Formalization and Verification of Reconfigurable Discrete-event System using Model Driven Engineering and Isabelle/HOL

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Abstract: This paper deals with the modelling and verification of reconfigurable discrete event systems using model driven engineering (MDE) and Isabelle/HOL. MDE is a software development methodology followed by engineers. Isabelle/HOL is an interactive/automated theorem prover that combines the functional programming paradigm with high order logic (HOL), which makes it efficient for developing solid formalizations. We are interested in combining these two complementary technologies by mapping elements of MDE into Isabelle/HOL. In this paper, we present a transformation process from Ecore models, to functional data structures, used in proof assistants. This transformation method is based on Model-driven engineering and defined by a set of transformation rules that are described using formal presentations. Furthermore, in order to avoid redundant computations in RDESs, we propose a new algorithm for improved verification. We implement the contributions of this paper using Eclipse environment and Isabelle tool. Finally, we illustrate the proposed approach through FESTO MPS case study.

1 INTRODUCTION

The development of safe systems in industry is considered as an important task because a failure can be critical according to a domain for example: air and railway traffic control (Khalgui et al., 2012), manufacturing systems (Khalgui et al., 2010), real time systems and intelligent control systems (Khalgui et al., 2010). In this context, the main objective of a system is to answer the compromise flexibility vs performance (Hafidi et al., 2019), which means that new developed systems guarantee performance by giving response to customer’s needs. Many existing works have been proposed in this perspective of flexibility, which give as result new types of systems. A class of these systems is that of reconfigurable discrete-event systems (RDESs) which are characterized by their discrete nature and their changeable structures. RDESs are affected by their internal as well as external events. An RDES is defined as a hardware or software automation system capable of modifying its internal structure to adapt its answers to its environment changes (Khalgui et al., 2019). We distinguish between two kinds of reconfigurations: static and dynamic (Zhang et al., 2017). The former is applied offline before running the system. The latter is applied automatically at run-time without any interruption. Dynamic reconfigurations can be executed: (1) manually by users, (2) automatically by agents (robot, machine, schedule, etc.), and (3) in a hybrid way which is the combination of manual and automatic reconfigurations. To deal with the safety of reconfigurable discrete event systems, researchers are following many verification approaches. Model checking (Clarke et al., 2018) is one of the most used solutions to validate systems. It presents an automatic verification technique to check functional properties. Model-checking uses mathematical methods to ver-
ify if a property is satisfied in a given system model. If the property is violated, a counter example of the system execution is provided. Authors in (Guezilouz et al., 2016) propose an extension to the IEC 61499 (Lewis, 2001) standard called Reconfigurable Function Block, encapsulating several reconfiguration scenarios in one function block. In order to verify the system and to evaluate its performance, authors model it using a class of Petri nets called GR-TNCES (Khlifi et al., 2015). After that, PRISM is used as a model checker to verify the safety of each reconfiguration scenario of the system. In (Zhang et al., 2013), authors propose a new extension of TNCES formalism named reconfigurable net condition/event systems (R-TNCESs). This last allows to deal with reconfiguration and time properties with modular specification in the same formalism. In (Hafidi et al., 2018), a new methodology for formal verification of reconfigurable discrete event control systems (RDECSs) is proposed in order to ensure the correctness of systems. The proposed contribution includes an improved modeling and verification of RDECSs. The main idea is based on the checking of reconfiguration scenarios (inter-verification) and also the checking of the internal behavior of each configuration (intra-verification). All these research works present significant results regarding the verification task of RDECSs. However, there has been a lack of researches about the optimization of the verification task considering analysed properties. Actually, the complexity of model checking depends on two parameters: the size of the model, and the number of properties to be verified. For instance, Bounded Model Checking (BMC) is based on a reduction of model checking to satisfiability formulae (Jiang et al., 2016). We propose, in this work a new methodology for the formalization and verification of RDECSs using theorem proving in Isabelle/HOL to overcome model checking limits. Using such a theorem proving has several advantages. First, it gives a certificate to formal proof when it succeeds. Second, when the verification of the given property fails, it generates a counterexample as a proof to the formula negation, instead of a sequence of states or trees labeled with states, as in traditional model checkers. To the author’s best knowledge, this is the first contribution addressing this problem. This paper presents the following contributions:

- We define a Meta-Model to model RDECSs using MDE. Which is part of the evolution by advocating the systematic use of models to facilitate understanding of a complex system and to automate some of the development processes followed by engineers.
- We propose a formalisation of RDECS in Isabelle, which is equivalent to this Meta-model.
- We establish the link between MDE and Isabelle by defining reconfiguration rules to allow automatic generation of system in Isabelle.
- In order to avoid redundant computations, we propose a new algorithm for improved verification.

The remainder of this paper is organized as follows, Section II presents background about Model Driven Engineering (MDE), and Isabelle/HOL. Sections III and IV involve details about the proposed approach. Section V presents the new Algorithm of improved verification. Section VI describes an application of proposed contributions on a real case study: FESTO benchmark system. Section VII illustrates performance evaluation of the suggested approach. Finally, Section VIII concludes this paper and highlights some perspectives of the work.

2 BACKGROUND

In this section, we present details about Isabelle/HOL theorem proving, and Model Driven Engineering.

2.1 Isabelle/HOL

Isabelle/HOL is an interactive/automated theorem prover that combines the functional programming paradigm with high order logic (HOL), which makes it efficient for developing solid formalizations (MeghZili et al., 2017). Using Isabelle/HOL, we can formalize a system and prove its properties (i.e., formalize systems, formulating lemmas and theorems on them) (Ali et al., 2007). Isabelle/HOL has a high degree of credibility for created proofs because it allows us to prove every step. and therefore the whole proof is correct. Isabelle has several methods, to describe data structures. In the following, we show the main Isabelle concepts used in this paper.

- The theory: The main concept enveloping all elements used to write a program in Isabelle/HOL.
- Types bool, nat and list: These are the most important predefined types. Although the lists are already predefined, and can define their own type.
- Types synonym: Synonym types are abbreviations for existing types.
- Function: In most cases, defining a recursive function is as simple as other definitions.
- Record: A record in Isabelle is an element enveloping more than one type, to define another type.
- Lemma: is used to prove a function or properties.
2.2 Model Driven Engineering

Model Driven Engineering (MDE) is a software development methodology followed by engineers, where meta-models are the central elements. A metamodel precisely defines concepts handled in the models as well as the relationships between these concepts. A model is a description, a specification of a system. A model transformation describes the switch from a source model to a target one. MDE is a general and open approach following the proposal of the MDA (Model Driven Architecture) standard proposed by the OMG in 2000 (Djeddai et al., 2012). We apply this method to describe, specify systems, then to define a generic transformation processce from Ecore models (As detailed in the next subsection) to Isabelle/HOL. Figure 1 shows an overview of our transformation. For the translation, we propose Ecore meta-model of the system. This meta-model is the constructor of source model of our transformation. We also define Isabelle/HOL meta-model to be the constructor of target model. To perform this transformation, we define a set of transformation rules (detailed in Section. 4) that maps components of the instance of Ecore meta-model to those instances of Isabelle/HOL meta-models.

- Ecore Meta-model
In this paper we use a subset of the Ecore meta-model. This subset essentially contains the elements we needed for translation from Ecore model to Isabelle/HOL. It is important to note that this subset of Ecore allows us to define basic models validated by Ecore. A subset of the Ecore meta-model consists of:

- The EPackage gathers all Eclasses and Edatatypes via EClassifiers. It is the root element of the Ecore models.
- The EClass is the element that represents the UML class in Ecore. Eclasses define the structure of the objects that make up the instances of the model. It contains EAttributes and EOperations.
- EReferences represent an entire/partial relationship called ≪value aggregation≫ in UML.

3 METHODOLOGY

In this section, we propose the “Meta-Model” to model RDES before transforming it in Isabelle/HOL. A “Meta-Model” consists of the elements and relations used to describe: (1) behavior of system which is all system configurations, and (2) Reconfigurations rules allowing automatic transformations between configurations.

3.1 ECORE Meta-model

Definition 1: An RDES is composed of n Units as follows: \( RDES = \sum_{i=1}^{n} Unit_i \) each subset can perform behavior modes as follows \( RDES_{\text{mode}} = (\text{mode}_1, \ldots, \text{mode}_i, \ldots, \text{mode}_n) \). The set of allowed configurations of the RDES is defined according to the communications between the \( n \) units. Using reconfiguration rules switching automatic between configurations.

Definition 2: A RDES is a structure defined as follows: \( RDES = (B, RR) \) where: \( B \) is the behavior and RR reconfiguration rules of system.

Definition 3: RDES Behavior. The behavior of a system \( B \) is the union of \( m \) configurations, represented as follows: \( B = Conf_0, Conf_1, Conf_2, \ldots, Conf_m \) Where:(1) \( Conf_0 \) is the initial configuration, (2) \( Conf_i \) represented by the following tuple:

\[
Conf_i = (U, L) \\
\text{Where:}(1) \ U: \text{the set of units}, \ (2) \ L: \text{the set of links between units.}
\]

Definition 4: RDES Reconfigurations Rules. The reconfigurations rules of a system \( RR \) is a set of transformations between configurations \( RR = r_1, \ldots, r_m \) allowing automatic transformations between configurations. A reconfiguration rule of a RDES \( r_i (Conf, Conf') \) is a structure changing the system from a configuration \( Conf \) to another one \( Conf' \) defined as follows \( r_i (Conf, Conf') = (\text{Condition}, \text{Operation}, S - Conf, D - Conf) \), where: (1) Condition \{True,
3.2 Isabelle/HOL Meta-model

An RDES consists of: a set of reconfiguration rules to switch from a configuration to another. A configuration is a stable situation that has a certain duration in which a system performs an activity, i.e., system’s components are in a specific communication with each other. We denote by SC: a configuration, Operation is including the addition/removal of units and links from a source Conf_i, to obtain a target Conf_j configuration, (2) Operation is including the addition/removal of units and links from a source Conf_i, to obtain a target Conf_j configuration, (3) S – Conf denotes the configuration Conf_i before the application of a reconfiguration rule r_i, and (4) D – Conf denotes the target configuration Conf_j after the reconfiguration rule r_i is applied. The reconfiguration rule r_i for the transformation from Conf_i to another Conf_j configuration, when we apply a reconfiguration scenario. If Condition = True, r_i is executable, otherwise it cannot be executed. The transformation from Conf_i to Conf_j, Figure 2 shows RDES Ecore Meta Model.

4 TRANSFORMATION FROM ECORE MODEL TO ISABELLE/HOL

In this section, we present the translation: from RDES models into data structures used in Isabelle/HOL. We
Table 1: Correspondences between ECORE and Isabelle/HOL elements.

<table>
<thead>
<tr>
<th>Ecore</th>
<th>Isabelle/HOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U = { \text{Unit } i, ..., \text{Unit } j }$</td>
<td>record UNIT</td>
</tr>
<tr>
<td>$L = { \text{Link } ii, ..., \text{Link } jj }$</td>
<td>record Arc</td>
</tr>
<tr>
<td>$B = { \text{Conf}_0, \text{Conf}_1, \text{Conf}_2, ... }$</td>
<td>record SC</td>
</tr>
<tr>
<td>$RR = { r_1, ..., r_m }$</td>
<td>record RR</td>
</tr>
</tbody>
</table>

RDES Ecore model record IsaSystem

- **Transformation Process**
  The transformation consists of a set of transformation rules. Each rule has the form:
  \[
  Tr : \text{Ecore model} \rightarrow \text{Isabelle Types}. \]
  The first rule is Instance Epackage To Theory. This rule triggers recursively other transformation rules.

- **Rule Instance EPackage To Theory**
  The components of the Ecore models are grouped in EPackages. When we transform Ecore models into Isabelle, we transform these packages into theories (Theory). The name of an EPackage gives the name of the Theory. Additional elements nsPrefix and nsURI are specific characteristics of Ecore. They are neither translated nor used in Isabelle. We call the rule by element (TrMclass, TrMAttribute, TrMReference, TrMgroup) to translate type instances Eclassifiers (EClass, EReference, EAttribute) contained in the Epackage instance.

- **Rule Instance EAttribute to Definition**
  If an EAttribute instance is formed of a primitive type (int, bool, string), the transformation generates a new definition. The name and value of this definition are the same of EAttribute instance.

- **Rule Instance EClass to Definition**
  The simplest case that we can face is how to transform an EClass instance that is independent (i.e., not linked with other EClasses). In this case, the EClass is translated into a definition. The name EClass gives the name of definition constructor. Then, for each instance EStructural feature contained in the instance EClass, we call the appropriate rule: \( TrMsf(x) \) to transform the instances of the Structural Feature \( x \) in (EAttribute, EReference, EClass) type. \( TrMsf(x) \) is the function that takes as input \( x \) and transforms it to Isabelle definition.

- **Rule Instance EReference to Definition**
  In this case we use the same instructions as in the previous rule (Rule Instance EClass to definition), with a simple modification, where the definition constructor name will take the name of EReference Type.

- **The Regrouping Rule**
  This rule is made to regroup EReferences of the same type in a single list. Therefore, we need to create a new definition.
list with the name of EReference, then we add all the definitions of this EReference.

\[ \text{TrMgroup()} = \]
\[ \text{List L=} \text{Create Liste();} \]
\[ \text{if (containment }=\text{true or UpperBound }=\text{)} \]
\[ \text{L.addAll (all definitions with the same constructor)} \]

When \text{Tr()} has a class instance of reconfiguration rule, it is necessary to add complementary treatment as follows: Create a new Isabelle function with the reconfiguration rule name in order to make the necessary changing in the system such as add/remove links and units according to the rule.

5 VERIFICATION OF RDES

The next step after generating the RDES system in Isabelle/HOL consists of improving the verification by avoiding redundant computations. To this end, we propose an algorithm that treats units and properties to be verified. The main idea is to identify for each configuration, related units that should be checked. A unit should be checked only once in the proposed verification algorithm. Thus, from a configuration to another, only the new unit should be verified. Mainly, the algorithm consists of two steps:

- **Step1**: determines the difference between two sets of units composing source and destination configurations.
- **Step2**: determines the properties that have relation with units selected in step1.

The Algorithm of verification (Algorithm 1) takes as input three variables:

- \text{PListe:} represents the set of all properties to be verified.
- \text{Confi} \_\text{Uniti} (respectively \text{Confi} \_\text{Unitj}): represents the set of all units composing \text{configurationi} (respectively \text{configurationj}). And it gives as result two sets: set of units and set of properties to be verified.

where,

- \text{difference} (\text{list1, list2}) is the function that takes as inputs two lists \text{list1, list2}, and returns the difference between them;
- \text{add} (\text{L}, i) is the function that adds the item \text{i} to the list \text{L}.

### Algorithm 1: Verification Algorithm.

Input: \text{PListe list properties,;}
\text{Confi} \_\text{Uniti}, \text{Confi} \_\text{Unitj}: list UNIT;
Output: \text{U, P};
\text{U} = \text{difference} (\text{Confi} \_\text{Uniti}, \text{Confi} \_\text{Unitj});
\text{/*U new set to save a result*/;}
for \text{ Unit uk, k } = 1..(\text{U.size}) do
  for \text{ property p, q } = 1..(\text{P.size}) do
    if \text{ exist a relation between: p and uk}
      then
        \text{add (P, item);}
        \text{/*P a new set to save a result*/;}
  end
end

6 APPLICATION TO FESTO

In this section, we apply the proposed approach to the RDES in order to illustrate our contribution. First, we present the production system FESTO as running example. Second, we apply the proposed approach on it.

6.1 Components & Working Process

FESTO consists of three stations: Distribution station, Testing station and Processing station. The Distribution station is formed of a pneumatic feeder and a converter which transmits cylindrical workpieces from a stock to the Test station. The Test Station is composed of a detector, a tester and an elevator. It performs tests on workpieces for height, type of material and color. Workpieces that satisfy these tests are transmitted to the Processing Station, which is composed of a rotating disk, a drill machine and a control machine. The rotating disk is composed of locations to contain and transport workpieces from the input position, to the drilling position, to the control position and finally to the output position. We assume in this paper that FESTO performs in different production modes by using two drilling machines Driller1 and Driller2, as follows:

- Light1 (respectively Light2): Only Driller1 (respectively Driller2) is activated and used to drill workpieces.
- Medium: Driller1 and Driller2 are activated but used sequentially to drill workpieces (i.e., Driller1 or Driller2 works).
- High: Driller1 and Driller2 are activated and used simultaneously to drill two pieces in the same time.
The system reconfigures in order to avoid any problem caused by a physical fault (i.e., when Driller1 or Driller2 breakdown) or to answer user requirements. The reconfiguration behavior of the studied system loses its usefulness when both machines Driller1 and Driller2 are broken. In the last case, the system totally stops. Figure 8 describes possible reconfigurations of FESTO.

6.2 Production Lines

Based to the different production modes as shown in Figure 7, FESTO behavior is represented by four production lines such that each line is a list of described as follows: Line1 represents the default production mode Light1. After the work of Unit3, a workpiece is moved to Unit4 or Unit5 according to the result of the test station. Light2 is described by Line2. Line3, line4 represent, respectively the medium and high production modes of the FESTO system.

- **Line1**: Unit1; Unit2; Unit3; Unit5; Unit6; Unit7; Unit11; Unit12.
- **Line2**: Unit1; Unit2; Unit3; Unit5; Unit6; Unit8; Unit11; Unit12.
- **Line3**: Unit1; Unit2; Unit3; Unit5; Unit6; Unit9; Unit11; Unit12.
- **Line4**: Unit1; Unit2; Unit3; Unit5; Unit6; Unit10; Unit11; Unit12.

We denote by: L1, L2, M, and H, the four possible system modes: Light1, Light2, Medium, and High, respectively. As shown in Figure 8, the set of FESTO RR are described as follows: \( RR_{FESTO} = \{r_1(M,L1), r_2(M,L2), r_3(M,H), r_4(H,L1), r_4(H,L2), r_5(H,M)\} \)
6.3 Formalization in Isabelle Tool

Figure 9 presents the Ecore model of our system in Isabelle tool. We apply the above transformation rules to get the following result: the system component (UNIT) shown in Figure 10, all possible links between units (Arc) shown in Figure 11, different configurations (SC), reconfiguration rules (RR) shown in Figure 12, and the complete system (Isa System) is shown in Figure 13.

![Figure 10: FESTO MPS Units Isabelle formalization.](image1)

![Figure 11: FESTO MPS Arcs Isabelle formalization.](image2)

6.4 Verification

As shown in Figure 14, from the mode (H) to (L1) (resp. (L2)), only Driller 1 (resp. Driller 2) need to be checked, the unchanged units do not have to be checked again. Furthermore, from the configuration mode (M) to (L1) (resp. (L2)), only Driller 1 (resp. Driller 2) need to be checked. Let us assume that the user wants to switch the system to configuration (H). In this case, the proposed algorithm of verification searches in the set of the already checked units. If a precedence relationship is found, then it is not necessary to check it again. Otherwise, it will be forwarded to the prover. The algorithm already determined the properties to be verified in the configuration (L1). Therefore, it searches in the set of the already checked units about the properties is necessary to verifier.

![Figure 12: FESTO MPS configurations (SC), reconfiguration rules (RR) Isabelle formalization.](image3)

![Figure 13: FESTO MPS Isabelle formalization.](image4)

![Figure 14: Verification of FESTO MPS.](image5)
we make the modification in the system, including
the remove of the unit Driller1-Or-Driller2 and add
the unit Unit7. The $r (M, L1)$ means the switching
from Driller1 to line2. After, $r (M, L1)$ is executed,
the workpieces are drilled by machine Driller1. In the
next, we present how to process a request, as follows:

Reconfiguration Rule M_to_L1!
If $\{M_to_L1,c\}$ then
Operation
activated (Piece Injection)
activated (converter)
activated (Tester1)
activated (Evacuate)
activated (Elevator1)
activated (Disc)
add (Driller1)
remove (Driller1 or Driller2)
activated (Tester2)
activated (Elevator2)
End If
End

Where: activated (Unit i) represents the working of
the Unit i. For example, activated (Unit 2) means the
execution of the operation convert.

7 PERFORMANCE EVALUATION

Figure 15 shows two curves corresponding to the ver-
ification process with and without using our proposed
algorithm. The values of the abscissae axis correspond
to the reconfigurations rules when the system runs two
times ((H to L1), (H to L2), (M to L1), (M to L2),
(M to H), (H to M)) in order. The ordinate axis cor-
respond to the number of checked units. The curve
in blue corresponds to the verification without pro-
posed algorithm. The curve in red corresponds to the
optimal verification using proposed algorithm. It is
important to note that the number of checked units
decreases gradually until the value zero when we use
the proposed algorithm. The reduction in the number
of units is followed by a reduction in the number of
properties.

8 CONCLUSION

This paper deals with the modeling and verification
of reconfigurable discrete event systems following
the MDE approach and using Isabelle/Hol theorem
prover. We define a Meta-Model to model RDESs
using MDE, we propose a new type Isabelle equiv-
ance to this Meta-model, and we establish the link
between MDE and Isabelle by defining a set of re-
configurations rules to allow automatic generation of
system in Isabelle. Further more, once the system de-
scribed in Isabelle, we apply the verification process.
In order to avoid redundant computations, we propose
a new algorithm for optimal verification. In a future
work, we plan to reduce verification time of RDESs
by minimizing the number of properties. We plan also
to deal the correctness of the transformation itself by
describing both metamodels and transformation rules
in in Isabelle/HOL, then, use its theorem prover to
verify some properties that are preserved by the trans-
formation (Meghzili et al., 2019).

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