R-TNCES State Space Generation Using Ontology-Based Method on a Distributed Cloud-Based Architecture

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Abstract. This paper deals with formal verification (accessibility graph generation & state space analysis) of RDECSs modeled with specified reconfigurable timed net condition/event systems (R-TNCESs) where the properties to be verified to ensure the well behave of systems are expressed by computation tree logic CTL. Reconfigurable discrete event control systems (RDECSs) are complex and critical systems, which, make their formal verification expensive in terms of complexity and memory occupation. We aim to improve model checking used for formal verification of RDECSs by proposing a new approach of state space generation that considers similarities and a parallel verification of CTL properties. In this approach, we introduce the modularity concept for verifying systems by constructing incrementally their accessibility graphs. Furthermore, we set up an ontology-based history to deal with similarities between two or several systems by reusing state spaces of similar components that are computed during previous verification. A distributed cloud-based architecture is proposed to perform the parallel computation for control verification time and memory occupation. The paper's contribution is applied to a benchmark production system. The evaluation of the proposed approach is performed by measuring the temporal complexity of several large scale system verification. The results show the relevance of this approach.

Keywords: Formal verification · Discrete-event system · Reconfiguration · Petri net · Ontology

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1 Introduction

Reconfigurable discrete event control systems (RDECSs) are the trend of future systems. RDECSs can be reconfigured in a static way (off-line) or in a dynamic way (automatically at run-time). In the latter, a reconfiguration scenario should be applied automatically and timely as a response related to dynamic environment, or user requirements. Therefore, an RDECS may go through several modes at run-time [3,9], increasing verification process complexity. Formal verification represents a reliable method to ensure the correctness of RDECSs. Usually, it consists in generating and analyzing the state spaces of studied systems. However, with the combinatorial growth, the state space size becomes too big, even with small sized systems. Hence, model-checking becomes quite challenging for industry and academia because of the state space explosion problem [19]. Several studies have been done to cope with state space explosion problems. The authors in [18] present symbolic model checking that represents the state space symbolically instead of explicitly, by exploiting the state graph regularity using boolean functions. In [6], bounded model checking (BMC) is proposed to look for a counter-example in executions whose length is limited by an integer k. If no bug is found, then k is increased until a possible bug is found. The above methods can proceed efficiently proceed to complex systems verification. However, they use an implicit representation of state spaces, which present limitation for computation of quantitative properties (e.g., state probabilities in stochastic models) [2]. With the apparition of new complex systems such as reconfigurable manufacturing systems, reconfigurable wireless networks, etc. [1], techniques and formalisms used for verification must evolve. Petri nets has been extended by many works. Reconfigurable Petri nets presented in [15], proposed for reconfigurable systems. However, although useful, being non-modular formalism, it can cause confusion to engineers for possible reusing. Timed net condition/event systems (TNCES) formalism presented in [7] as modular extension of Petri nets to deal with time constraints. TNCES is used for their particular dynamic behavior, modularity and interconnection via signals. However, dynamic behavior of reconfigurable systems is still not supported. Reconfigurable net condition/event systems (R-TNCESs) are developed as an extension of the TNCES formalism in [20], where reconfiguration and time properties with modular specification are provided in the same formalism while keeping the same semantics of TNCESs. With R-TNCES formalism, physical system processes are easily understood thanks to modular graphic representations. In addition, it can capture complex characteristics of an RDECS. Formally an R-TNCES is a multi-TNCES defined as a couple (B, R), where B is a set of TNCESs, and R is a set of reconfiguration rules [20]. A layer-by-layer verification method is proposed where similarities between TNCESs are considered. This method is improved in [7] where the authors propose a new method for accessibility graph generation with less computing time and less required memory. The previous methods improve classical ones. However, with large scale systems, their application using a unique machine (i.e., a centralized system) may be expensive in terms of time.

In this paper, we are interested in reconfigurable systems, modeled with the R-TNCES formalism where the RDECS behavior is represented by the behavior of control components (CCs) and the communication between them (synchronization) [20]. We propose a new verification method that aims to improve R-TNCES formal verification. The verification of an R-TNCES requires checking of each configuration, namely each TNCES. TNCESs which describe configurations often contain similarities called internal similarities. On another hand, some RDECSs share the same system components, so their model contains similarities called external similarities, which implies redundant calculation during checking of these systems. Thus, in order to avoid many repetitive computation due to previous problems, we propose in this paper the following contributions:

1. An ontology-based history to facilitate the detection of external similarities: Ontologies allow us to describe the RDECSs (components, work process, component relationships..., etc.) in an abstracted way than the formal model. Thus, we can efficiently detect the similarities between RDECSs with less computing time and resources, thank the ontology alignment method [13]. Each model must be accompanied by a system ontology, which describes the system to be verified. The system ontology is aligned to the ontology-based history, which contains descriptions of already verified systems. The detected similarities allow reusing state spaces computed during previous verification.
2. Incremental construction of the accessibility graphs to deal with similarities: The verification of R-TNCES requires the verification of each TNCES that composes the R-TNCES model. In order to deal with similarities that TNCESs contain (similar control components), we construct the accessibility graph in an incremental way in two steps: (i) Fragmentation: During this step, we proceed to the decomposition of the R-TNCES models into a set of CCs. Then, we generate an accessibility graph for each different CC, while preserving semantics. (ii) Accessibility graph composition: Accessibility graphs recovered thanks to ontology alignment, and those computed during the fragmentation step are composed following an established composition plan based on priority order.
3. A new method parallel CTL properties verification: The method considers the relationships that exist among properties, performs the verification in parallel way via SESA tool [16] and considers the similarity that can exist among properties.
4. An adequate distributed cloud-based architecture to perform parallel executions for formal verification: This distributed architecture is composed of computation units organized in three hierarchical levels that are: Master, workers, and sub-workers. Data storage is ensured by Amazon simple storage service S3 [11].

This paper is an extended version of our previous paper [5], presented at the 'IC-SOFT 2020' conference. The method improves by

– Improving the ontology alignment method.
– Setting up an adapted algorithm for ontology fusion.
– Integrating CTL properties parallel verification method.

The main objective of this paper is to propose a new formal verification method that improves the classical ones by controlling complexity. As a running example, we use the FESTO MPS benchmark system presented in [10], to demonstrate the relevance of the proposed contributions. The obtained results are compared with different works. The comparison shows that the sate spaces generation is improved in terms of computed states and execution time (i.e., less complexity to compute state spaces). The remainder of the paper is organized as follows. Section 2 presents some required concepts. The distributed formal verification is presented in Sect. 3. The method and the proposed algorithms are presented in Sect. 4. Section 5 presents the evaluation of the proposed method. Finally, Sect. 6 concludes this paper and gives an overview about our future work.

2 Background

In this section, we present required concepts to follow the rest of the paper.

2.1 Reconfigurable Timed Net Condition/Event System

R-TNCES represents an extension of TNCESs [17], based on Petri nets and control components CCs. R-TNCES is used for formal modeling and verification of RDECSS.

Formalization. An R-TNCES is defined in [20] as a couple $RTN = (B, R)$, where R is the control module and B is the behavior module. B is a union of multi TNCES-based CC modules, represented by

$$B = (P; T; F; W; CN; EN; DC; V; Z_0) \tag{1}$$

where, 1.P (resp, T) is a superset of places (resp, transitions), 2. $F \subseteq (P \times T) \cup (T \times P)$[1] is a superset of flow arcs. 3. W: $(P \times T) \cup (T \times P) \rightarrow \{0,1\}$ maps a weight to a flow arc, $W(x,y) > 0$ if $(x,y) \in F$, and $W(x,y) = 0$ otherwise, where $x, y \in P \cup T$, 4. $CN \subseteq (P \times T)$ (resp, $EN \subseteq (T \times T)$) is a superset of condition signals (resp, event signals), 5. $DC : F \cap (P \times T) \rightarrow \{[l_1, h_1], .., [l_{F\cap(P\times T)}, h_{F\cap(P\times T)}]\}$ is a superset of time constraints on input arcs of transitions, where $\forall$ i$\in$ $[1, |F \cap (P \times T)|]$, l_i, $h_i \in \mathbb{N}$ and $l_i < h_i$. 6. $V : T \rightarrow \wedge, \vee$ maps an event-processing mode (AND or OR) for every transition. 7. $Z_0 = (M_0, D_0)$, where $M_0 : P \rightarrow \{0,1\}$ is the initial marking, and $D_0 : P \rightarrow \{0\}$ is the initial clock position. R consists of a set of reconfiguration functions, formalized as follows. $R = \{r_1, .., r_n\}$ where: $r = (Cond, s, x)$ such that: 1. $Cond \rightarrow$ {true, false} is the pre-condition of r, which means specific external instructions, gusty component failures, or the arrival of certain states. 2. $s : TN(^*r) \rightarrow TN(r^*)$ is the structure modification instruction such that $TN(^*r)$(resp. $TN(r^*)$) is the original (resp. target) TNCES before (resp.

[1] Cartesian product of two sets: $A \times B = \{(a, b)|a \in A, b \in B\}$.

Table 1. Fundamental structure modification instructions of an R-TNCES.

Instruction	Symbol
Add condition signals	$Cr(cn(x,y))$
Add event signals	$Cr(ev(y,y))$
Add control component	$Cr(CC)$
Delete condition signals	$De(cn(x,y))$
Delete event signals	$De(ev(y,y))$
Delete control component	$De(CC))$

After) r application. 3. x : $last_{state}(TN(^*r))\rightarrow initial_{state}(r^*)$ is the state processing function, where $last_{state}(TN(^*r))$ (resp. $initial_{state}(TN(r^*))$) is the last (resp. the initial) state of $TN(^*r)$ (resp. $TN(r^*)$). The application of r makes a modification of the R-TNCES structure by the mean of instructions presented in Table 1. We denote by x a place, y a transition, CC a control component module, and "+" the AND of instructions to represent complex modification instructions.

R-TNCES Dynamics. The dynamics of R-TNCESs is represented by:

1. The reconfiguration between TNCESs in module behavior B, by applying a reconfiguration function r when its pre-condition is fulfilled.
2. The firing transition in each TNCES, depends on the rules of firing transitions in TNCESs and the chosen firing mode.

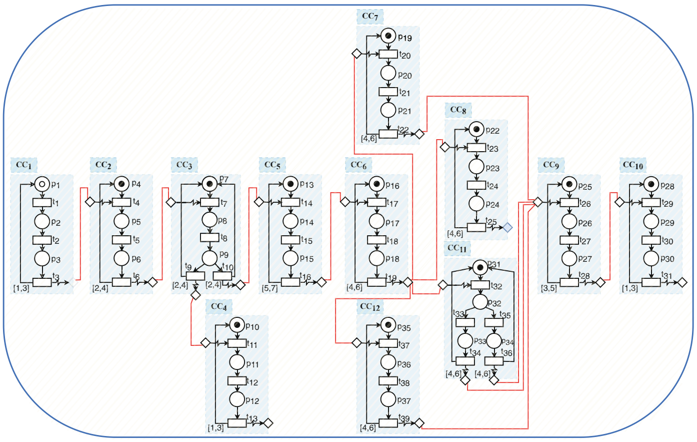
Reconfiguration changes the system from a configuration to another, however, the initial and the new configurations can contain similarities. In the original paper [5], we propose definition of similarities as follow:

Definition 1. *Internal similarity is the property of sharing the same physical process between different configurations of a unique RDECS. Thus, the model contains similar parts. It is caused by the fact that a reconfiguration is rarely radical.*

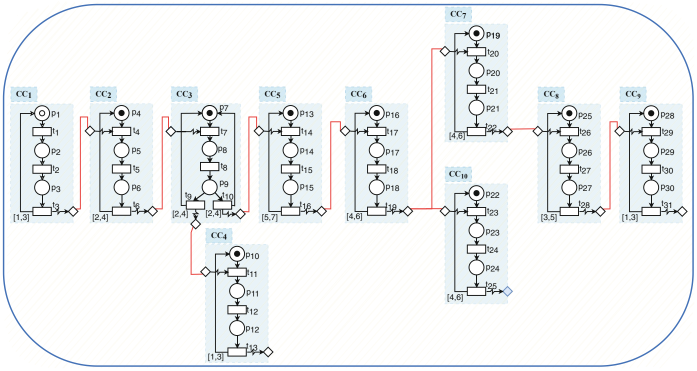
Definition 2. *External similarity is the property of sharing the same physical process between configurations of two or several R-TNCESs. It is caused by the fact that some systems share same components or stations.*

2.2 Production Systems: FESTO MPS and THREADING HOLE SYSTEM

This subsection presents two production systems FESTO MPS and THREADIN HOLE SYSTEM.



(a) Behavior module of $RTN_{Sys_{01}}$.



(b) Behavior module of $RTN_{Sys_{02}}$.

Fig. 1. Behavior module of $RTN_{Sys_{01}}$ and $RTN_{Sys_{02}}$.

FESTO MPS. FESTO MPS is a well-studied system for research and educational purposes which is defined and detailed in [7,17]. It is composed of three units. The distribution contains a pneumatic feeder and a converter. It forwards cylindrical workpieces from the stack to the testing unit. The testing unit contains the detector, the elevator and the shift out cylinder. The detection unit performs checks on workpieces for height, material type and color. Workpieces that successfully pass this check are forwarded to the processing unit. The processing unit is composed of a rotating disk, drilling machines, a checker and an evacuator. The drilling of the workpieces is performed as the primary processing of this MPS. The result of the drilling operation is then checked by the checking machine and the workpieces is forwarded for further processing to another mechanical unit. FESTO MPS performs three production modes: (i) High mode: when $Driller_1$ and $Driller_2$ are both activated and ready to work simultaneously, (ii) Medium mode: when $Driller_1$ and $Driller_2$ are both activated but work sequentially, (iii) Light mode: when only one driller is activated at once. We denote $Light_i$, when $Driller_i/i \in \{1,2\}$ works. FESTO MPS is modeled with an R-TNCES $RT_{FESTO}\{B_{FESTO}, R_{FESTO}\}$ such that: B_{FESTO} $=\{High, Medium, Light_1, Light_2\}$ is the behavior module where the combination of CC_s describes the system modes. As shown in Fig. 1a.

R_{FESTO} $=\{r_{H,L_1}, r_{H,L_2}, r_{H,M}, r_{M,H}, r_{M,L_2}, r_{L_1,L_2}\}$ is a set of different system reconfigurations. The set of control chains describing FESTO MPS control system is presented as follows: $Cchain_1 = CC_1, CC_2, CC_3, CC_4,$
$Cchain_2 = CC_1, CC_2, CC_3, CC_5, CC_6, CC_7, CC_9, CC_{10},$
$Cchain_3 = CC_1, CC_2, CC_3, CC_5, CC_6, CC_8, CC_9, CC_{10},$
$Cchain_4 = CC_1, CC_2, CC_3, CC_5, CC_6, CC_{11}, CC_9, CC_{10},$
$Cchain_5 = CC_1, CC_2, CC_3, CC_5, CC_6, CC_{12}, CC_9, CC_{10}.$

This paper uses the description and the R-TNCES model of FESTO MPS for the construction of the proposed ontology as shown in Fig. 3a.

Threading Hole System. It is modeled using R-TNCES formalism. It is composed of three units:

(i) the distribution unit,
(ii) the testing unit, and
(iii) the processing unit.

The first two units are used in FESTO MPS. The processing unit is composed of a rotating disk, threading hole machine, a checker and an evacuator perform the threading of the workpiece holes as the primary processing task of the system. The result of the threading operation is then checked by the checking machine and the workpieces are forwarded for finally further processing to another mechanical unit. Behavior module B_{THS} and ontology O_{THS} are presented in Fig. 1b and Fig. 3b respectively on page 9. such that:

$B_{THS} = \{High, Light\}$ is the behavior module shown in Fig. 1b. $R_{THS} = \{r_{H,L}, r_{H,L}\}$ is a set of different system reconfiguration.

The set of control chains describing THS control system is presented as follows:

$Cchain_1 = CC_1, CC_2, CC_3, CC_4,$
$Cchain_2 = CC_1, CC_2, CC_3, CC_5, CC_6, CC_7, CC_8, CC_9,$
$Cchain_3 = CC_1, CC_2, CC_3, CC_5, CC_6, CC_{10}, CC_8, CC_9.$

2.3 Ontology Concept

As defined in [14] an ontology is an explicit description of concepts or classes in a certain domain that constitutes a knowledge base. An ontology is defined mathematically as quadruple $O = (C, S, Re, I)$ where:

Table 2. Generic ontology which modeled RDECSs [5].

Concepts ∈ C	RDECS	Domain	Unit	Physical process	Mode
Properties ∈ S	Id: String Name: String Description: Text Synonym: String	Id: String Name: String Synonym: String	Id: String Name: String Description: Text Synonym: String	Id: String Name: String Description: Text Control chain: String Synonym: String	Id: String Name: String Description: Text Synonym: String

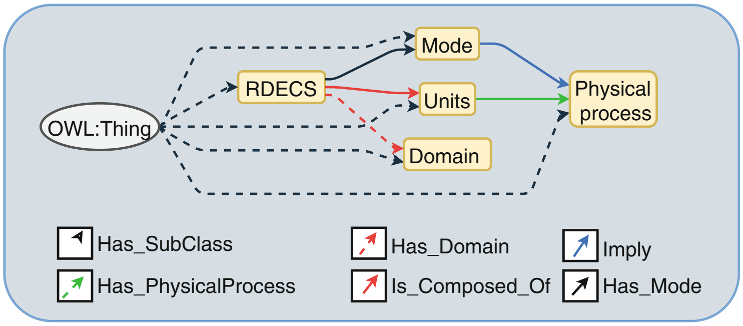


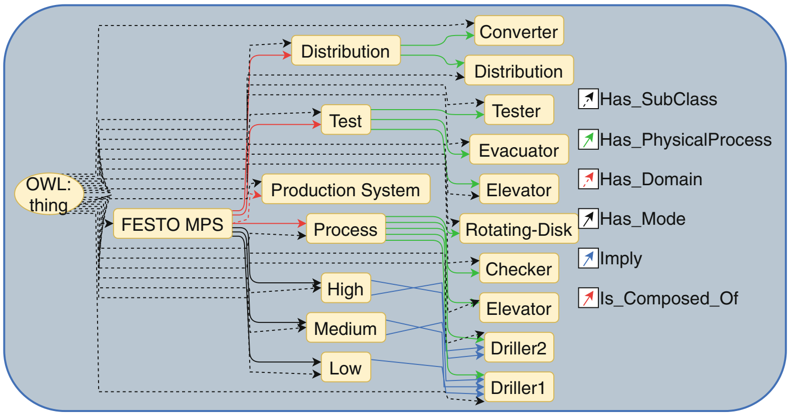
Fig. 2. Generic ontology [5].

1. $C = c_1, .., c_m$ is a set of concepts that refer to a real world objects.
2. $S = s_1, .., s_n$ is a set of properties that refer to a property of a concept, which is a value of a simple type such as Integer, String or Date.
3. $Re = Re_1, .., Re_p$ is a set of relationships defined between concepts.
4. $I = i_1, .., i_q$, where each i_w is an instance of some concept $c_x \in C$. It include a value for every property s_y associated to c_x or its ancestors.

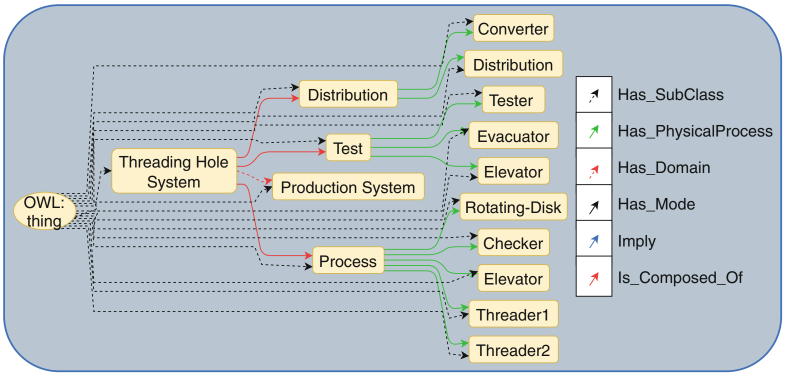
An ontology can be presented graphically as a formed graph $O = G(C, E)$ where C is a set of concepts linked by a set of directed edges E which specifies concept relations. The function y defines the type of edges, i.e., $y : E \rightarrow T$ where T is the set of possible edge types (transitivity, symmetry and reflexivity). In [5], we define a generic ontology $Gen = (C, S, Re, I)$, which is instantiated to model the verified RDECS. Table 2 shows the defined concepts $\in C$ and their properties include in S, note that the property synonym is facultative [5]. Figure 2 shows the relations $\in Re$.

3 New State Space Generation Method

We present in this section the proposed method for state space verification during formal verification of R-TNCESs. We extend the approach proposed in [5].



(a) Ontology $Osys_{01}$



(b) Ontology $Osys_{02}$

Fig. 3. Ontologies that describe Sys_{01} and Sys_{02}.

Thank to this approach, we minimize temporal complexity by proposing a distributed architecture on cloud server [8] for similarities detection, accessibility graph generation and CTL properties verification. Thus, we improve model-checking of reconfigurable systems and make it more efficient.

3.1 Motivation

The correctness of RDECSs can be ensured by a formal verification. The exploration of the state space is widely used for analyzing models formalized with R-TNCES, or related formalisms. The complexity of R-TNCES makes the verification task complex, because of combinatorial growth of the state space according to the model size. The verification of an R-TNCES requires the checking of each configuration, namely each TNCES. TNCESs that describe the configurations often present similarities which implies redundant calculation during

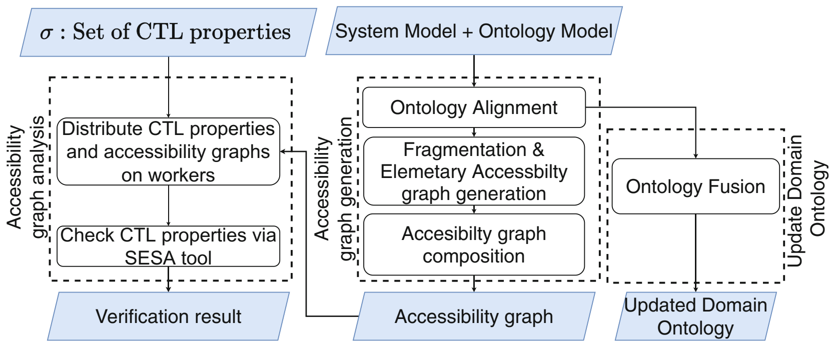

σ : Set of CTL properties
System Model + Ontology Model
Accessibility graph analysis
Distribute CTL properties and accessibility graphs on workers
Check CTL properties via SESA tool
Verification result
Accessibility graph generation
Ontology Alignment
Fragmentation & Elemetary Accessbilty graph generation
Accesibilty graph composition
Accessibility graph
Ontology Fusion
Update Domain Ontology
Updated Domain Ontology

Fig. 4. Global idea for state space generation.

checking of these systems. Thus we propose an adequate approach that avoids many repetitive computations. To ensure this objective, this paper proposes a new method where verification is executed in a distributed architecture to control R-TNCESs complexity. The formal verification is performed through the following tasks: fragmentation, alignment and fusion of ontologies, accessibility graph composition. And CTL properties verification. Figure 4 presents the main steps of the proposed method and highlight the main improvement still to the original paper [5].

3.2 Formalization

In this section, we present accessibility graph generation steps according to our proposed method.

Ontology Alignment. According to the definition presented in [13], aligning two ontologies is to find a set of correspondences, where each correspondence is described by: a unique identifier Id, the concept $c_i \in O_1$, the concept $c_j \in O_2$ and σ_{ij} the degree of similarity between c_i and c_j evaluated in the interval [0,1]. Formally, it is to find $|O_1| \times |O_2|$ correspondences $(Id_{ij}, c_i, c_j, \sigma_{ij})$. A threshold τ is defined and compared with σ_{ij}. The correspondence is established only if $\sigma_{ij} > \tau$. We updates the proposed method presented in [5]. Indeed, we propose a new method for Global similarity σ_{ij} computation by considering synonyms between concepts. Therefore, σ_{ij} is computed through the following steps:

1. Compute semantic similarity by comparing concepts neighbors using Tversky measurement: $Tm_{ij} = \frac{|(n_i \cap n_j)|}{|(n_i \cap n_j)| + \alpha|(n_i - n_j) + \beta|(n_j - n_i)|}$, where:
   n_i (resp. n_j): Neighbor set of c_i (resp. c_j).
   $n_i \cap n_j$: Number of common neighbors between c_i and c_j.
   $n_i - n_j$ (resp. $n_j - n_i$): Number of neighbors that exist $\in n_i$ and $\notin n_j$ (resp. $\in n_j$ and $\notin n_i$).

Table 3. Application of ontology alignment on running example where $Concept_1 \in O_{FESTO}$ and $Concept_2 \in O_{THS}$.

Properties / Concepts	Name	Neighbors	Descriptions	
Concept 1	Process	{Driller1, Driller2, checker, Evacuator Rotating disk}	Workpieces that pass the test unit successfully are forwarded to the rotating disk of the processing unit, where the drilling of workpieces is done. It is assumed that in this work there exist two drilling machines Drill1 and Drill2 to drill workpieces. The result of the drilling operation is next checked by a checker and finally the finished product is removed from the system by an evacuator.	
Concept 2	Process	{Threader1, Threader2, checker, Evacuator Rotating disk}	Workpieces are received by rotating disk of the process unit, where the threading of workpieces is done. It is assumed that in this work there exist one threading hole machine to thread workpieces. The result of the is next checked by a and finally the finished product is removed from the system by an evacuator.	
Similarities	$SimLex = 1$	$Tm = 0.46$	$Simdes = 0.6$	$SimLing = 0.76$ $\sigma = 0.61$

2. Compute lexical similarity, a weighted sum of *normalized Leveinstein* and *n-gram* similarities: $SimLex_{ij} = \alpha * LevNorm(i,j) + \beta * g_(i,j)$.
3. Compute semantic similarity by comparing concepts synonyms using Tversky measurement: $SimSyn_{ij} = \frac{|(n_i \cap n_j)|}{|(n_i \cap n_j)| + \alpha|(n_i - n_j) + \beta|(n_j - n_i)|}$, where:
   n_i (resp. n_j): Synonyms set of c_i (resp. c_j).
   $n_i \cap n_j$: Number of common synonyms between c_i and c_j.
   $n_i - n_j$ (resp. $n_j - n_i$): Number of synonyms that exist $\in n_i$ and $\notin n_j$ (resp. $\in n_j$ and $\notin n_i$).
   The similarity between each pair of synonyms is computed using $n - gram$ measurement. Note that this similarity is computed only if concept have synonyms.
4. Compute partial similarity of concept descriptions using the cosinus function: $SimDes_{(A,B)} = cos(\theta) = \frac{A.B}{|A||B|} = \frac{\sum A \times B}{\sqrt{\sum A^2} \times \sqrt{\sum B^2}}$.
5. Compute linguistic similarity is computed according to the comparison between lexical similarity $SimLex$ and synonyms similarity $SimSyn$ as follow:
   If $SimLex_{(i,j)} > SimSyn_{(i,j)}$, Thus, $SimLing_{(i,j)} = \alpha SimLex_{(i,j)} + \beta SimDes_{(i,j)}$.
   Otherwise, $SimLing_{(i,j)} = \alpha SimSyn_{(i,j)} + \beta SimDes_{(i,j)}$. with $\alpha = 0.4$ and $\beta = 0.6$.
6. Calculate the global similarity which is a weighted sum of linguistic and semantic similarity: $\sigma_{ij} = \alpha SimLing_{ij} + \beta Tm_{ij}$, with $\alpha = \beta = 0.5$.

Example 1. Let O_{FESTO} and O_{THD} two ontologies, which describe the production systems presented in Subsect. 2.2. Given two concepts $Process \in O_{FESTO}$ and $Process \in O_{THS}$. Table 3 shows an application of ontology alignment where, we compute:

i) lexical similarity, which concerns the concepts property "Name".
ii) semantic similarity, which concerns concepts Neighbors.
iii) description similarity, which concerns the concepts property "Description".

iv) synonyms similarity, which concerns the concepts property "synonyms".
v) linguistic similarity, which is a weighted sum of lexical/synonyms and description similarities.
vi) global similarity by combining the said similarities.

$\sigma(Process, Process) = 0.61$ (low value) and the threshold $\tau = 0.8$ (fixed). We conclude that $Process \in O_{Sys_{FESTO}}$ and $Process \in O_{Sys_{THS}}$ are non-similar. Thus, the non-similar and similar parts are efficiently distinguished and redundant calculations are avoided.

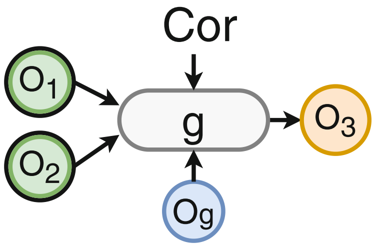
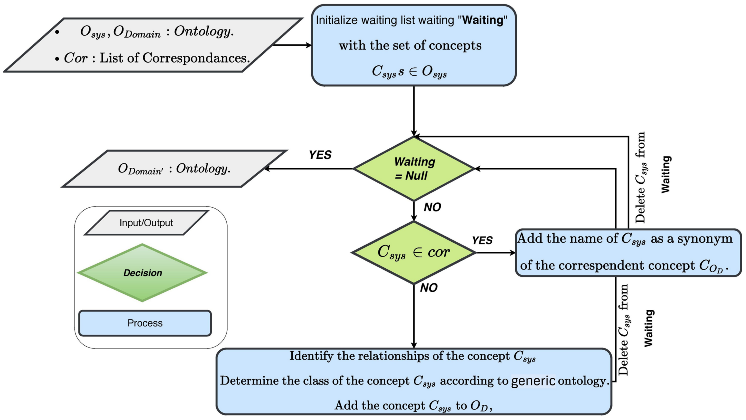


Fig. 5. Ontology fusion function (g).

Ontology Fusion. According to the definition in [12], ontology fusion is the process to detect similarities (i.e., correspondent concepts) between two ontologies and to derive from it a new ontology that brings together all the similarities and dissimilarities of concepts, while preserving semantics. Formally, ontology fusion is defined in this paper as a function g, which from two ontologies O_1, O_2, a generic ontology O_g (presented in Subsect. 2.3) and a set of correspondences Cor (computed during ontology alignment) product a new ontology O_3. The function g is illustrated in Fig. 5. Ontology fusion proceeds in three steps:

1. Enrich the concept present in the merged ontology with the name of the similar concept $\in Cor$ as a synonym property,
2. detect the class of dissimilar concepts according to the generic ontology , and
3. add the concepts according to their classes in the new ontology,

Example 2. Let apply ontology fusion on the ontologies presented in Example 1. We know that $Process \in O_{THS}$ and $Process \in O_{FESTO}$ are non-similar thank to ontology alignment. Thus, we have to add the concept $Process \in O_{FESTO}$ to O_{THS} which represent our domain ontology. Indeed, first we detect the class of concept "Process" according to the generic ontology, which is "Unit". Then, we add this concept to the domain ontology depending on its class. Figure 7 shows the result of ontology fusion (i.e., adding non-similar concepts to our domain ontology).



• O_{sys}, O_{Domain} : Ontology.
• Cor : List of Correspondances.
Initialize waiting list waiting "Waiting" with the set of concepts $C_{sys}s \in O_{sys}$
Waiting = Null
YES
$O_{Domain'}$: Ontology.
NO
$C_{sys} \in cor$
YES
Add the name of C_{sys} as a synonym of the correspendant concept C_{O_D}.
NO
Identify the relationships of the concept C_{sys}
Determine the class of the concept C_{sys} according to generic ontology.
Add the concept C_{sys} to O_D,
Delete C_{sys} from Waiting
Delete C_{sys} from Waiting
Input/Output
Decision
Process

Fig. 6. Operative steps of the ontology fusion function where *Waiting* is the list of concepts $\in O_{Sys}$.

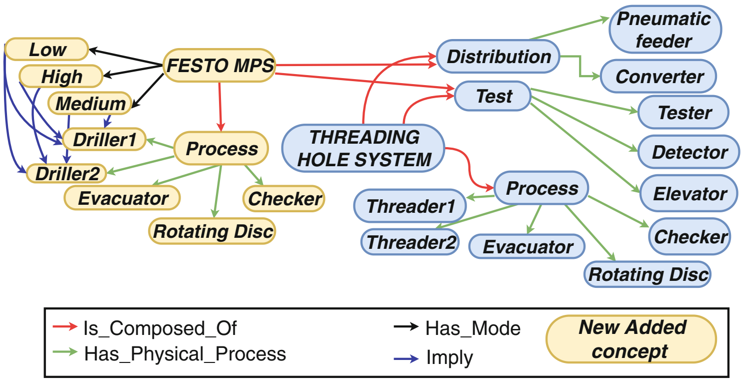


Fig. 7. Domain ontology O_D after the application of ontology fusion.

Fragmentation. Fragmentation consists on decomposing an R-TNCES into a set of CC and generating elementary accessibility graph $EAGs$ for CCs that are not concerned by the correspondences computed in the previous step.

Example 3. To show the application of fragmentation, we consider production systems presented in Subsect. 2.2. They are modeled by RT_{FESTO} (to be verified) and RT_{THS} (already verified). Let Cor be a set of correspondences computed during alignment of O_{FESTO} and O_{THS}. Table 4 shows application of fragmentation on RT_{FESTO}. It runs in two steps: 1. decomposing RT_{FESTO} into a set of $CC\ f = \{CC_1, .., CC_{12}\}$, and 2. computing elementary accessibility graphs EAGs of each $CC \notin f \cap cor$. During fragmentation, CCs synchronization transitions are stored for reuse when composing the accessibility graph AG. Real RDECSs encompass millions of transitions, which increases accessibility graph generation complexity. Fragmentation allows us to control complexity. Moreover, it allows us to deal with internal similarities.

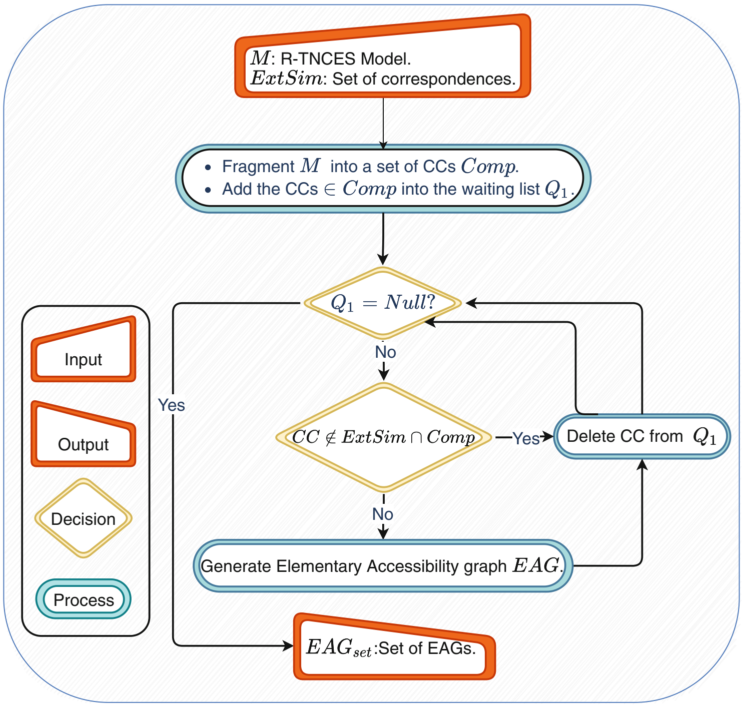

M: R-TNCES Model.
$ExtSim$: Set of correspondences.
Fragment M into a set of CCs $Comp$.
Add the CCs $\in Comp$ into the waiting list Q_1.
$Q_1 = Null?$
No
Yes
$CC \notin ExtSim \cap Comp$
Yes
Delete CC from Q_1
No
Generate Elementary Accessibility graph EAG.
EAG_{set}:Set of EAGs.
Input
Output
Decision
Process

Fig. 8. Operative steps of the fragmentation function where $Waiting$ is the list of CCs to be computed.

Table 4. Application of fragmentation on FESTO MPS [5].

System	FESTO MPS
f	$\{CC_1, .., CC_{12}\}$
cor	$\{CC_1, CC_2, CC_3, CC_4, CC_5, CC_6, CC_{10}\}$
$EAGs$	EAG_{CC_7}, EAG_{CC_8}, EAG_{CC_9},$EAG_{CC_{10}}$, $EAG_{CC_{11}}$, $EAG_{CC_{12}}$

Planning. We set up a priority order for accessibility graph composition. Let RTN be a system modeled by R-TNCES and described by ontology O_{sys}. We extract from O_{sys} control chains $Cchains$. $Cchains$ are then en-queued to a queue Q depending on their length such as the smallest one is en-queued firstly.

Example 4. By using the behavior module B of RTN_{FESTO}, the composition plan to be followed for AG_{FESTO} generation for test failure case described by C_{chain_1} is presented as follows:

$$EAG_{CC_1} \times EAG_{CC_2} > PAG_{CC_{12}} \times CC_3 > PAG_{123} \times CC_4.$$

Accessibility Graph Composition. Full accessibility graph AG is computed by composing $EAGs$ computed during fragmentation step and partial accessibility graphs $PAGs$ retrieved during ontology alignment step as shown in Fig. 10. The composition is done according to the established plan.

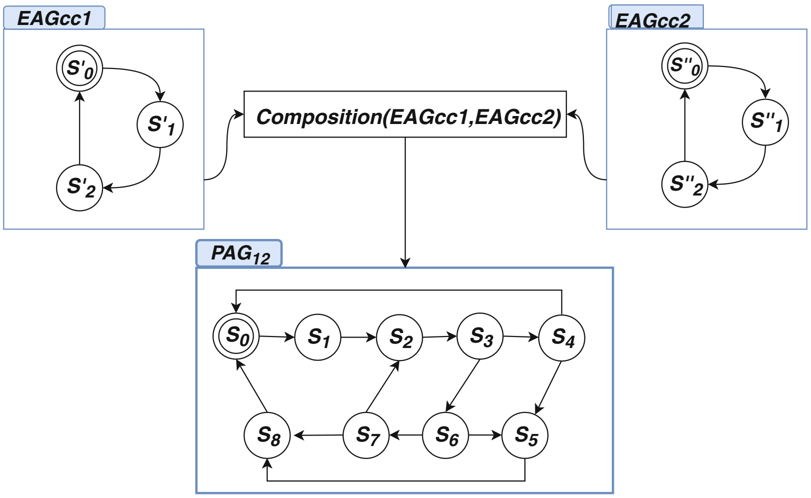


Fig. 9. Composition of EAGcc1 & EAGcc2 [5].

Example 5. During AG_{FESTO} generation, several composition of EAGs are executed. Indeed, we run $Composition(EAG_{CC_1}, EAG_{CC_2})$ function to obtain PAG_{12} shown in Fig. 9. It proceeds as follows:

1. Creates initial state S_0 by concatenating initial states S'_0 and S''_0 of both EAG_{CC_1} and EAG_{CC_2},
2. searches the set of enabled transitions from S'_0 and S''_0, and
3. checks whether the transition t is a common transition. If yes, then we create a new state S_1 by concatenating the current target states from S'_0 and S''_0. Otherwise, if t belongs only to EAG_{CC_1}, then a new state S_1 is obtained by concatenating the current state S''_0 from EAG_{CC_2} and the current target state S'_1 from EAG_{CC_1} and vice versa.

We repeat these steps for the remaining states until we get the whole state space.

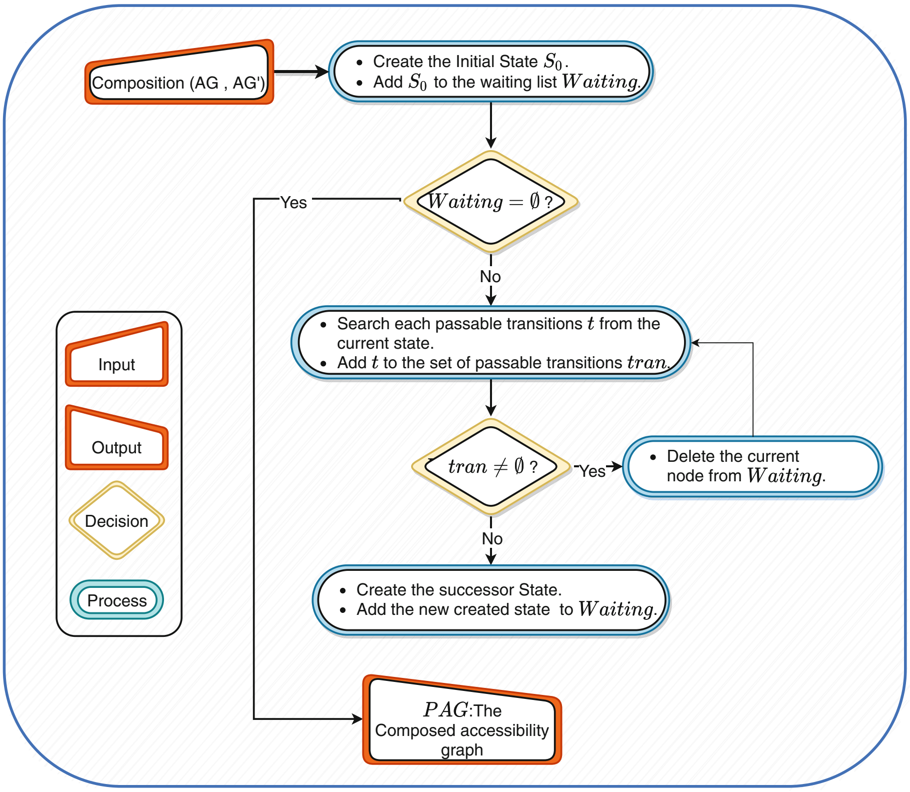

Composition (AG , AG')
Create the Initial State S_0.
Add S_0 to the waiting list $Waiting$.
$Waiting = \emptyset$?
Yes
No
Search each passable transitions t from the current state.
Add t to the set of passable transitions $tran$.
$tran \neq \emptyset$?
Yes
Delete the current node from $Waiting$.
No
Create the successor State.
Add the new created state to $Waiting$.
PAG:The Composed accessibility graph
Input
Output
Decision
Process

Fig. 10. Operative steps of the graph composition function, where ***t*** is the set of the fixed passable transition and ***Waiting*** is the list of nodes to be computed.

Parallel CTL Properties Verification. In short-term we integrate CTL properties verification method inspired from methods proposed in [4,17]. This method consider relationships which exist among properties to be verified (Equivalence, dominance and composition) and processes the verification in parallel way. The method proposed in this paper processes as follow:

– *Step 1 (Relationships detection):* We extract different relationships that exist among CTL properties to be verified (Dominance & equivalence).
– *Step 2 (Matrix and tree parallelization generation):* First, we generate a square matrix S, where, the value of each element of S describes the nature of relationship between each pair of properties as follow: $S[i, j] = 0$ means that there is no relation between P_i & P_j and $S[i, j] = 1$ (resp. $S[i, j] = 2$) means that there is a dominance (resp. equivalence) relation between P_i & P_j. Then, we generate parallelization tree in order to coordinate the execution of properties verification. Indeed, we identify the redundancies and the factorization between properties to be verified. Each level of the tree represents the prop-

erties which can be verified simultaneously. Thus, the verification order of the CTL properties is established by exploring the parallelization tree by level.
- *Step 3 (CTL Properties verification)*: We proceed to the verification of CTL properties thanks to the SESA Tool developed in [20].

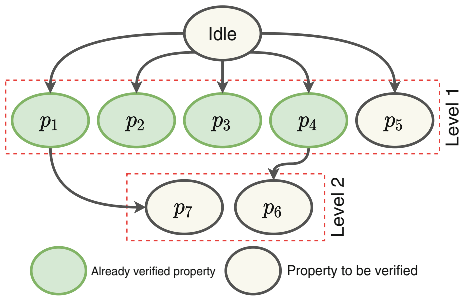


Fig. 11. Parallelization tree.

Table 5. CTL properties to be verified.

σ_{FMPS}: Set of CTL properties
$P_1 : AF(p_3)$
$P_2 : AF(p_4)$
$P_3 : AF(p_9)$
$P_4 : AF(p_{18})$
$P_5 : EF(p_{33})$
$P_6 : AG(EF(p_{12}) \rightarrow AF(p_{18})$
$P_7 : AG(p_3 \rightarrow AF(p_{30}))$

Example 6. To show the application of CTL properties verification according to the proposed method, we consider a set of properties that aims to verify the safety and vivacity of Sys_{01} (FESTO MPS). Note that we consider that Sys_{02} has already been verified, indeed at this stage we have available:

1. State space generated during previous tasks.
2. Result of CTL properties verified during Sys_{02}.

Given σ_{FMPS} a set of properties to verify the safety and the vivacity of Sys_{01}. First, we proceed to the detection of relationships that exist among the properties presented in Table 5. Then, we generate the parallelization tree shown in Fig. 11, after that we check for properties already verified during Sys_{02}, in the present case it concerns the properties $p_{i/i=1,\dots 4}$. Finally, we proceed to the verification of the remaining CTL properties using SESA tool [16].

4 Distributed Cloud-Based State Space Generation

This section presents Cloud-based distributed architecture and how to perform formal verification on it.

4.1 Distributed Architecture for State Space Generation

In this subsection, we present hierarchical and distributed architectures propose in the conference paper [5] depicted in Fig. 12. The idea that motivates the development of this architecture is to increase computation power and storage availability. It is composed of computational and storage resources. To develop the architecture shown in Fig. 12 we need the following units.

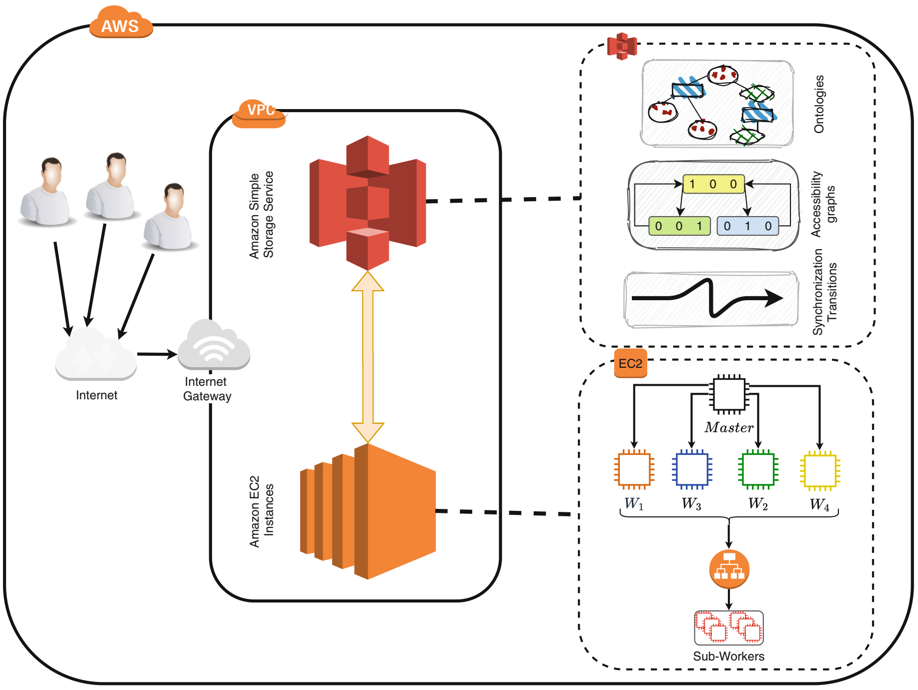


Fig. 12. Distributed architecture for formal verification.

- Computational units: Execute tasks defined in Subsect. 3.2 by means of $M+n$ machines where:
  (i) M represents the number of machines (i.e., 5 machines in our approach). The set of machines are composed of a master and four workers $W_1, ..., W_4$ that have specific tasks.
  (ii) n is the number of sub-workers that execute the high complex tasks (i.e., $EAGs$ generation and $PAGs$ composition). n depends on system size.
- Storage unit: represents the allocated cloud database that stores domain ontologies, $EAGs$ temporary and $PAGs$ permanently.

4.2 Distributed State Space Generation

This subsection presents the process of distributed Formal verification on a cloud based architecture.

Example 7. The user sends a verification request $req(R_{FESTO}$: $R\text{-}TNCES, O_{FESTO} : Ontology)$. The master ensures tasks coordination by receiving the verification request and sending R_{FESTO} and O_{FESTO} to workers to carry out their tasks as follows. 1. sending simultaneously ontology O_{FESTO} to workers W_1, W_4 and R_{FESTO} to worker W_2, 2. waiting signals from W_1 and W_2 and to receive the composition plan from W_4 to forward it to W_3. 3. waiting

signal from W_3 to allow beginning ontology fusion by W_1. W_1 has two main tasks: (i) Ontology alignment to extract correspondences and (ii) Ontology fusion to update domain ontology-based history, we merge O_{FESTO} AND O_D.
W_2: At the reception of R_{FESTO}, it proceeds to the fragmentation, sends CCs to sub-workers after applying a load balancer algorithm and sends a signal to master which announces the end of these two tasks: fragmentation and generation of $EAGs$.
W_3 receives the composition plan and collects the elements that it needs from the database for the AG composition. Finally, it sends a signal to master which announces the end of its task.
W_4 is responsible for planning compositional order for full accessibility graph generation. It extracts the control chains concepts from O_{FESTO}. Then the plan is sent to the master.

CTL properties presented in *Example 6* are performed in the presented architecture as follow:

- W_2: performs Relationships detection,
- W_3: performs matrix and palatalization tree generation,
- W_4: performs the exploration of the palatalization tree by level, and
- *workers* perform CTL properties verification and return the result.

4.3 Implementation

In this subsection, we present the main algorithms used in our method.

Algorithm 1. Ontology Fusion.

```
Input: $O_D, O_{sys}$: Ontology; $Cor$: Set of correspondences ;
Output: $O'_D$: Ontology;
for  $int\ i = 0\ to \mid \sum C_{sys} \mid$ do
    if $(\ C_{sys} \in Cor))$ then
        $Enrich(O_D, C_{O_{sys}}.Name, C_{O_D}.synonym)$;
        else
            $Classe \leftarrow IdentifyRelationships(C_{Sys}, O_{sys})$;
            $Insert(C_{sys}, O_D, Classe)$;
        end
    end
    $O'_D \leftarrow O_D$;
end
return  $O'_D$
```

Algorithm 1 describes the ontology fusion. It takes the domain ontology O_D, the system Ontology O_{sys}, and the set of correspondences Cor and returns a new updated domain ontology O'_D. It adds the dissimilar verified concepts to the domain ontology for next verification to process. The functions:

Algorithm 2. Fragmentation

```
Input: $RTN$: R-TNCES; $TN_0$: TNCES;
Output: $S\_EAG$: Set of elementary accessibility graphs;
for $int\ i = 0\ to \mid \sum TN \mid$ do
    for $each\ CC \in TN$ do
        if $( !Tagged\ (CC))$ then
            $Insert(S\_EAG, Geneate\_State\_Space(CC))$; tag(CC);
        end
    end
end
return $S\_EAG$
```

Algorithm 3. State Space Composition.

```
Input: $S\_AG$: Set of accessibility graphs(EAG, PAG); $\sum CChain$: Set of $Cchains$ ;
Output: $AG$: Set Accessibility graphs;
for $int\ i = 0\ to \mid \sum CChain \mid$ do
    $AG \leftarrow EAG_{CC_i^0}$;
    for $int\ j = 0\ to \mid \sum CC_i \mid$ do
        $AG \leftarrow Compose(AG, EAG_{CC_i^j})$;
    end
end
return $AG$
```

- $Enrich(O : Ontology, C_1.Name : String, C_2.synonym : String,)$ Takes the value of the property 'Name' of the concept C_1 and add it as a value of the property 'synonym' of concept C_2 in the ontology O,
- $IdentifyRelationships(C, O)$; returns the class of a the concept C in the onotlogy O according to the generic onotlogy, and
- $Insert(C, O, Class)$ inserts the concept C in the ontology O according to his class.

Algorithm 2 describes the fragmentation task. It decomposes the R-TNCES in a set of CCs and generates their accessibility graphs EAGs. Algorithm 3 describes the steps for the full accessibility graph composition AG. It composes the accessibility graphs recovered thanks to the ontology alignment and the ones computed during fragmentation to return the full accessibility graph of the verified model.

4.4 Complexity of Distributed State Space Generation

The verification is based on three main functions: (i) the ontology alignment, (ii) the fragmentation, and (iii) the $EAG/PAGs$ composition. The ontology alignment complexity on this scale is always polynomial, thus we focus on the two other function presented respectively in Algorithm 2 and 3. As mentioned in [20], TNCES verification complexity is expressed by $\mathcal{O}(e^t)$ where t is the number of transition, in our case, we use it for each CC of the verified R-TNCES. For an R-TNCES with $TN = |B|$ the number of TNCESs composing the verified R-TNCES and C the average number of CCs that every TNCES contains, The complexity of Algorithm 2 is $\mathcal{O}(TN \times C \times e^t)$. For a composed graph with n' the number of nodes computed by the composition graph function and j the average number of the enabled transitions from each state, Algorithm 3 complexity is expressed by $(n' \times j)$. Thus, verification time complexity is: $\mathcal{O}((TN \times C \times e^t) + (n' \times j))$. Therefore, our method complexity is expressed by

$$\mathcal{O}(\max \mathcal{O}(TN \times C \times e^t), \mathcal{O}(n' \times j)) = \mathcal{O}(TN \times C \times e^t).$$

The complexity of methods presented in [7,20] is:

$$\mathcal{O}(e^m \times TN) \text{ with } m \times TN = TN \times C \times t.$$

Thus, to assert that our complexity is better, we have to prove that:

$$\mathcal{O}((TN \times C \times e^t) < \mathcal{O}((TN \times e^m),$$

which is intuitively correct.

5 Evaluation

The performance of the proposed verification method is evaluated in this section. We make a comparison between the proposed method, that uses a distributed tool to compute accessibility graphs, and the method reported in [7] that uses Rec-AG tool. Then we proceed to different evaluations in large scale systems by considering different similarities. The external similarity rate of R-TNCES R_1 with descriptive ontology O_L is given by the following formula.

$$ExternalSimilarity(R_1) = \left(\frac{AlignedConcepts(O_L)}{Concepts(O_L)}\right) \tag{2}$$

where, (i) $AlignedConcepts(O_L)$ returns the number of similar concepts between O_L and the related domain ontology O_D, (ii) $Concepts(O_L)$ returns the total number of concepts that O_L contains. The internal similarity rate is given by the adapted method used in [7] as follows.

$$InternalSimilarity(R_1) = \left(\frac{Max(\{SimCC(TN_i, TN_j)\}_{i,j \in 0\ldots(n-1)\ and\ i<j})}{Max(NumberOfCC(TN_k))}\right) \tag{3}$$

where, (i) $SimCC(TN_i, TN_j)$ is the function that returns the number of similar control components between two TNCESs, (ii) $NumberOfCC$ takes a TNCES and returns its number of control components, and (iii) Max returns the maximum among a set of natural numbers. We define three degrees of Internal Similarity (resp, External Similarity): High, Medium and low where, *InternalSimilarity* (resp, *ExternalSimilarity*) is 50%–100%, 20%–50% and 0%–20%.

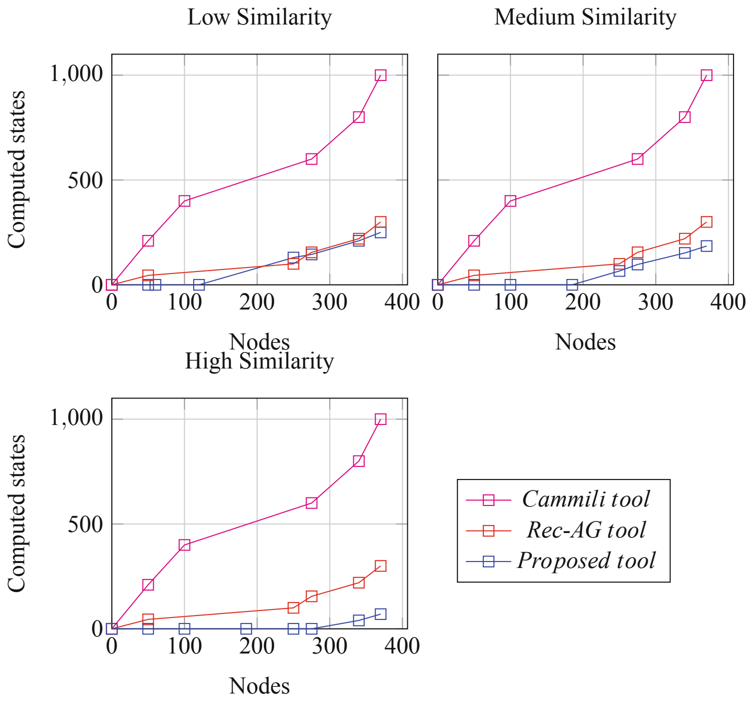


Fig. 13. Proposed verification in large scale systems considering external similarity.

5.1 Evaluation in Large Scale Systems Considering External Similarity

We apply the new proposed method on the case study used in [5]. Figure 13 describes the verification result of an R-TNCES model by considering three levels of external similarity. The model is composed of three TNCESs represented by three parallel control chains of equal length, with $Complexity(CC_{ij}) = 3$, $i \in 1...100$ and $j \in 1...3$ (i.e., each CC contains 3 nodes). By analyzing the plots in Fig. 13, we notice that: In the case of low external similarities, the number of states computed using the proposed method and the one proposed in [7] in its best case (i.e., in the case of a high internal similarity rate) becomes nearly equal with the ascent of the number of system nodes. It is explained by the fact that the difference in the number of nodes to explore is minimal and becomes non-significant when the system is larger. Nevertheless, low similarity must be exploited because it improves the results in both cases of medium and high internal similarity. In the case of high and medium external similarities: the proposed method takes advantage of those presented in [2] and [7]. It is explained by the fact that the number of nodes to explore is reduced. Thanks to the external similarity that allows us to eliminate redundancies. While in the three cases, the proposed method presents better results than the one used in

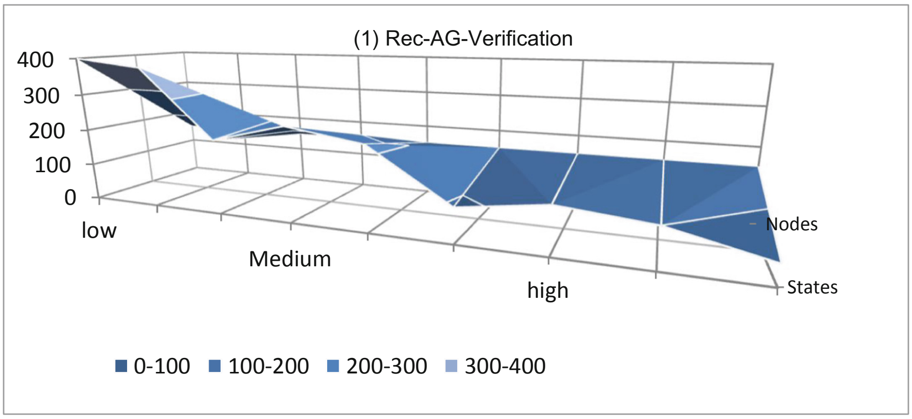


Fig. 14. Proposed verification in large scale systems considering external and internal similarities.

[2], which generates AGs via the classical methods. The proposed method can reduce calculations by more than 50%, depending on model size and similarity rates. This represents the main gain of the paper.

5.2 Evaluation in Large Scale Systems by Considering External and Internal Similarities

The surfaces in Fig. 14 describe the results of both the proposed method and the one used in [7], by using three factors: External similarities, internal similarity and nodes to be explored for a state generation. In their worst case (i.e., $InternalSimilarity = ExternalSimilarity = 0\%$) performance of both methodologies presents limits, with same results using the method reported in [20]. However, in the remaining cases, the proposed method always presents better results according to similarity rates. It performs best with: (i) Less computed states, thanks to the external source of partial graphs and elimination of internal redundancies, and (ii) less nodes to be explored for state space generation thus less complexity to generate a state, thanks to the incremental way used when composing the accessibility graph.

5.3 Evaluation of CTL Properties Verification Method Considering Similarities

Let assume we have to verify a system model with 2500 TNCESs. In order to ensure the well-behave of the system we have to verify at least 4 properties for each TNCES. Thus, we need to verify 10000 CTL properties. We assume that the similarity rate among properties: (i) *Low* in $0, 20\%$, (ii) *Medium* in $20, 60\%$, or (iii) *High* when more than 60%. The results show in Fig. 15 that the gain increases proportionally to decomposable properties rate. Thus, the gain is clearly shown when similarity rate is 'High'.

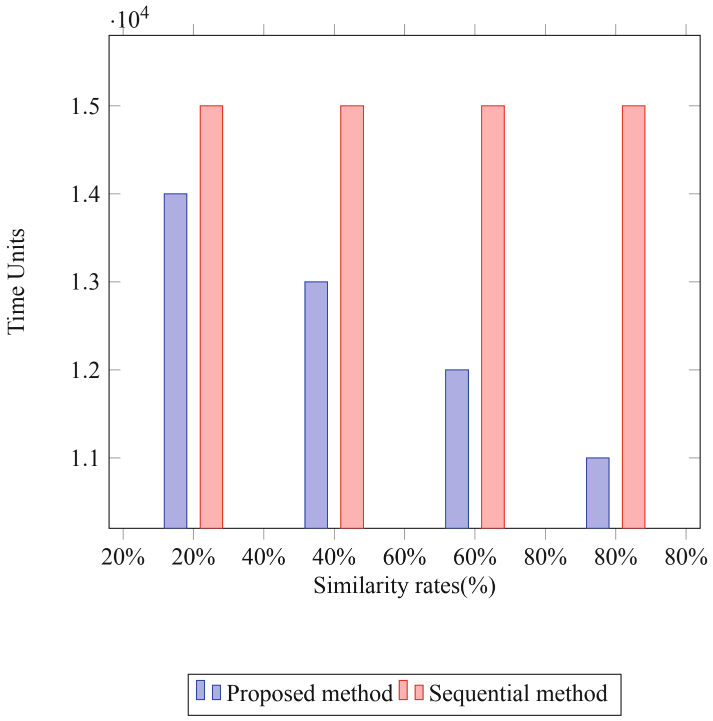


Fig. 15. Sequential method vs proposed method.

6 Conclusion

This paper deals with formal verification of RDECSs that we model with R-TNCES. The proposed method aims to improve formal verification by using a distributed architecture. We developed a distributed architecture with three hierarchical levels (Master, worker and sub-worker) and a cloud-based-storage (Amazon Simple Storage S3 [11]). It allows us to increase computational power, data availability and to perform parallel execution. For the state space generation steps, we incorporates ontologies for RDECSs verification. We set up an ontology-based history, which allows us to detect external similarities thanks to an ontology alignment. Thus, we avoid many redundant calculation. In order to deal with internal similarities, we introduce modularity concept by affecting specific tasks to each unit of our architecture, including fragmentation and accessibility graph composition, which allow us to deal with RDECSs fragment by fragment and to construct incrementally accessibility graphs. For the state space analysis, we proposed a parallel CTL properties verification, where similarities and relationships that can exist among properties are considered. An evaluation is realized and experimental results are reported. The results prove the relevance of the developed architecture and the efficiency of the proposed contribution. Future works will: 1. Deploying the distributed architecture in Amazon Elastic Compute Cloud (EC2) [11]. 2. Incorporate an automatic classification of properties thank to ontologies. 3. Extending the proposed tool to support other formalism that models RDECSs and different temporal logics.

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