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Analysis and verification of ECA rules in Intelligent Environments

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Abstract

Intelligent Environments (IEs) are physical spaces where Information Technology (IT) and other pervasive computing technologies are combined in order to achieve specific goals for the users and the environment. IEs have the goal of enriching user experience, increasing awareness of the environment. A number of applications are currently being deployed in domains ranging from smart homes to e-health and autonomous vehicles. Quite often IE support human activities, thus essential requirements to be ensured are correctness, reliability, safety and security. In this paper we present how a set of techniques and tools that have been developed for the verification of software can be employed in the verification of IE described by means of event-condition-action rules. More precisely, we reduce the problem of verifying key properties of these rules to satisfiability and termination problems that can be addressed using state-of-the-art Satisfiability Modulo Theory (SMT) solvers and program analysers. Our approach has been implemented in a tool called `vIRONy`. Our approach has been validated on a number of case studies from the literature.

1 Introduction

IE are physical environments that combine together information, sensor and communication technologies into everyday physical objects, infrastructures, and the surroundings we live in. IE enhance everyday activities and allow new applications that were not possible before. IE applications and scenarios include smart homes, e-healthcare, e-learning, smart factories and autonomous vehicles [1]. IE are a type of *reactive systems* [2] which maintain a continuous interaction with the environment by reacting to any stimulus (or event) that occurs in it.

The paradigm *Event-Condition-Action (ECA)* [3, 4] is a widely used approach to program reactive systems. An ECA program contains rules of the form: if a certain *event* happens and a *condition* is met, then a specific *action* is executed. IE have a great impact on daily life, thus it is essential for IE to meet requirements of correctness, reliability, safety, security and desired reliable behaviour [5]. These properties are quite hard to be ensured since programming rule-based systems is a difficult and error-prone process [6, 7]. More precisely, the interactions of rule actions can cause the

system behaviour to be unpredictable or unsafe, thus verification of consistency and safety properties of IE systems has become a necessity [8].

Various approaches have been proposed in order to ensure IE properties. For instance, software testing [9] has been widely used to improve software quality. While testing can provide correctness of different systems, it is not adequate for IE where an adequate notion of coverage is missing and the environment in which the system runs is unpredictable. Formal methods techniques can provide an effective solution for analysing and establishing the correctness of IE systems, especially for applications where safety is a critical issue. One of the formal approaches closer to ours is presented in [10]. It proposes a method to analyse the dynamic behaviour of a set of ECA rules by first translating them into an extended Petri Net [11]. This allows the checking of termination and confluence properties. Authors in [12] investigate the possibility of using a pure Binary Decision Diagram ([13]) representation of integer values, and they focus on a particular class of programs. These are ECA rule-based programs with restricted numerical operations. In [14] a tool-supported method for verifying and controlling the correct interactions of ECA rules is presented. This method generates correct rule-based controllers and is based on formal models that are related to reactive systems. The authors in [15] propose a formalisation of an ECA rule-based system that is translated into a Heptagon/BZR program. This offers to the users a combination of a high-level ECA rule language with a compiler and a formal tool support for Heptagon/BZR. In [16], a set of ECA rules is transformed into different kinds of automata and then the automata verification tool Uppaal [17] is applied. The approach is limited to performing model checking of timed automata and their correspondence to the provided ECA rule set.

1.1 Our contribution

In this paper we present a novel theoretical framework for the verification of ECA rules in intelligent environments. Our framework is based on software verification techniques and is implemented in the vIRONy tool ¹. vIRONy is based on the combination of formal methods and simulation techniques, with the aim of supporting programmers and end-users during the modelling and verification phases of IE systems that are based on ECA-rules. The features of vIRONy include:

- a *syntactic analyser* for checking the correctness of the source program and for enabling users to identify and avoid syntactic errors;
- a *formal verification component* based on different techniques (SMT solvers and program analysers) to check safety and correctness of the program expressed as a set of ECA rules;
- a *simulation environment* to generate and investigate specific behaviours of the system;

¹The current version of vIRONy is open source and it is available at <https://gitlab.com/MichelangeloDiamanti/ecaProject>.

```

1 Program ≡ ( Device | Rule | VarDecl )+;
2 Device ≡ PhysicalDevice | LogicalDevice | Set;
3 PhysicalDevice ≡ physical (sensor|actuator)
4 Type Id [= Exp]
5 node(Id Sep Id)[in id (Sep Id )*][where BoolExp];
6 LogicalDevice ≡ logical (sensor|actuator)
7 Type Id = Exp[in Id (Sep Id )*] [where BoolExp];
8 Set ≡ set (sensor | actuator) Type Id;
9 Rule ≡ rule Id on Id (Sep Id )*when BoolExp then Action;
10 Action ≡ [Id = Exp ]+;
11 Exp ≡ BoolExp | IntExp;

```

Figure 1: The IRON extended BNF

- a *semantic analyser* used to perform qualitative and quantitative analysis of the system in terms of number of rules invoked, energy efficiency, etc.

Compared to our approach, the ones in [10] and [12] do not provide methods for verifying application-specific properties like redundancy, consistency and usability of rules. The work presented in [16] is not tailored to a specific rule language and requires a specific model checking tool, while the verification methods proposed in our work are based on a domain-specific language for IE, and allow the definition and the implementation of verification algorithms that can use efficient techniques such as SMT solvers and theorem provers. These can enable the verification of application-specific properties. With respect to our approach, in [14] properties such as correctness and usability are not considered for verification. Redundant rules are not directly detected by Heptagon/BZR [15]. Duplicated rules are compiled and executed at run-time and rule actions are activated using the `OR` operator. Instead, our approach enables end-users to identify redundant rules and decide how to modify the program; therefore it allows a deeper analysis and understanding in the design phase, giving to the programmer a greater control on the system he or she intends to develop.

2 Preliminaries and notation

In this section we recall IRON [18], a domain-specific language for IE based on ECA rules and the formal model expressing its semantics [19].

IRON (Integrated Rule ON data) is a restricted first-order logic language that supports the categorisation of devices into sets [20], allows the definition of properties over sets and supports multicast and broadcast abstractions. We report the main constructs of the IRON syntax in Fig. 1 [21].

The formal model for the execution of ECA rules in IRON exploits the features that are typical of IE, taking into account the fact that a generic action defined by the user can only change actuator configurations. For the sake of simplicity but without loss of generality, the formal model does not include the definition of sets and the distinction between logical and physical devices included in IRON (these could be introduced at the cost of additional notation but do not affect the overall partitioning strategy described below).

This uses the function ψ_{a_i, a_j} of Figure 7 which returns true when two different actions a_i and a_j modify the actuators in the same ways (i.e., no contradiction occurs).

We consider an ECA-rule based system consisting of: (i) a set D of variables representing the input/output devices of the system, denoted with i and o respectively (to refer to a generic element of D we use the letter d); (ii) a set Inv of static constraints inv of the system identifying the admissible values for each device (each invariant is a restricted first-order logic predicate as defined by the IRON grammar); (iii) a set R of ECA rules of the form $Event[Condition]/Action$.

A *state* of the system is an assignment of values to the devices in D and the *universe* is the set of states. In detail:

Definition 1. A state of the system is a function $\varphi : D \rightarrow Val$ where Val is a finite set of integer or boolean values.

Definition 2. The universe Φ of an ECA-rule based system is the set of all possible states of the system, i.e., the set of all possible functions φ in definition 1.

By adding constraints to the system, i.e. conditions that must be satisfied, we can define the *admissible state space*:

Definition 3. Let Φ be the universe. The admissible state space Φ_a is the subset of Φ whose elements are all the states φ that satisfy the constraints of the system.

Given D and Φ , we consider a finite set R of labels for ECA rules $R = \{r_1, r_2, \dots, r_k\}$ for $k \in \mathbb{N}_0$. A generic rule r in R is represented as $e_r[c_r]/a_r$, where e_r, c_r, a_r are labels for the event, the condition and the action of r respectively.

We observe that devices can change their values according to *external changes* (sensors) or *internal changes* (actuators change their values in response to ECA rules being triggered). As a consequence, the evolution of the system can be partitioned into two sets: the set of *artificial transitions* resulting from the activation of ECA rules, and the set of *natural transitions* that result from changes in the environment. According to this partitioning, we can distinguish between stable and unstable states: the system is in a *stable state* if only natural transitions can be applied, while *unstable states* are those states to which only artificial transitions can be applied.

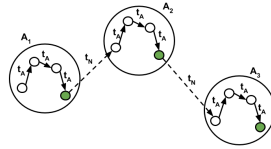


Figure 2: System behaviour

We use the generic example represented in Fig. 2 for a clarification of how natural transition (denoted by t_N and dotted arrows) and artificial transition (denoted by t_A and solid arrows) interact. In this figure, white circles are unstable states in Φ_a , while green states are stable states. States are grouped together into three sets, A_1, A_2, A_3 in which the input sensors do not change value. Natural transitions link together these

sets. Inside each set, the states are linked to each other via artificial transitions, since changes are due only to actuator values.

The representation of the evolution of the system is based on two important hypotheses: (1) the initial admissible configuration of the system is given by an external entity; (2) artificial transitions take much shorter time than natural transitions.

Finally, since we consider a finite set of devices that can assume a finite set of values, it is possible to represent the evolution as a Finite State Automaton (FSA) [22], where the edges correspond to the transitions of the system and the vertices to its states.

3 Properties and verification algorithms

Our aim is to avoid “unsafe” and “incorrect” situations deriving from erroneous definitions of ECA rules that may result in inefficient or potentially dangerous effects on the real world. Based on literature review of related and previous works [18, 14], we identify the following properties that can be considered representative for “safety” and “correctness” of ECA rule-based systems: *termination*, *consistency* and *determinism*. We formally define each of them and we present the verification algorithms below.

3.1 Termination

Definition 4. *An ECA rule-based system satisfies the termination property when all stable states (that satisfy the conditions of some rules) always lead (with the application of a finite number of rules) to a new stable state.*

In order to prove termination we make use of T2² (see [23, 24, 25]), a tool designed to prove temporal properties of programs, such as safety and termination. The tool implements the TERMINATOR-based approach to termination proving (see [26]) with some modifications. The idea of the technique is to reduce the checking of termination arguments to an incrementally evolving safety problem. T2 represents programs as graphs of program locations connected by transition rules with conditions (expressed by the command “assume”) and assignments to a set of integer variables V . The canonical initial location is called `START`.

Given a generic rule-based program written in IRON syntax, we show the encoding into T2 format in Fig. 3. Consider a generic program in IRON consisting of a set of devices D , a set of rules R and a set of invariants Inv_set (see lines 1 – 3 in Fig. 3). We consider the set of initial states characterised by an assigned configuration of actuator values (line 4). We define a set of variables in lines 5 – 13 that are used for the translation. Lines 14 – 40 describe the algorithm for generating the program in T2 format. This program corresponds to the automaton represented in Fig. 4 that is characterised by two states that we generically name 0 and 1. The execution starts from state 1, characterised by the assigned configuration of values, a generic configuration of sensors (the function `nondet()` assigns values randomly). In addition, state 0 is admissible, as the invariants are assumed as valid (line 17). A natural transition (line 26) corresponds to a transition from state 0 to state 1. When a natural transition moves

²available at <https://github.com/mmjb/T2>.

```

1  let  $D = I \cup O$  the set of declared labels
2  let  $R := \{r_1, \dots, r_k\}$  the set of rules such that each  $r \in R$  is of the form  $r: e_r[cr]ar$  where  $e_r = \{d_{w_1}, \dots, d_{w_f}\} \subset D$  and
    $ar = \{o\alpha_1 \leftarrow v\alpha_1, \dots, o\alpha_p \leftarrow v\alpha_p\}$ , with  $o\alpha_1, \dots, o\alpha_p \in O$ 
3  let  $Inv\_set := \{inv_1, \dots, inv_p\}$ 
4  let  $o = val$  the initial value for  $o \in O$ 
5  define  $Inv = \bigwedge_{j=1}^p inv_j$ 
6  for each  $d \in D$ :
7  define  $d\_changed$ 
8  for each  $r \in R$ 
9  for each  $o\alpha_j \in ar$ 
10  define  $o\_prime$ 
11  for each  $d \in e_r$ 
12  let  $d\_check = (d\_changed = 0)$ 
13  define  $eT2\_r = \bigvee_{d \in e_r} d\_check$ 
14  write
15  START: 0;
16  FROM: 0;
17  assume(Inv); //invariants
18  for each  $i \in I$  // sensor initial values
19  write  $i := nondet()$ ;
20  for each  $o \in O$  // actuator initial values
21  write  $o := val$ ;
22  for each  $o\_changed$  //actuators changes
23  write  $o\_changed := 0$ ;
24  for each  $i\_changed$  //sensors changes
25  write  $i\_changed := nondet()$ ;
26  TO : 1;
27  for each  $r \in R$ 
28  write //rule r
29  FROM: 1;
30  assume((Inv)  $\wedge$   $eT2\_r$   $\wedge$   $(c\_n)$ );
31  for each  $o\alpha_j \in ar$ 
32  write
33   $o\_prime := v\alpha_j$ ;
34   $o\_changed := (o \neq o\_prime)$ ;
35   $o := o\_prime$ ;
36  for each  $o \in O$  such that  $o \neq o\alpha_j \in ar \forall j$ 
37  write  $o\_changed := 0$ ;
38  for each  $i \in I$ 
39  write  $i\_changed := 0$ ;
40  TO : 1;
41  end

```

Figure 3: Algorithm for translating input files from IRON to T2 format.

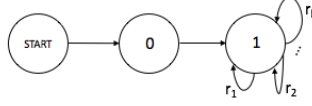


Figure 4: Execution model of IRON programs in T2.

the state from 0 to 1, the rules in R , i.e., the artificial transitions of the system, as shown in Fig. 4, can be applied when their corresponding event is met (line 30).

Proposition 1. *The algorithm in Fig. 3 is correct.*

Proof. First, we show that if a generic ECA rule can be activated in an IRON program (P_{IRON}), then it can be activated in the corresponding T2 program (P_{T2}) too, and vice-versa. Indeed, given a generic P_{IRON} and a generic ECA rule $r : e_r[c_r]a_r$ such that $r \in P_{IRON}$, the rule is activated if and only if: (i) the invariants are valid; (ii) the event e_r is triggered (i.e., if a change concerning the value of at least one of the labels in e_r occurs); (iii) the condition c_r is valid. As shown in Fig. 3, these three conditions are all reported verbatim in the `assume` at line 30. Now we show that there is an equivalence in the execution semantics of P_{IRON} and P_{T2} programs. If a natural change occurs, then ECA rules whose events capture this natural evolution are considered for an eventual activation. The natural transitions correspond in P_{T2} to the transition `FROM 0; [..] TO 1;` (line 16 – 26), and the natural changes correspond to the assignments to sensor variables through the `nondet ()` function (line 19). When a natural evolution occurs, and the program P_{T2} is in state 1 then, if conditions (i)-(iii) are met for a certain ECA rule, this rule is executed. Furthermore, the activation of the ECA rules in P_{IRON} is non-deterministic, and this non-determinism is maintained in P_{T2} , since all rules are applied to the state 1 (`FROM 1` at line 29). When an activation of an ECA rule in P_{IRON} is performed, the system is frozen, in the sense that natural transitions are not taken into account: this condition in P_{T2} is fixed at lines 38 – 39. The T2 program does not allow any other kind of transition between states, and therefore the executions of the IRON and the T2 program are isomorphic. \square

3.2 Consistency

Definition 5. *An ECA rule-based system satisfies the consistency property if its rules are neither unusable nor incorrect nor redundant.*

The notions of *unused*, *incorrect* and *redundant* rule are defined as follows.

Definition 6. *An ECA rule $r \in R$ is called unused if the condition c is false for every state $\varphi \in \Phi_a$.*

Since the set Φ_a is the set of all states in Φ satisfying all the invariants of the system, we can alternatively say that r is unusable if the logical predicate

$$P = c \wedge inv_1 \wedge inv_2 \wedge \dots \wedge inv_v \quad (1)$$

is such that $P(\varphi)$ is false for all states φ .

Definition 7. Incorrect rules are those rules that can lead to a state that is outside of Φ_a .

Definition 8. Given $r_i, r_j \in R$ such that $r_i : e_i[c_i]/a_i$, $r_j : e_j[c_j]/a_j$ we say that r_i is redundant with respect to r_j if the following conditions are met:

1. $e_i \subseteq e_j$;
2. $c_i \wedge Inv \Rightarrow c_j$ is satisfiable (where, by slight abuse of notation, we denote with Inv the conjunction of all invariants); and,
3. for every state φ satisfying $c_i \wedge Inv$, applying a_i to φ is equivalent to applying a_j to φ , which we write as $\varphi[a_i] = \varphi[a_j]$.

The algorithms for verifying the consistency property are described in detail in [21]. The key insight of the verification approach is observing that it is possible to perform consistency verification of ECA rule-based systems by using Satisfiability Modulo Theories (SMT) [27, 28] and predicate transformer techniques ([29, 30]). We briefly report in this paper the verification algorithms.

An *SMT solver* is any software that implements a procedure for satisfiability *modulo* some given theory, for example the theory of linear arithmetic. Typically, SMT solvers support several fragments of First Order Logic (FOL). The solution of an SMT problem is an interpretation for the variables, functions and predicate symbols that make the formula true [28]. We use Z3 [31], a high-performance SMT Solver implemented in C++ and developed by Microsoft Research.

The detection of unused rules is based on definition 6. Given a generic rule $r : e[c]/a$, we have to check whether the rule can be triggered and whether the condition c is satisfiable in Φ_a . This is equivalent to asking a (sound and complete) SMT solver whether there exists φ such that formula P defined in (1) is satisfiable. If P is satisfiable, the rule r can be used, otherwise it is unusable. The algorithm is reported in Fig. 5.

```

1 let  $R := \{r_1, \dots, r_k\}$ 
2 let  $I := \{inv_1, \dots, inv_n\}$ 
3 define  $Inv = \bigwedge_{j=1}^n inv_j$ 
4 for each  $i = 1, \dots, k$ :
5   if  $(c_i \wedge Inv)$  is unsatisfiable:
6     declare  $r_i$  unused
7 end

```

Figure 5: Algorithm for detecting unused rules.

In order to verify the correctness of the generic rule $r : e[c]/a$ according to definition 7, we compute the weakest precondition P_{Inv} for the set of invariants, i.e., the formula $P_{Inv} = \text{wp}(a, Inv)$. In order to declare the rule r correct, the set of states where the rule may apply must be contained into the set of states P_{Inv} , otherwise there would exist a state where the rule applies, but from which we can reach a state outside those satisfying the invariants. Therefore, we translate this problem into the following SMT instance: $(c \wedge Inv) \wedge \neg P_{Inv}$ and we verify that this is *not* satisfiable. If the solver answers

```

1  let  $R := \{r_1, \dots, r_k\}$ 
2  let  $I := \{inv_1, \dots, inv_v\}$ 
3  define  $Inv = \bigwedge_{j=1}^v inv_j$ 
4  for each  $i = 1, \dots, k$ :
5    if  $(c_i \wedge Inv) \wedge \neg wp(a, Inv)$  is satisfiable:
6      declare  $r_i$  incorrect
7  end

```

Figure 6: Algorithm for incorrectness verification.

that the proposition is satisfiable, then we conclude that the rule r is incorrect, otherwise we declare that r is correct. The algorithm is described in Fig. 6.

The detection of redundant rules is performed under the following hypothesis on the ECA rule structure: we will consider only rules $r : e[c]/a$ where a is a non-empty set of linear functions over integer variables in D . In order to detect redundant rules, we have to check whether conditions 1-3 of definition 8 are verified. The algorithm is described in Fig. 8.

$$\Psi_{a_i, a_j}(o) = \begin{cases} \top & \text{if } o \uparrow a_i \text{ and } o \uparrow a_j \\ o = E_j & \text{if } o \uparrow a_i \text{ and } (o \leftarrow E_j) \in a_j \\ E_i = o & \text{if } (o \leftarrow E_i) \in a_i \text{ and } o \uparrow a_j \\ E_i = E_j & \text{if } (o \leftarrow E_i) \in a_i \text{ and } (o \leftarrow E_j) \in a_j \end{cases}$$

$$\Psi(a_i, a_j) = \bigwedge_{o \in O} \Psi_{a_i, a_j}(o)$$

Figure 7: Preliminary definition.

```

1  let  $R := \{r_1, \dots, r_k\}$ 
2  let  $I := \{inv_1, \dots, inv_v\}$ 
3  define  $Inv = \bigwedge_{j=1}^v inv_j$ 
4  for each ordered pair  $(r_i, r_j) \in R^2$  such that  $r_i \neq r_j$  and
5  such that  $r_i, r_j$  are usable:
6    if  $(e_i \subseteq e_j)$  and  $\text{not}(c_i \wedge Inv \Rightarrow c_j)$  is unsatisfiable) and
7     $\text{not}(c_i \wedge Inv \Rightarrow \Psi(a_i, a_j))$  is unsatisfiable):
8      declare  $r_i$  redundant with respect to  $r_j$ 
9  end

```

Figure 8: Algorithm for redundancy verification.

3.3 Determinism

Definition 9. Given $r_i, r_j \in R$ such that $r_i : e_i[c_i]/a_i$, $r_j : e_j[c_j]/a_j$, we say that the system is non-deterministic if the following conditions are met:

1. $e_i \cap e_j \neq \emptyset$;

2. $c_i \wedge Inv \wedge c_j$ is satisfiable;
3. $\exists \varphi$ that satisfies $c_i \wedge Inv \wedge c_j$ and $\varphi[a_i] \neq \varphi[a_j]$.

A pair of rules r_i, r_j is non-deterministic if there is at least one admissible state in which both rules are triggered and the effects of their actions on the system are not the same. Condition 1 means e_i and e_j have at least a common label. Thus this condition, if met, guarantees that at least the occurrence of an event triggers both r_i and r_j . If both 1. and 2. are verified, then r_i and r_j are applicable to the same state. If the result of applying action a_i is different from the result of applying a_j for at least one state φ in $c_i \wedge Inv \wedge c_j$, then r_i and r_j make the system non-deterministic.

The verification procedure of the determinism property is very similar to that one of redundancy, and it is performed under the same hypothesis. The algorithm is described in Fig. 9. All the pairs of distinct rules are considered. According to definition 9, three conditions must be verified: if two rules are triggered together, i.e., the event parts have a least a common label, both conditions are met, and the actions have different effects on the system, then the system is non-deterministic. The procedure described below must be performed for all pairs of rules (line 4).

```

1  let R := {r1, ..., rk}
2  let I := {inv1, ..., invv}
3  define Inv =  $\bigwedge_{j=1}^v inv_j$ 
4  for each pair  $r_i, r_j \in R^2$  such that  $r_i \neq r_j$  and such that  $r_i, r_j$  are usable:
5    if  $(e_i \cap e_j)$  is non-empty and  $((c_i \wedge Inv \wedge c_j)$  is satisfiable)
6      and  $\neg(c_i \wedge Inv \Rightarrow \Psi(a_i, a_j))$  is satisfiable):
7        declare the system nondeterministic
8  end

```

Figure 9: Algorithm for verifying determinism.

Proposition 2. *The algorithm in Fig. 9 is correct.*

Proof. The proof is similar to that one of the correctness of the algorithm for the verification of redundancy (see [21] for further details). Indeed, requirements (1) and (2) of definition 9 are checked verbatim in the algorithm. Thus, it remains to show that the algorithm is correct w.r.t. requirement (3). It can be rewritten as follows: $\exists \varphi \not\models c_i \wedge Inv \wedge c_j, \varphi[a_i] = \varphi[a_j]$. Notice that requirement (3) of definition 9 is equivalent to the negation of requirement (3) of definition 8. \square

4 The tool vIRONy

In this section we give a quick overview of vIRONy, the prototype tool that has been implemented to evaluate the proposed approach.

- **Graphical User Interface (GUI):** Fig. 10 depicts the GUI of the tool: users can select input files written in IRON syntax and select the desired functionality.

When the user opens a file for the first time, a *TabbedPane* is opened. The main components of the *TabbedPane* are:

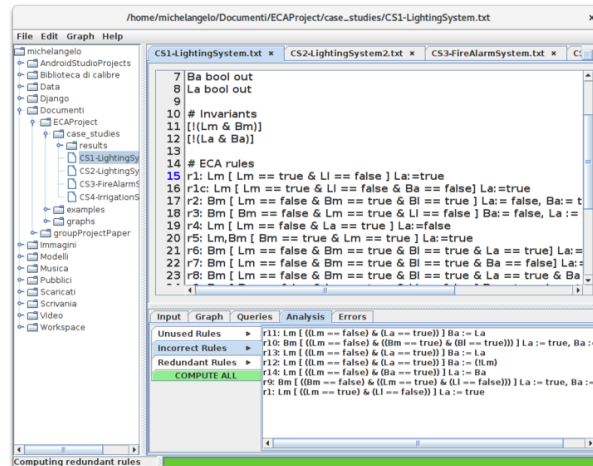


Figure 10: Graphical User Interface of vIRONy

- *Development* area: it is a *TextArea* the user can use to write or modify the program.
- *Functionality* panel: the user can access the desired functions in order to analyse or generate a simulation of the program.

In detail, by accessing the *Functionality* panel the user can insert the initial configuration of values (*Input* tab), visualise the resulting graph of the simulation generated by using the *GraphStream* library (*Graph* tab), make queries on the resulting simulation (*Queries* tab), perform a formal analysis of the program (*Analysis* tab), check if the output console gives errors (*Errors* tab). At the bottom, a *Progress Bar* indicates which operation is currently performed.

- **Syntactic analysis** The parser of vIRONy is implemented using Java Compiler Compiler³. The vIRONy parser only accepts input files written in IRON. As we showed in Section 2, the IRON language consists of two main components, the static part which includes labels and invariants, and the dynamic part that is made up of ECA rules. Labels are used to uniquely identify the devices of the system. Each label declaration must contain the name of the device, the value type (*int* or *bool*) and the device category (*in* or *out*). The declaration of the invariants consists in a boolean expression enclosed by square brackets. The syntax of ECA rules is *rule* : *event*[*condition*]*action*, where *rule* is a string that uniquely identifies a rule, the *event* is a non-empty set of labels (guards) separated by commas, the *condition* is a boolean expression, the *action* is a set of assignments to actuators. It is only possible to specify a non-empty set of assignments to be executed simultaneously; as a consequence an actuator label can be written in at most one left hand side of an assignments. This property is controlled through a semantic check. In addition, the labels in the event and action parts must

³See <https://java.net/projects/javacc> for further information.

have been declared in the declarative part of the program and the the expression on the right side of each assignment must be of the same type of the actuator on the left side.

The user can write the input file using the *TextArea* or visualise an existing one and, before performing any kind of operation (e.g. simulation, formal analysis, etc.), the parser is automatically called in order to check the syntactic correctness of the program. If there are errors, the chosen operation is cancelled and it is possible to visualise the errors found through the *Errors* tab that is automatically opened by the tool.

- **Formal verification:** The verification procedure is based on the formal techniques described in Section 3. Given an input file, the user can access the formal verification by using the *Analysis* tab. For each property a specific tab is provided to the user to perform specific analysis. Furthermore, an additional button *Consistency* allow the verification of correctness, non-redundancy and usability, and the user can visualise the results in a specific area.

Termination verification: vIRONy provides the users with a procedure for translating the input file written in IRON syntax into the T2 format. The file is then stored in the computer, and available as input file for T2. T2 is run from the command line, using the `termination:` command line argument (to prove (non)termination). The user can select the initial configuration of values for the actuators, and then by submitting them, verification of termination is performed.

Consistency and determinism verification: The verification of consistency and determinism properties implemented in vIRONy makes use of the SMT solver Z3. From an implementation perspective, in order to use Z3, a recursive algorithm has been implemented to translate the expressions generated by the parser into expressions semantically equivalent to the initial ones that can be verified using the SMT solver. According to definition 5, in order to verify if a given ECA-rule based system written in IRON syntax is consistent, we have to check whether its rules are neither incorrect nor unusable nor redundant.

Determinism: for what concerns the verification of the determinism property, the tool implements the algorithm presented in Section 3.

- **Simulation:** we provide users and programmers with a function to simulate a possible behaviour of the system given a particular configuration of actuators. The simulation generated by vIRONy is based on the formal model introduced in Section 2 and explored in detail in [19]. Before explaining the simulation procedure, we make a preliminary observation: for the sake of simulation and differently from the verification step using Z3 and T2, devices can assume only a finite set of values (we choose for integers the range $[-128, 127]$, but this arbitrary choice can be easily changed).

From the user perspective, the *Simulation* menu allows to start a computation. After having pressed the button *Start simulation* the *Input* tab at the bottom is configured to allow the user to set the initial configuration of values. Then Z3 checks if it is admissible for the system: if the configuration is admissible, the simulator starts the procedure, otherwise an alert is generated for the user. If the user only gives the configuration of the actuators, the system automatically searches for the configuration of sensors such that the complete state is admissible (by default the system searches for

the “minimum” sensor configuration according to the lexicographic order of the elements of the table containing only sensor labels). Once a configuration is found, the simulator starts the generation procedure of the transitions (for performance reasons, unused rules are not taken into account). The tool automatically visualises the resulting graph in the corresponding tab for further analysis. It is possible to export the graph in the GraphML format⁴ or as an image by selecting the desired option from the *Graph* menu.

We provide different strategies for a deeper understanding of the rules applied during the simulation from a quantitative perspective that is strictly linked to energy saving problems. Different algorithms have been implemented and they have been grouped together under the *Queries* tab. We highlight the fact that the analysis is based only on the graph resulting from the simulation, so the results depend on the initial configuration chosen by the user. We mention here a subset of the algorithms available:

- *Rules count*. This indicator counts how many times each rule is triggered during the simulation. When the simulation presents a cycle, the number assigned to those rules associated to the cycle is infinite (this would also implies that the system is non-terminating).
- *Most used rules*. This query is used to find out the rules that are used the maximum number of times during the simulation.
- *Initial rules*. This query asks the simulation for those rules that are triggered by a natural event.
- *Actuator updates*. This measure counts how many times the values of the actuators are modified by ECA rules.
- *Find cycles*. The query extracts the cycles from the graph and reports the graphical representation of each cycle.
- *Find paths*. This query explores the graph and finds out all possible paths reaching a certain state of the system starting from another one.

5 Evaluation

In this section we consider four case studies taken from related and previous work and we present performance results. We report only results and we refer to the files available on-line for further details. All the experiments have been performed on an Intel Core i7-4700MQ CPU @ 3.4GHz with 8GB of RAM running Debian Linux.

The first case study (CS1) is a lighting control system in a simple scenario and it has been adapted from the example presented in [21]. The input file for vIRONy is shown in Figure 11. For what concerns the consistency property, the verification procedure declares *r5* as unusable, rules *r1, r9, r10, r11, r12, r13, r14* as potentially incorrect (for instance, rule *r1* doesn't identify any condition on *Ba*, while *r1c* is a possible correct version of *r1*), rules *r4, r6, r7, r8, r19* do not satisfy the non-redundancy property. In

⁴<http://graphml.graphdrawing.org>

addition, the system is declared non deterministic. For what concerns the termination verification, the result is “Termination/nontermination proof failed”, meaning that the tool T2 cannot find a proof strategy in this case. This means that developers may need to provide manual evidence of termination properties. In this simple scenario the house is composed of two rooms: the living room (L) and the bedroom (B). The entrance is in the living room and the bedroom is accessible from the living room. Both rooms contain a motion sensor (m), a light sensor (l), a light switch (s) to turn on and off the light manually, a light actuator (a) to automatically turn on and off the lamp.

We assume that only one person has access to the house at any given time. In Figure 11 the invariants of the system are declared at lines 2 – 3. The first constraint states that the person cannot stay in both rooms simultaneously. The second one states that light actuators cannot be both on at the same time. As a consequence, according to the first constraint, a state having both light actuators on is not admissible. At the end of the verification procedure, among the rules reported in Fig. 11, the rule $r5$ is declared unused, since the condition is never met, $r1$ is incorrect, since it could lead outside of the domain if applied to a state having $Ba := true$ (a possible correct version of $r1$ is $r1c$). Rules $r11$ and $r13$ are incorrect, since they lead the system to a non-admissible state. Among usable and correct rules, the verification procedure declares rule $r7$ redundant with respect to $r2$, rules $r4$ and $r19$ are mutually redundant, rule $r6$ is redundant with respect to $r2, r7, r8$, while rule $r8$ is redundant with respect to $r2, r6, r7$.

The second case study (CS2) has been adapted from [10], where a light control subsystem in a smart home for senior housing is considered. The number of devices is greater than that of CS1, and also the overall dynamic of the system is more complex. Indeed, by using motion and pressure sensors (Mtn, Slp respectively), the system attempts to reduce energy consumption by turning off the lights in unoccupied rooms or if the occupant is asleep, and it also provides automatic adjustment for indoor light intensity based on an outdoor light sensor ($ExtLgt$). We made some changes in the admissible values for $lgtSTmr$ and in the rules involving this variable. Indeed, our tool automatically fixes upper and lower bounds (we choose the values of $+127, -128$ respectively) for those integer variables that have no limited values. We also defined some additional rules with respect to the original version of the case study in order to have a greater number of rules to be analysed. We report in Figure 12 a subset of input file for vIRONy. The formal analysis declares $r14$ as unusable, rule $r2$ as potentially incorrect (since there is no upper bound for $lgtSTmr$, but for instance rule $r2c$ is a possible correct version of $r2$), rule $r11$ is redundant with respect to $r5$. In addition, the system is declared non-deterministic. In this case, T2 can find a proof of termination and it gives the result “Termination proof succeeded”. Notice that by relaxing our additional constraints on variable bounds and by removing the additional rules the scenario would be non-terminating.

The third case study (CS3) has been developed starting from the example presented in [32] and described in [21]: a fire alarm system composed of temperature sensors, smoke detectors and sprinkler actuators is described by means of ECA rules. When a temperature sensor reads a value that exceeds a specified threshold and a smoke sensor detects smoke all the sprinklers are activated. Among the rules defined in Figure 13, rules $r7, r8, r11$ are declared unused, there are no incorrect rules and for what concerns redundancy, $r9$ is redundant with respect to $r1$ and $r10$ is redundant with respect to $r2$.

```

1 # Declaration
2 Bl bool in
3 Bm bool in
4 Bs bool in
5 Ll bool in
6 Lm bool in
7 Ls bool in
8 Ba bool out
9 La bool out
10
11 # Invariants
12 [!(Lm & Bm)]
13 [!(La & Ba)]
14
15 # ECA rules
16 r1: Lm [ Lm == true & Ll == false ] La:=true
17 r1c: Lm [ Lm == true & Ll == false & Ba == false] La:=true
18 r2: Bm [ Lm == false & Bm == true & Bl == true ] La:= false, Ba:= true
19 r3: Bm [ Bm == false & Lm == true & Ll == false ] Ba:= false, La := true
20 r4: Lm [ Lm == false & La == true ] La:=false
21 r5: Lm,Bm [ Bm == true & Lm == true ] La:=true
22 r6: Bm [ Lm == false & Bm == true & Bl == true & La == true] La:= false, Ba:= true
23 r7: Bm [ Lm == false & Bm == true & Bl == true & Ba == false] La:= false, Ba:= true
24 r8: Bm [ Lm == false & Bm == true & Bl == true & La == true & Ba == false] La:= false, Ba:= true
25 r9: Bm [ Bm == false & Lm == true & Ll == false ] Ba:= true, La:= true
26 r10: Bm [ Lm == false & Bm == true & Bl == true ] La:= true, Ba:= true
27 r11: Lm [ Lm == false & La == true ] Ba:= La
28 r12: Lm [ Lm == false & La == true ] Ba:= !Lm
29 r13: Lm [ Lm == false & La == true ] Ba:= La
30 r14: Lm [ Lm == false & Ba == true ] La:= Ba
31 r15: Ba [ Ba == true & La == false ] Ba:= false, La:= true
32 r16: La [ Ba == false & La == true ] Ba:= true, La:= false
33 r17: Bm [ Lm == false & Bm == true & Bl == true ] La:= false, Ba:= false
34 r18: Bm [ Bm == false & Lm == true & Ll == false ] Ba:= false, La := false
35 r19: Lm [ Lm == false & La == true ] La := false

```

Figure 11: CS1: IRON program for the lighting control system in a simple scenario.

```

1 # Invariants
2 [ ExtLgt >= 0 & ExtLgt <= 10 ]
3 [ lgtsTmr >= 0 & lgtsTmr <= 120 ]
4 # ECA rules
5 r2: Mtn, ExtLgt, Slp [ lgtsTmr >= 1 & Mtn == false ] lgtsTmr:=-lgtsTmr+1
6 r2c: Mtn, ExtLgt, Slp [ lgtsTmr >= 1 & Mtn == false & lgtsTmr < 120 ] lgtsTmr:=-lgtsTmr+1
7 r5: ChkExtLgt [ ChkExtLgt == true & Lgts == false & ExtLgt <= 5] Lgts:=true
8 r11: ChkExtLgt [ ChkExtLgt == true & Lgts == false & ExtLgt <= 4] Lgts:=true

```

Figure 12: (CS2) ECA rules for the light control system of a smart home.


```

1 # Invariants
2 [ temperature > -80 & temperature < 60 ]
3 # ECA rules
4 r1: temperature [ temperature < 16 ] heating:=true
5 r2: temperature [ temperature > 18 ] heating:=false
6 r7: temperature [ temperature < 30 & temperature > 30 ] tempAlarm:=true
7 r8: temperature [ temperature >= 1000 ] tempAlarm:=true
8 r9: temperature [ temperature == 14 ] heating:=true
9 r10: temperature [ temperature > 20 ] heating:=false
10 r11: temperature [ temperature < 15 & temperature > 50 ] tempAlarm:=true

```

Figure 13: (CS3) ECA rules for a fire alarm system.

```

1 # Invariants
2 [ !(f | w) ]
3 [ !(r & w) ]
4 [ c >= 0 & c < 120 ]
5 [ t >= 0 & t < 120 ]
6 # ECA rules
7 r2: t,w [ t-c > 2 & w == true ] w:=false;c:=t
8 r2c: t,w [ t-c > 2 & w == true & f == false ] w:=false;c:=t
9 r4: t,w [ t-c > 2 & w == true ]w:=false
10 r7: t,w [ t-c>8 ] w:=false c:=t+1
11 r8: r [ r==true & w==true ]w:=false
12 r9: r [ r==true & w==true ] c:=t+1

```

Figure 14: (CS4) ECA rules for an automatic irrigation system.

The verification declare the program non-deterministic and the termination verification using T2 gives the following result:“Termination/nontermination proof failed”. The fourth case study (CS4) consists of a Wireless Sensor and Actuator Network (WSAN) composed of five devices for an irrigation management system and controlled use of fertilizers. In detail, the network is composed of a a rain sensor r to sense precipitation, a water valve actuator w , a fertilizer valve actuator f , a timer sensor t and a timer actuator c for the sprinkler. In Figure 14 we define the invariants of the system and a set of ECA rules. The formal analysis gave the following results: $r5, r8, r9$ are declared unusable, $r2, r4, r7$ are declared incorrect ($r2c$ is a possible correct version of $r2$), and there are no redundant rules. Furthermore, the program is declared non-deterministic and the termination verification declares “Termination proof succeeded”. Notice that, due to the non-deterministic nature of T2 and due to the size of the example, T2 sometimes throws an exception on this example (timeout or out of memory).

In Table 1 we report some information about the case studies and the corresponding results of the formal analysis performed using the vIRONy tool.

In detail, we report the cardinalities of the universe $|\Phi|$ and of the admissible state space $|\Phi_a|$. We also give the number of analysed ECA rules N_{tot} , the number N_{dev} of devices, the number of unusable, incorrect and redundant rules (denoted with N_{un} , N_{inc} , N_{red}) detected by the tool. Furthermore, we measure the performance of the verification procedure in terms of time. The indicators T_{un} , T_{inc} and T_{red} , T_{det} (expressed in milliseconds) refer, respectively, to the duration time of the verification for unusability, incorrectness, redundancy, determinism and T_{ter} is the duration time of the verification of the termination property.

Table 1: Formal analysis: synthesis of the results.

	CS1	CS2	CS3	CS4
$ \Phi $	2^8	2^{30}	2^{16}	2^{19}
$ \Phi_{\alpha} $	$9 \cdot 2^4$	$1331 \cdot 2^{14}$	$2^8 \cdot 59$	$225 \cdot 2^8$
N_{rot}	20	17	14	17
N_{dev}	8	9	9	5
Unusable Rules	$r5$	$r14$	$r7, r8, r11, r12$	$r5, r8, r9$
N_{un}	1	1	4	3
T_{un} (ms)	135	141	105	141
Incorrect Rules	$r11, r10, r13, r12, r14, r9, r1$	$r2$	no	$r3, r4, r6, r7, r1, r2$
N_{inc}	7	1	0	7
T_{inc} (ms)	235	252	173	230
Redundant Rules	$r4, r6, r7, r8, r19$	$r11$	$r9, r10$	none
N_{red}	5	1	2	0
T_{red} (ms)	715	696	419	495
Determinism	non-det	non-det	non-det	non-det
T_{det} (ms)	183	190	125	228
Termination	Failed	Yes	Failed	Yes
T_{Ter} (s)	88	9	7	457

The results in Table 1 show that our approach allows for the verification of the consistency property of non-trivial examples that include both boolean and integer variables in approximately 1 second (see [21] for further details). The table also shows that the running time for verifying the consistency does not seem to be affected by the size of the state space (compare for instance CS1 with CS2), but rather by the number of rules. In particular, among the properties of unusability, incorrectness, redundancy, the verification of redundancy is the most computationally expensive step, as the verification happens for each pair of rules, and thus it requires a number of iterations that is quadratic in the number of rules to be checked. All the examples presented here are non-deterministic. The verification of this property requires a more-or-less constant time that is independent of the size of the state space and is only partially affected by the number of rules. The analysis of verification of termination requires special care: as it can be seen from the examples, the tool T2 is able to prove termination in 50% of the cases. This is expected, as proving termination is an undecidable problem. However, T2 is a sound tool and therefore, if an answer is provided, then we know that the result can be trusted. Verification of termination is a slower process if compared to the other properties. In particular, the process can take up to 10 minutes for larger examples (CS4). Moreover, it should be remarked that T2 is non-deterministic: this means that the tool may select different strategies even if it is invoked on the same example. As a result, in some cases (such as for CS4) it may happen that the tool sometimes finds a proof, and sometimes it fails with an out-of-memory or timeout error.

The evaluation is also used to assess the performance of the simulation environment of vIRONy. Table 2 reports for each case study the performances of the simulator implemented in vIRONy. The performances are measured in terms of time T_{sim} (expressed in milliseconds), and the initial configuration of actuators is detailed for each case study (the value ‘‘F’’ represents ‘‘false’’).

In Table 3 some of the results obtained by the semantic analysis performed on the generated simulations (ref. to Table 2) are reported. End-users can benefit from these results as they allow to analyse the system in terms of energy consumption and efficiency of the system, for a deeper understanding of the rules and the system from a quantitative perspective that is strictly linked to energy saving problems.

Table 2: Simulation: synthesis of the results.

	CS1	CS2	CS3	CS4
T_{sim}	2066	5673	359002	5030
Initial Values	Bl: F, Bm: F, Bs: F, Ll: F, Lm: F, Ls: F, Ba: F, La: F	lgtsTmr: 0, intLgts: -128, Lgts: F, ChkExtLgt: F, ChkMtn: F, ChkSlp: F, Mtn: F, Slp: F, ExtLgt: 0	temperature: -9, smoke: F, presenceLiving: F, sprinkler: F, heating: F, tv: F, light: F, tempAlarm: F, smokeAlarm: F	c: 0, f: F, w: F, r: F, t: 0

Table 3: Simulation analysis: synthesis of the results.

	CS1	CS2	CS4
Initial Rules	r10, r7, r17, r2: 1 time	r8: 3 times	r1c, r6, r7, r7c, r1: 3 times
Time (ms)	21,5	16,8	84,4
Actuators Updates	La, Ba : ∞ times	ChkExtLgt, Lgts, ChkMtn : 0 time, ChkSlp : 24 time, lgtsTmr : 1 time, intLgts : 25 times	c, w : 15 times, f : 3 times
Time (ms)	67,9	2,9	0,7
Find cycles	3	0	0
Time (ms)	69,2	27,9	0,1
Find Paths Time (ms)	328,1	n/a	184,0

6 Conclusions and future work

This paper combines different software verification techniques for modelling and verifying properties of ECA rules in intelligent environments. We first define a domain-specific language (IRON) that can be employed both by developers and by end-users to program and configure an ECA rule-based system for IE. The expressivity of IRON enables the application of high performance methods for verifying certain requirements that are specific for ECA-rule based systems for IE. We have implemented our approach in the open source tool vIRONy that has been validated by considering four cases studies from the literature. As future work we plan to add into our system data analysis in order to discover the global properties of the system. This rules will be encoded in iron and will be formally verified [33, 34, 35].

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