a set that comes in two morphisms as in

– When i = 2 then $Context^2 = \{<\gamma_1, \gamma_2> | \gamma_1, \gamma_2 \in Context\}$ is obtained by



– When i=3 then $Context^3 = \{<<\gamma_1, \gamma_2>, \gamma_3> | \gamma_1, \gamma_2, \gamma_3 \in Context\}$ is obtained by



In particular, we have

– If i = 0 then $Context^0 = \{\}$
– If i = 1 then $Context^1 = Context = \{\gamma_1 | \gamma_1 \in Context\}$

The CA is based on mapping one configuration to another. Let's consider the following situations. A particular CA can be specified by the following morphism:

$$CA : (IOMT \times Context) \longrightarrow IOMT \tag{6}$$

(i.e., $CA : (IOMT \times Context^1) \longrightarrow (IOMT \times Context^0)$ or denoted by CA $(IOMT \times Context, IOMT))$

Another specific CA can be specified by

$$CA : (IOMT \times Context) \longrightarrow (IOMT \times Context) \tag{7}$$

(i.e., $CA : (IOMT \times Context^1) \longrightarrow (IOMT \times Context^1)$ or denoted by CA $(IOMT \times Context, IOMT \times Context))$

Again, we can also specify another specific CA as

$$CA : (IOMT \times Context^n) \longrightarrow (IOMT \times Context) \tag{8}$$

(i.e., $CA : (IOMT \times Context^n) \longrightarrow (IOMT \times Context^1)$ or denoted by CA $(IOMT \times Context^n, IOMT \times Context))$

and in exactly the same way, any other specific CA can be specified as in.

Definition 2. *In general, an arbitrary context-awareness in DIOMT is specified by*

$$CA : (IOMT \times Context^{i \in T}) \longrightarrow (IOMT \times Context^{j \in T}) \tag{9}$$

Now, we can prove the following corollaries.

Corollary 1 (CA in DIOMT). *The morphism CA in* (9) *defines context-awareness in* DIOMT

Proof. This comes from (9) and the actuality that *CA* is described as context-awareness in DIOMT. Q.E.D.

CA is often described as self-*. Formally, think of self-* as the set of self-_. Each self-_ becoming an element in self-* is called *self-* aspect*. That is,

$$\text{self-*} = \{\text{self-\_} \mid \text{self-\_ is a self-* aspect}\} \tag{10}$$

We found that self-CHOP includes four self-* aspects which are self-configuration, self-healing, self-optimization and self-protection. Therefore, self-CHOP is a subset of self- *, i.e. self CHOP = { self-configuring, self-healing, self-optimizing, self-protecting} ⊂ self-* [8].

A set $\{CA_{k \in \mathbb{N}}\}$ of mappings is defined by morphism *CA* in (9) such that

$$\{CA_{k \in \mathbb{N}}\} : (IOMT \times Context^{i \in T}) \longrightarrow (IOMT \times Context^{j \in T}) \tag{11}$$

Hence, we have the corollary as the following.

Corollary 2 (CA aspects in DIOMT). *The set* $\{CA_{k \in \mathbb{N}}\}$ *in* (11) *defines context-awareness aspects in* DIOMT. *Each mapping* $CA_{k \in \mathbb{N}}$ *is called a context-awareness aspect.*

Proof. This originates from the result of the fact that *CA* is the set of context-awareness aspects. Q.E.D.

To investigate more clearly, we can build a category of DIOMT configurations sets and set up CA-algebras as specified in the following corollaries.

Corollary 3 (Category of the sets of DIOMT configurations). *A category is determined by The* DIOMT *configurations sets as in Definition 1.*

Proof. Indeed, as in [18], let **Cat(DIOMT)** be such a category of the DIOMT configurations sets, whose structure is built as follows:

- Each configurations set $IOMT \times Context^{i \in T}$ specifies an object. That is, $Obj(\mathbf{Cat(DIOMT)}) = \{IOMT \times Context^{i \in T}\}$.
- Each CA determines a morphism. That is, $Arc(\mathbf{Cat(DIOMT)}) = \{CA : (IOMT \times Context^{i \in T}) \longrightarrow (IOMT \times Context^{j \in T})\}$.

Easily check that the identity and associativity properties on all CAs are satisfied. Q.E.D.

Corollary 4 (CA-algebra(DIOMT)). *Each morphism CA in the category* **Cat(DIOMT)** *determines an algebra, aka CA-algebra*(DIOMT)*.*

Proof. This originates as the result of the truth that definition of T-algebra [18], where functor T is determined such that $\mathsf{T} = \biguplus\{CA\}$. Note that the notation $\biguplus$ stands for *disjoint union* or *coproduct*. Q.E.D.

As a result originates from of Corollary 4, a formal definition of DIOMT is attained as follows.

Definition 3 (DIOMT). *Each* DIOMT*is determined by a CA-algebra*(DIOMT)

5.2 CA in NIOMT

CA in NIOMT we want model to be multiple partial morphism applications in intuition, such as

$$\phi_0 \xrightarrow{\gamma_0 | x_0} \phi_1 \xrightarrow{\gamma_1 | x_1} \phi_2 \xrightarrow{\gamma_2 | x_2} \phi_3 \cdots \tag{12}$$

in which

- All indexes i in T, ϕ_i and γ_i have the same meaning as those mentioned in (1)
- x_i is a real number that can be thought of as *multiplcity* (or *weight*) where the adjustment from ϕ_i to ϕ_{i+1} appears.

Adjustment process of CA in NIOMT in diagram (12) can be split into two complementary parts as follows:

$$\phi_0 \xrightarrow{\gamma_0} \phi_1 \xrightarrow{\gamma_1} \phi_2 \xrightarrow{\gamma_2} \phi_3 \ldots \tag{13}$$

and

$$\phi_0 \xrightarrow{x_0} \phi_1 \xrightarrow{x_1} \phi_2 \xrightarrow{x_2} \phi_3 \ldots \tag{14}$$

On the one hand, diagram (13) stresses $1 \xrightarrow{\gamma_i} Context$, for all i in T, in the adjustment process. This allows us to conveniently explore the γ_i series as contextual data series. On the other hand, diagram (14) gives rise to $1 \xrightarrow{x_i} \mathbb{R}$, for all i in T, as the weight of the context data series during tuning to support the evaluation of quantitative behaviors based on the weight of the context data series.

Some of the first steps of the tuning process in (12) can also be described as

(15)

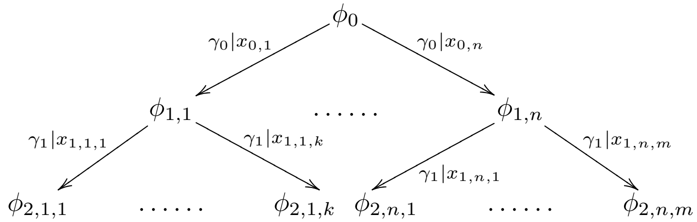


Diagram (15) is thought of as

- For the first step,

$$\phi_1 \in \{\phi_{1,1}, \ldots, \phi_{1,n}\} \subset IOMT$$
and
$$x_0 \in \{x_{0,1}, \ldots, x_{0,n}\} \subset \mathbb{R}$$

- For the second step,

$$\phi_2 \in \{\phi_{2,1,1}, \ldots, \phi_{2,1,k}\} \cup \ldots \cup \{\phi_{2,n,1}, \ldots, \phi_{2,n,m}\} \subset IOMT$$
and
$$x_1 \in \{x_{1,1,1}, \ldots, x_{1,1,k}\} \cup \ldots \cup \{x_{1,n,1}, \ldots, x_{1,n,m}\} \subset \mathbb{R}$$

and the meaning of (12) is seen as a following morphism.

$$CA : (IOMT \times Context) \longrightarrow (IOMT \longrightarrow \mathbb{R}) \tag{16}$$

The adjustment morphism CA in (16) is nondeterministic and this can be explained as follows: CA specifies for each configuration in $IOMT \times Context$ a morphism $IOMT \longrightarrow \mathbb{R}$ that can be seen as a kind of *nondeterministic configuration* (aka *distribution configuration*) and assigns each state ϕ'in$IOMT$ a multiplicity (or weight) $CA(< \phi, \gamma >)(\phi')$ in $\mathbb{R}$.

This nondeterminism of CA in NIOMT extends the ability to represent the categorical models mentioned in Subsect. 5.1. Let's consider the following situations.

A specific CA in NIOMT, indicated by the following morphism, is an extension of (6):

$$CA : (IOMT \times Context) \longrightarrow (IOMT \longrightarrow \mathbb{R}) \tag{17}$$

(i.e., $CA \; : \; (IOMT \times Context^1) \longrightarrow ((IOMT \times Context^0) \longrightarrow \mathbb{R})$ or denoted by $CA\;((IOMT \times Context), (IOMT \longrightarrow \mathbb{R}))$)

The model in (7) is extended to the CA in the NIOMT determined by

$$CA : (IOMT \times Context) \longrightarrow ((IOMT \times Context) \longrightarrow \mathbb{R}) \quad (18)$$

(i.e., $CA : (IOMT \times Context^1) \longrightarrow ((IOMT \times Context^1) \longrightarrow \mathbb{R})$ or denoted by $CA\,((IOMT \times Context), ((IOMT \times Context) \longrightarrow \mathbb{R}))$)

Again, we determine another specific CA in NIOMT as an extension of (8) in

$$CA : (IOMT \times Context^n) \longrightarrow ((IOMT \times Context) \longrightarrow \mathbb{R}) \quad (19)$$

(i.e., $CA : (IOMT \times Context^n) \longrightarrow ((IOMT \times Context^1) \longrightarrow \mathbb{R})$ or denoted by $CA\,((IOMT \times Context^n), ((IOMT \times Context) \longrightarrow \mathbb{R}))$)

and, in the correct way we create an arbitrary CA in NIOMT as follows.

Definition 4. *In general, an arbitrary context-awareness in* NIOMT *is specified by*

$$CA : (IOMT \times Context^{i \in T}) \longrightarrow ((IOMT \times Context^{j \in T}) \longrightarrow \mathbb{R}) \quad (20)$$

There is a corollary as described below.

Corollary 5 (CA in NIOMT). *The morphism CA in* (20) *defines context-awareness in* NIOMT

Proof. This originates from (20) as the result of the truth that CA is described as context-awareness in NIOMT. Q.E.D.

A set $\{CA_{k \in \mathbb{N}}\}$ of mappings is defined by morphism CA in (20) such that

$$\{CA_{k \in \mathbb{N}}\} : (IOMT \times Context^{i \in T}) \longrightarrow ((IOMT \times Context^{j \in T}) \longrightarrow \mathbb{R}) \quad (21)$$

Thus, there are the following corollaries.

Corollary 6 (CA aspects in NIOMT). *The set* $\{CA_{k \in \mathbb{N}}\}$ *in* (21) *defines context-awareness aspects in* NIOMT*. Each mapping* $CA_{k \in \mathbb{N}}$ *is called a context-awareness aspect.*

Proof. This originates from the result of the fact that context-awareness is the set of context-awareness aspects. Q.E.D.

Corollary 7 (Category of the sets of NIOMT configurations). *A category* **Cat(NIOMT)** *of the sets of* NIOMT *configurations is determined by the category* **Cat(DIOMT)** *equipped with structure* $(IOMT \times Context^{i \in T}) \longrightarrow ((IOMT \times Context^{j \in T}) \longrightarrow \mathbb{R})$.

Proof. This stems immediately from the result of Corollary 3. Q.E.D.

Corollary 8 (*CA*-algebra(NIOMT)). *The structure* $(IOMT \times Context^{i \in T}) \longrightarrow ((IOMT \times Context^{j \in T}) \longrightarrow \mathbb{R})$ *in the category* **Cat(NIOMT)** *determines an algebra, aka CA-algebra*(NIOMT).

Proof. This stems from definition on T-algebra [18], in which functor T is determined such that $\mathsf{T} = \biguplus\{CA\}$ (similar to Corollary 4) with CA determined in (20). Q.E.D.

As a result originates from the Corollary 8, a formal definition of NIOMT is attained as follows.

Definition 5 (NIOMT). *Each* NIOMT *is determined by a* CA*-algebra*(NIOMT)

Furthermore, we have the following theorem to get a meaningful relationship between DIOMT and NIOMT.

Theorem 1 (Relationship between DIOMT and NIOMT). DIOMT *is just of a specific* NIOMT*. In other words, using categorical language,* DIOMT $\xrightarrow{\subset}$ NIOMT

Proof. Indeed, by the adjustment morphism in (20) of NIOMT, let f be the morphism $f : (IOMT \times Context^{j\in T}) \longrightarrow \mathbb{R}$, *Config* be $IOMT \times Context^{j\in T}$ and the finite set $\mathbb{R}(Config) = \{1 \xrightarrow{c} Config | f(c) \neq 0\} \xrightarrow{\subseteq} Config$. So it follows that when
$\exists!\ 1 \xrightarrow{c} Config : f(c) = 1$ but $\forall c' \neq c : f(c') = 0$ (i.e., the set $\mathbb{R}(Config)$ is a singleton set of configuration with weight of 1. Note that the notation $\exists!$ is understood as "exist only") then (20) begins to be the adjustment morphism of DIOMT as in (9). In other words, in the case, NIOMT will begin to be DIOMT. Q.E.D.

6 Conclusions

In the content of the paper, the concept of CA in IOMT has rigorously been established from which formal features of the CA become visible. CA in deterministic and nondeterministic IOMT (DIOMT and NIOMT) have been considered , in which configuration of IOMT at every adjustment step has been specified as an element in the set $IOMT \times Context^{i\in T}$, then CA as a morphism from a configuration to another for finding the important properties of CA.

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