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Test Case Generation to Medical Cyber-Physical Systems: A Scoping Review

Geração de Casos de Teste para Sistemas Médicos Físico-Cibernéticos: Uma Revisão de Escopo

Generación de Casos de Prueba para Sistemas Médicos Físico-Cibernéticos: Una Revisión de Alcance

Johnattan Douglas Ferreira Viana[1], Álvaro Alvares de Carvalho César Sobrinho[2], Lenardo Chaves e Silva[3]

ABSTRACT

Keywords: Test Case Generation; Medical Cyber-Physical Systems; Scoping Review

Objective: This article presents a Scoping Review (ScR) identify the approaches to automatically generate test cases from Cyber-Physical Systems (CPS) models, more specifically, Medical Cyber-Physical Systems (MCPS) models. **Method:** ScR was performed by identifying indexed articles in five electronic databases using a specific search string and selection criteria, defined in a review protocol. **Results:** When protocol was executed, 467 studies were returned, from which 12 were summarized. Several formal and semi-formal notations used in CPS modeling were identified, as well as tools for generating test cases for such systems. Furthermore, we present an overview of the state-of-the-art regarding automatic test case generation for such systems models. **Conclusion:** Based on the results, we conclude there is a research gap with regard to tools for the fully automatic test case generation in MCPS.

RESUMO

Descritores: Geração de Casos de Teste; Sistemas Médicos Físico-Cibernéticos; Revisão de Escopo

Objetivo: Este artigo apresenta uma Revisão de Escopo (RE) para identificar as abordagens para gerar automaticamente casos de testes a partir de modelos de Sistemas Físico-Cibernéticos (SFC), mais especificamente, Sistemas Médicos Físico-Cibernéticos (SMFC). **Método:** A RE foi realizada pela identificação de trabalhos indexados em cinco bases eletrônicas de dados usando termos de busca e critérios de inclusão, definidos em um protocolo de revisão. **Resultados:** Ao executar o protocolo foram retornados 467 estudos, dos quais sumarizaram-se 12. Foram identificadas várias notações formais e semi-formais usadas na modelagem de SFC, bem como ferramentas para gerar casos de teste para esses sistemas. Além disso, foi apresentada uma visão geral do estado da arte em relação à geração automática de casos de teste para esses modelos de sistemas. **Conclusão:** Com base nos resultados obtidos, conclui-se que ainda há uma lacuna de pesquisa no que diz respeito às ferramentas para a geração totalmente automática de casos de teste para SMFC.

RESUMEN

Descriptores: Generación de Casos de Prueba; Sistemas Médicos Físico-Cibernéticos; Revisión de Alcance

Objectivo: En este artículo se presenta una Revisión de Alcance (RA) para identificar los enfoques para generar automáticamente casos de prueba a partir de modelos de Sistemas Físico-Cibernéticos (SFC), más específicamente, Sistemas Médicos Físico-Cibernéticos (SMFC). **Método:** La RA se realizó mediante la identificación de artículos indexados en cinco bases de datos electrónicas utilizando términos de búsqueda y criterios de selección, definidos en un protocolo de revisión. **Resultados:** Al ejecutar el protocolo se devolvieron 467 estudios, de los cuales se resumieron 12. Se han identificado varias notaciones formales y semiformales utilizadas en el modelado de SFC y SMFC, así como herramientas para generar casos de prueba para estos sistemas. Además, se presentó una descripción general del estado del arte en relación a la generación automática de casos de prueba para estos modelos de sistema. **Conclusión:** Con base a los resultados obtenidos, se concluye que hay una brecha de investigación con respecto a las herramientas para la generación de casos de prueba totalmente automática en MCPS.

[1] *Master's student. Postgraduate Program in Computer Science (PPgCC), Federal Rural University of Semi-Arid - UFERSA and State University of Rio Grande do Norte - UERN, Mossoró (RN), Brazil*
[2] *PhD, Professor, Federal University of the Agreste of Pernambuco - UFAPE, Garanhuns (PE), Brazil.*
[3] *PhD, Professor, Federal Rural University of Semi-Arid - UFERSA, Pau dos Ferros (RN), Brazil.*

Autor Correspondente: **Johnattan Douglas Ferreira Viana**
e-mail: **johnattan.viana@alunos.ufersa.edu.br**

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INTRODUCTION

Cyber-Physical Systems (CPS) are composed of collaborative computational elements that are integrated into the environment to control physical entities. When developed to be applied in a medical context, CPS are called Medical Cyber-Physical Systems (MCPS)[1]. Such systems are increasingly used in hospitals to provide continuous high-quality healthcare to patients[2].

Due to the safety-critical nature of MCPS, models are usually defined to represent medical devices, medical systems, and clinical scenarios that describe patients' clinical conditions. Such systems need to be carefully validated because their correct functioning is essential. For that reason, they are considered safety-critical systems. Recent approaches to software engineering, such as Model-Based Testing (MBT), are promising to validate MCPS[3], since this approach generates test cases from system models to create test scripts[4]. Such a system model abstracts the system input and defines the expected output.

The MBT approach can be applied to MCPS to assist in preventing injuries or fatalities, since developers use MBT to design abstract tests from models of the system's behavior. In this sense, Model-Based Development (MBD) emerged as an approach to assist the development process, since MBD allows developers to perform rigorous verification of the model and then derive code that preserves verified properties[2].

In this regard, MBT is a convenient approach for the certification of MCPS in general, since the testing process is aimed at models. Besides, it is necessary to define a complete modeling process that uses verification and validation techniques and aims at guaranteeing the quality of the software. However, to test MCPS, the industry needs to evolve to automatically create test cases, not just run them automatically.

Thus, the main objective of this research is to carry out a Scoping Review (ScR) to identify the approaches for automatic test case generation from CPS models, more specifically, MCPS models. We analyzed the characteristics (e.g., automation level) of CPS approaches and their applicability in the medical context. Therefore, this work presents a review carried out in the main bases of journals in the area of Computer Science, with the objective of identifying studies that present approaches for the purpose of automatic test case generation. The intention is to promote a discussion on identified test case generation approaches and give an overview of the area, aiming to promote a better perception of current development needs and opportunities in the area.

This ScR does not evaluate the effectiveness of approaches, risk of bias or the quality of evidence. Our objective is to present an overview of research evidence related to the existing approaches for automatic test case generation in CPS and their applicability in the medical context.

RESEARCH METHODOLOGY

The present study is a ScR, what imply in a knowledge synthesis that follows a systematic approach to identify key concepts and knowledge gaps on a topic, with a broader scope than traditional systematic reviews[5]. In this work, we followed guidelines for a ScR production[6]: i) develop the ScR protocol; ii) define the research questions for the review process; iii) summarize the evidence by means of the tabulation of the characteristics and qualities of the respective studies; and iv) interpret the results. This ScR was registered in Open Science Framework*. Additionally, we used the StArt as a tool support to carry out this review[7]. The remaining of this section describes the review protocol.

RESEARCH QUESTIONS

The primary question that guides this ScR is: what solutions available in the literature are used to generate test cases for CPS? Thus, we defined the following Secondary Questions (SQ):

- SQ1: what is the main contribution of the study? Specification (E), Methodology (M), Tool (T) and Other (O);
- SQ2: what formalism/specification was used for modeling?
- SQ3: what support tools were used?
- SQ4: what is the level of automation of the approach? Automatic (A), Semi Automatic (SA), and Non-Automatic (NA);
- SQ5: what was the context or application scenario of the solution?
- SQ6: is it applicable to the medical systems? Yes (Y) or No (N).

SCOPE

The scope of the research can be specified by defining the studies that present solutions to generate test cases automatically from computational models. Besides, the identification of techniques, tools, approaches, and algorithms that are presented in the literature. The ScR is guided by previous evidence[8-12] and focuses on a list of techniques, tools, algorithms, and approaches for the automatic generation of test cases that can be applied to validate medical systems.

SEARCH STRATEGY

This review focused on finding articles published between January 2010 and September 2020, in English, in the main databases of electronic journals in the area of Computer Science, namely: IEEE Xplore Digital Library (IEEE) (www.ieeexplore.ieee.org), ACM Digital Library (ACM DL) (dl.acm.org/), Science Direct (www.sciencedirect.com), Scopus (www.scopus.com), and Web of Science (www.webofknowledge.com).

Advanced search mechanisms of such databases were used to search for the key terms that delimit this study: *Model-Based Testing*; *Automatic Test Case Generation*; *Cyber-*

* Link to Open Science Framework: https://osf.io/587wa/

Physical Systems; and *Medical Cyber-Physical Systems*. The terms were searched for in the titles, abstracts, and keywords of the articles. Due to the particularities of the search engines of each database, it was necessary to adapt for each one the following search string: ("Model-Based Testing" OR "Automatic Test Case Generation") AND ("Cyber-Physical Systems" OR "Medical Cyber-Physical Systems").

CRITERIA FOR SELECTION AND EXCLUSION

For selecting the articles for the summarizing stage, we defined one Inclusion Criterion (IC) and five Exclusion Criteria (EC):

- IC: studies that present solutions using MBT for generating test cases for the validation of CPS;
- EC1: duplicate studies, indexed in more than one search database;
- EC2: study that does not sufficiently detail the solution, making it impossible to extract data about the elements for the design of such solutions;
- EC3: studies that are not in the scope of interest of the research;
- EC4: studies that the full text does not have access availability;
- EC5: studies that are not complete articles or book chapters (abstract, expanded abstract, posters, videos, and web pages).

RESULTS AND DISCUSSIONS

In this section we describe the review execution and the summary of the selected articles. The included primary studies complied to the CI and were not covered by any of the ECs.

Execution

The selection process returned a total of 467 articles, which were submitted to the study selection stages. In Figure 1, a flowchart of the study selection process is presented according to the PRISMA-ScR guidelines[13]. Regarding the returned studies, 109 are from IEEE, 223 from ACM DL, 56 from Science Direct, 54 from Scopus and 19 from Web of Science. After the selection steps, 12 studies were selected for analysis.

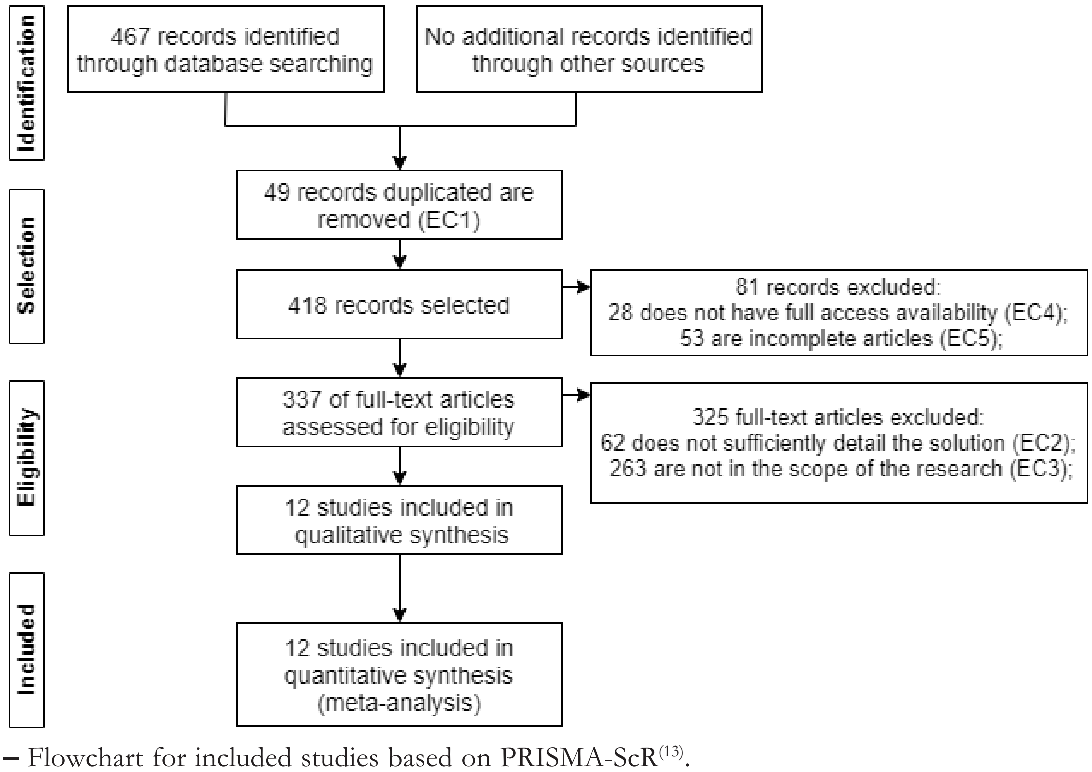

Figure 1 – Flowchart for included studies based on PRISMA-ScR[13].

Table 1 – Questions answered for each summarized study.

Authors and Year	SQ1	SQ2	SQ3	SQ4	SQ5	SQ6
Zhang M, Ali S, Yue T (2019) [8]	T	UML State Machine;	UncerTest;	A	Industry;	Y
Peranandam P, Raviram S, Satpathy M, Yeolekar A, Gadkari A, Ramesh S (2012)[9]	T	StateFlow; SAL;	STGen; Matlab; Simulink;	SA	Industry;	Y
Khoo TP (2018)[10]	M	Automata;	PAT;	NA	Passenger elevator system;	Y
Aerts A, Reniers MA, Mousavi MR (2017)[11]	T	HTSS; Automata;	Acumen;	A	Electrical engineering;	Y
Sinha R, Pang C, Martínez GS, Kuronen J, Vyatkin V (2015)[12]	T	State Machine; Ontology;	REBATE;	SA	Industry;	Y
Bernardeschi C, Domenici A, Masci P (2018)[14]	M	Automata;	PVS; Simulink;	NA	Medical devices;	Y

Authors and Year	SQ1	SQ2	SQ3	SQ4	SQ5	SQ6
Mangharam R, Abbas H, Behl M, Jang K, Pajic M, Jiang Z (2016)[15]	M	Automata;	UPPAAL; Simulink;	NA	Medical devices; Industry; Autonomous Vehicles;	Y
Drave I, Hillemacher S, Greifenberg T, Rumpe B, Wortmann A, Markthaler M, et al.[16]	M	SMArDT; UML;	MontiCore;	NA	Automotive software;	Y
Sinha R, Pang C, Martínez GS, Kuronen J, Vyatkin V (2016)[17]	T	State Machine; Ontology;	REBATE;	SA	Industry;	Y
Loffler R, Meyer M, Gottschalk M (2010)[18]	E	UML;	Fujuba4Eclipse;	SA	Medical context;	Y
Sarma M, Murthy PVR, Jell S, Ulrich A (2010)[19]	T	UML;	Qtronic; SpecExplorer;	SA	Medical systems;	Y
Aerts A, Mousavi MR, Reniers MA (2015)[20]	T	State machine; Logical models;	HTG; S-TaLiRo; RRT-REX; Acumen;	AS	Thermostat;	Y

Summarizing

The remaining 12 studies have gone through a complete reading to extract information, highlighting what type of main contribution is presented in the study, in what context it is applied. Table 1 shows a summary of the information extracted from the selected studies. More details about each study can be found in the supplementary material of this ScR**.

As shown in Table 1, we identified four methodologies, one specification and seven tools. Among them, two methodologies[14-15], one specification[18] and one tool[19] is directed to the medical context. The analyzed studies use the MBT approach to generate test cases for CPS. This is done through the validation of the models of these systems, instead of the systems themselves. This approach is useful when applied to medical contexts because it prevents putting the patient at risk, since what is being tested is just a model, which is not in direct contact with the patient. This ScR identified several formal and semi-formal notations for CPS modeling: automata, UML, SAL, state machine, logical models, and ontology. However, only automata[14-15] and UML[18-19] were utilized for MCPS modeling.

Answering the primary question of this ScR, several approaches use these models to generate test cases for CPS: PVS (Prototype Verification System), UPPAAL, Fujuba4Eclipse, Qtronic, STGen, UncerTest, PAT, HTG, Acumen, and REBATE. Concerning medical contexts, PVS[14], Simulink[14-15] and UPPAAL[15] were applied to automata models with non-automatic approaches. Fujuba4Eclipse[18], Qtronic and SpecExplorer[19] were applied to UML models with semi-automatic approaches.

The methodology presented for Bernardeschi C, Domenici A, and Masci P[14] can be applied in other simulations in medical contexts and is applicable to other systems modeled with automata networks. Mangharam R et. al[15] shows a methodology for CPS modeling in three different contexts: medical, industrial, and automotive. In the medical context, case studies are made with implantable medical devices (cardiac pacemakers and defibrillators), and physiological control systems (infusion pumps), and can be applicable in other scenarios of medical contexto to verify, validate, and test this model systems in a closed loop.

** Supplementary material available from: https://osf.io/587wa/

Loffler R, Meyer M, and Gottschalk M[18] present a formal specification language to describe the use case scenarios from UML 2.0 diagrams. These specifications are used to automatically derive an integration test model. However, systems need to be modeled according to the specification presented by the authors[18]. Sarma M, Murthy PVR, Jell S, and Ulrich A[19] evaluate two MBT tools that make use of UML: Conformiq's Qtronic 2.0 and Microsoft's SpecExplorer 3.0. Both generate semi-automatic test cases.

Although studies identified in this ScR relate to specific medical applications[14-15, 18-19], they can be reused in other medical contexts. However, they only use semi-automatic and non-automatic approaches to generate case tests, evidencing a research gap in fully automatic approaches to MCPS. Only one approach[20] that allows the fully automatic generation of test cases can be applied in MCPS, as long as these are modeled in automata[20]. UML state machines[8] may not be suitable for modeling MCPS due to the large number of real-time systems. Thus, it is inherent that the formalism used in their modeling is capable of representing time constraints.

Aerts A, Reniers MA, Mousavi MR (2017)[11] study is defined generically for Hybrid-Timed State Sequences (HTSS) and hybrid automata and, hence, are applicable to a wide set of languages. The formalism presented in[11], since it allows the representation of time, can be applied in the modeling of MCPS. Another formalism that also makes these restrictions possible is the Colored Petri Nets (CPN), which are widely used for the modeling of medical systems. However, CPN has not been used in any identified study.

A limitation of this review is that the search string definition may not have returned all published studies previously presented. To reduce this limitation, the search string was carefully defined with key terms. In addition, to increase the reliability of the search string coverage we use the most relevant databases in the computing field.

It has not been found studies that systematically synthesizes fully automatic generation of test cases approaches for MCPS. Therefore, to the best of our knowledge, this is the first ScR directed to identify approaches for this purpose.

CONCLUSIONS

This ScR highlighted that the most used approach for validating CPS is through the validation of these systems models. In the summarized articles, we identified several formal and semi-formal notations used in CPS modeling: Automata, UML, SAL, State machine, logical models, and Ontology. Besides, we identified approaches for test cases generation from such models: PVS, UPPAAL, Fujuba4Eclipse, Qtronic, STGen, UncerTest, PAT, HTG, Acumen, and REBATE. However, initiatives identified for generating test cases specifically for MCPS are only non-automatic or semi-automatic. To the best of our knowledge, there is still a research gap with regard to tools for the fully automatic generation of test cases from MCPS models. The approaches identified have potential to be applied in the medical contexts, if these systems are modeled using formalisms has some representation of time. Finally, we identified that another possible approach to generate test cases for MCPS is to perform the validation from formal models or approaches that deal with uncertainty, since the complexity of human physiology makes some test cases not deterministic.

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