

Tackling Uncertainty in Cyber-Physical Systems with Automated Testing

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Abstract

The U-Test-EU¹ project aims at developing new methods and techniques for testing Cyber-Physical Systems (CPSs) under uncertainty. This paper aims to provide the current status of the results achieved in the project during the first one and half years. Our ultimate aim is to enable collaboration among several Horizon2020 projects focusing on CPSs. This paper focuses on the research results from the following four perspectives in the context of the project: 1) Understanding uncertainty in CPSs, 2) Modeling uncertainty in CPSs to support automated testing, 3) Discovering unspecified uncertainties, 4) Testing CPSs under the specified and discovered uncertainties. In addition to the research results, we also present a set of standardization activities that are planned in the project with the final goal of bringing results to a wider audience than the targeted projects and consortium of the project.

Keywords: Cyber-Physical Systems, Uncertainty, Model-Based Testing, Search-Based Testing.

1 Introduction

Uncertainty in Cyber-Physical Systems (CPSs) cannot be evaded and must be tackled explicitly in a systematic way starting from their development to testing and even after deployment. The current state-of-the-art and state-of-the-practice lack the systematic and automated approaches and methods to test CPSs under both *known* and *unknown* uncertainty [1; 4; 12] [3]. The U-Test-EU project aims to develop such automated and systematic approaches to test CPSs that explicitly consider uncertainty *known* at the design time in addition to discovering *unknown* uncertainties using search-based techniques such as genetic algorithms.

The aim of this paper is to present the current status of the results produced in the project to facilitate collaboration among other EU projects related to Cyber-Physical Systems. More specifically, we present the results related to 1) *Understanding* uncertainty in CPSs, 2) *Modeling known*

uncertainty with the purpose of supporting automated testing, 3) *Discovering unknown* uncertainty, and 4) *Testing* CPSs under specified and discovered uncertainties. Notice that in this paper, we only present high-level details of solutions and their associated key results to facilitate discussion among projects. However, we provide appropriate references, where further details can be consulted. In addition, in the footnote,² we provide links to the slides that were presented during the workshop for sharing the results with other projects.

The rest of the paper is organized as follows: Section 2 presents the results related to understanding uncertainty in CPSs, Section 3 discusses our modeling solution to model test ready models of CPSs, Section 4 discusses our solution for evolving test ready models to discover unknown uncertainties, and Section 5 presents the current status of testing solutions. Section 6 presents the planned standardization activities and finally we conclude the paper in Section 7.

2 Understanding Uncertainty with U-Model

In terms of understanding uncertainty in CPSs, the key outcome is an uncertainty conceptual model (U-Model) for Cyber-Physical Systems presented in [17]. Due to the lack of common understanding of uncertainty in the current literature, we developed the U-Model with the aim to provide a unified understanding of uncertainty in CPSs. In addition, we aimed to classify uncertainties in CPSs at the three logical levels of CPSs including Application, Infrastructure, and Integration levels [17]. Since there wasn't any existing uncertainty model in the context of CPSs available, we developed the U-Model by reviewing existing literature from other domains such as physics, healthcare, and statistics [17].

The U-Model took a subjective approach to understanding uncertainty in CPSs, where a belief agent (e.g., a modeler or a group of modeler) holds some belief about some aspects of CPSs (test ready models in our context to

¹ www.u-test.eu

² <http://www.cister.isep.ipp.pt/ae2016/presentations/utest1.pdf>
<http://www.cister.isep.ipp.pt/ae2016/presentations/utest2.pdf>

generate test cases). The U-Model has three sub-models as described in [17]: *Belief Model*, *Uncertainty Model*, and *Measure Model*. The *Belief Model* captures the basic concepts related to beliefs and belief agents, whereas the *Uncertainty* model captures the concepts specifically related to uncertainty such as various types of uncertainties, patterns, and measurements. The *Measure Model* aims at capturing uncertainty measures at a very high level. More details of the *U-Model* and its associated sub-models can be consulted in [17]. The U-Model was specialized into three uncertainty taxonomies at each level of CPSs, i.e., *Application*, *Infrastructure*, and *Integration*. More detailed taxonomies are presented in the associated technical report [17] and deliverable on the project website³.

In order to validate the completeness and correctness of the U-Model, we validated it using uncertainty requirements collected from the two CPSs case studies that are available to us as part of the project [17]. The first case study is from the healthcare domain and is called GeoSports (GS) provided by Future Position X (FPX), Sweden (www.fpx.se). The second CPS case study is about Automated Warehouse (AW) provided by ULMA Handling Systems, Spain (<http://www.ulmahandling.com/>). Details of the validation are also presented in [17].

3 Modeling Test Ready Models with Uncertainty using The Uncertainty Modeling Framework

The second key result of the project is the Uncertainty Modeling Framework (UMF) presented in [13]. The main objective of the UMF is to provide a standard-based modeling framework to create test ready models of a CPS with explicit consideration of uncertainty. The test ready models created with the UMF are used by the Uncertainty Testing Framework (UTF) (Section 5) as input to generate test cases for execution based on various test strategies [13].

The core of the UMF relies on the implementation of the U-Model as a UML profile called the UML Uncertainty Profile (UUP) [13] that allows modeling concepts related to beliefs and uncertainties defined in the U-Model on UML models. In addition, the UMF uses the UML Testing Profile (UTP) V.2 [9] to make the models test ready. In addition, to facilitate modeling uncertainty with a variety of uncertainty measurements, we have created an extensive set of model libraries including *Measure*, *Pattern*, *Time* and *Risk* libraries. These libraries extend the UML profile for Modeling and Analysis of Real-Time and Embedded Systems (MARTE) [10]. Within the UMF we have defined a set of guidelines to model test ready models with UUP, UTP, and the model libraries at the three testing levels of CPSs including *Application*, *Infrastructure*, and *Integration* levels. Interested readers may consult [13] for further details on the UMF.

A preliminary evaluation of the UMF was performed using the two industrial case studies, i.e., GS and AW in addition

to one open source case study available from the literature [11]. The evaluation involved creating test ready models for the three case studies. The UMF was evaluated from several aspects including 1) *Completeness* and *correctness* of the various parts of the UMF were evaluated including the UUP and its associated model libraries with respect to the U-Model and the MARTE profile. The U-Model is at the core of the UUP, whereas the MARTE profile is at the core of the model libraries, 2) Effort required to create test ready models with UMF in terms of time for the three case studies, 3) To check the correctness of the test ready models in terms of wrong model elements, incomplete model elements, and redundant model elements, the test ready models were executed with test data using the IBM Rational Software Architecture (RSA)'s simulation toolkit [5]. The detailed results are presented in the technical reports [13; 15].

4 Evolving Test Ready Models with the U-Evolve Framework

The third key result of the project is a preliminary version of the model evolution approach embedded in the U-Evolve framework [16]. The overall aim of U-Evolve is to take input the test ready models created with the UMF and evolve the models with the aim of discovering new uncertainties [16].

The U-Evolve includes several steps to evolve the test ready models; however, at its current stage, the U-Evolve uses dynamic inference techniques to discover uncertainties. Since the dynamic techniques require data, we used the real data available for the case study from its actual use. The U-Evolve works in the following three steps [16]:

In the first step, we verify the initial version of test ready models with the real data. Test ready models explicitly capture uncertainty. The verification is performed by executing the test ready models with real data by enriching the models with the UML Action Language (UAL) code, which is based on the Action Language for Foundational UML (ALF)⁴ standard. The IBM RSA's simulation toolkit [5] was used for this purpose. In the second step, the objective uncertainty values were introduced to the verified test ready models based on the real data. In the third step, we used the Daikon tool [2] that applies machine learning techniques to infer likely invariants based on data. In our context, we used the Daikon tool [2] to further refine constraints on the test ready models based on the real data. The key constraints were specified in the Object Constraint Language (OCL)⁵ included: State Invariants on states in UML state machines modeling test oracles, and guard conditions on transitions of UML state machines specifying test data specifications.

The U-Evolve framework was evaluated with the GS case study as part of the project. More details on the U-Evolve framework and results can be found in the technical report [16].

³ www.u-test.eu

⁴ <http://www.omg.org/spec/ALF/>

⁵ <http://www.omg.org/spec/OCL/>

5 Uncertainty-based Test Case Generation and Minimization

One of the key activities in the project is to generate test cases from the test ready models developed using the UMF and also from the evolved test ready models after using U-Evolve [16]. We have performed some preliminary work in this part, where we have defined in total two test case generation and four test case minimization strategies using multi-objective search algorithms relying on uncertainty theory [6]. The test strategies are implemented in a tool called U-TCsMG and further details can be consulted in [14].

For U-TCsMG [14], first, we conducted an empirical study using the SafeHome case study to evaluate the proposed test strategies. Based on the results of the empirical evaluation, we selected the best test strategy (test case generation followed by test case minimization), which managed to minimize test cases up to 91% and achieved 100% mutation score [14]. With the best test strategy, we tested the real industrial case study of GeoSports. The results showed that from the total of 2085 test cases generated, the best strategy managed to reduce the test cases to 336 (83.9%). We executed the minimized set of test cases on the real system and managed to found 98 uncertainties (incorrect locations of devices). Of these 98 observed uncertainties, 80 were because of the intentionally introduced indeterminacy source, where 18 occurred because of the unknown reason(s). We are analyzing the observed uncertainties to find the indeterminacy sources to prevent them happening in the future executions.

6 Standardization

To achieve the wider impact of the results produced in the project, one of the key activities is to standardize some of the results of the project. As part of the project, we are working in the three directions: 1) The standardization of the UML Testing Profile V.2 in the Object Management Group (OMG). Our efforts in this direction can be followed at [9], 2) Initiation of a new standard corresponding to the U-Model and the UUP profile at the OMG. The efforts in this direction can be followed at [8], 3) Towards the end of the project, we are planning to write recommendations based on the project results to various standardization bodies such as the European Telecommunications Standards Institute (ETSI). In this direction, we are already contributing to the development of Request For Proposals (RFP) of Systems Modeling Language (SysML) V.2 based on the results from the project. The progress can be followed at [7].

7 Conclusion

This paper presented the results achieved in the first one and half years of the U-Test-EU project. This involved the results related to understanding uncertainty, modeling uncertainty, discovering uncertainty, and testing CPSs under uncertainty in the context of the ongoing EU project. In addition, we also presented the standardization efforts that are being performed as part of the project.

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