Toward Requirements for Embedded Systems

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Abstract. *Our objective is to analyze and understand studies of RE approaches that are used for the development of Embedded Systems (ES). Thus, we carried out a Systematic Literature Review (SLR) in order to find answers to our questions and better understand the requirements engineering context for ES. As a result, we found 92 studies, evidenced the benefits of using studies in requirements engineering activities, the existing challenges/problems, and others. In addition, we proposed a research agenda. Thus, in this article we present a body of knowledge in ER for ES derived from a large-scale SLR. We believe that the results will benefit researchers and practitioners.*

1. Introduction

We are interested in Requirements Engineering (RE) for Embedded System (ES), as we know the importance of this type of system nowadays. An ES can be defined as a system that regulates a physical device by sending control signals to actuators in reaction to input signals provided by its users and by sensors capturing the relevant state parameters of the system [10]. It is fact, that people are dependent on services supported by ES, for example they can run in engines, brakes, seat belts, airbag, and audio system in car. They can command robots on a factory floor, power generation in a power plant, processes in a chemical plant, and traffic lights in a city [28].

Requirements engineering problems continue to occur despite the efforts and advances in their understanding [36]. Due to their unique properties, ES require different approaches, methods, and tools to improve their quality. Some studies provide insights into the state of art and practice of RE for embedded systems [21,46,47,50]. However, there is no recent, systematic attempt to perform an extensive identification, mapping, and constraints of requirements approaches for ES.

Hence, in this work, we investigate the RE research problems addressed by studies. We find out which RE phases (e.g., elicitation, analysis, specification,

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validation and management) are attracting more attention to the ES community and which ones deserve a special care. We investigate also the main requirements modeling styles (scenario-based, goal-oriented, textual requirements, etc.) used. We focused on finding which RE approaches for ES have been used to manage both functional and non- functional requirements. Furthermore, we find out which domains need more attention with respect to RE and the current tools used by the approaches. Finally, it was critical to detect the open problems in order to identify gaps in current research and suggest areas for further investigation.

In this paper, we perform an SLR [24] to evaluate and synthesize the evidence available in the literature to answer research questions (see Table 1) related to the use of approaches, methods, techniques, and processes to support the RE in the ES domain. We also summarize the existing evidence concerning RE for embedded systems to highlight empirical evidence of the challenges/problems of the published studies [24]. Last but not least, we propose a research agenda to RE community.

The results presented in this systematic review can be beneficial to the RE community, since it gathers evidence from the primary studies included in the review, forming a body of knowledge regarding requirements engineering for embedded systems.

The remainder of this paper is organized as follows: Section 2 presents related work. The research methodology adopted to conduct the SLR is outlined in Section 3. The results and the analysis of our research questions are described in Section 4. Finally, conclusions and future works are shown in Section 5.

2. Related work

Similar to our work, another secondary study that synthesizes RE in embedded systems domain is discussed in [47]. The authors present an SLR on requirements elicitation and specification for embedded systems. Their work differs from ours by means of a time interval, RE activities, the number of databases, and research questions. Our SLR considered studies from a 48-year period. It considered all activities of the RE process and included seven databases in the studies selection, while [47] considered studies from 2000 to 2014 and only included those related to elicitation and specification activities. Regarding the databases, the authors in [47] used six, while we considered seven. It is important to highlight that our research questions are different from those proposed in [47].

Ossada et al. [37] presented a Requirements Elicitation Guide for Embedded Systems (GERSE). The authors propose a set of organized and practical requirements elicitation activities for the domain of embedded systems. However, their work focuses only on elicitation activity of the RE process. Although the authors stated that their study contributed to decrease the gap between software engineering and embedded systems engineering, they suggested that more work is required to include activities related to production and control quality of the product. In our SLR we considered studies that address at least one RE phase, and we also provide a set of embedded systems characteristics to support elicitation and specification of these systems.

In 2012, Sikora et al. published the results [46] of an industrial survey in the embedded systems domain to identify RE needs for ES. In their survey, the authors focused on five aspects of RE: use of natural language versus requirements models; support for high system complexity; quality assurance of requirements; the transition between RE and design; and the interrelation of requirements engineering and safety engineering. Our work differs from [46] in two main aspects. First, we performed a retrospective on RE for embedded systems. This, in turn, contributes to the identification of RE approaches that solve some particular RE problem. Second, we considered studies from academy and industry. This has helped us to identify a more significant number of concepts and challenges on RE for ES compared to the results depicted in [46].

Although the above works cover several aspects related to requirements engineering for ES, none of these works perform an extensive identification and mapping of requirements approaches for embedded systems.

In our previous work [38], we presented some limited results. It differs from this new work in terms of time interval, method description, presentation and discussion of the results, research questions, and research agenda. It is worth noting that this SLR was updated and considered studies from 1970 to June 2019, while [38] recognized studies from 1970 to October 2016. As a result, seventeen new studies were considered. The quality assessment of the studies, as well as their overview, were not described in [38]. In this work, we carefully detailed the quality assessment criteria, and we provided an overview of the studies by publication year, application context, research method, and type of source. Finally, the findings presented in this work are more representative. Moreover, we also provide a set of questions for further investigation.

3. Research methodology

A systematic literature review, as well as other kinds of review studies, is an exploratory study to investigate evidence in the literature about a specific theme [26]. To perform this SLR, we used guidelines and the protocol template proposed by Kitchenham and Charters [24], whose process involves several activities grouped into three main phases: planning, conducting, and reporting of the review. It consists of the following steps: (1) identification of the need for a systematic review, (2) development of a review protocol, (3) a comprehensive, exhaustive search for primary studies, (4) quality assessment of included studies, (5) data extraction and monitoring, (6) data analysis and synthesis, and (7) report-writing.

The purpose of this systematic literature review is to analyze and understand how the RE approaches are used for embedded systems development as well as to understand which information regarding embedded systems should be specified by requirements engineers to reduce the gap about what should be considered when performing RE for ES. Thus, we intend to answer the research questions described in Table 1.

The SLR was motivated by the need of specific RE processes for embedded systems desired by academia and industry as reported in many studies [7], [33], [34], [37], [46], [47]. The gap that exists between the traditional requirements engineering processes, methodologies, tools, and notations and the ones used for embedded systems also contributes to the need of this SLR.

An automatic search was conducted in the electronic databases ACM Digital Library, El Compendex, IEEE Xplore, ISI Web of Science, Science Direct, Scopus, Springer Link, and validated by requirements experts. We selected these libraries because they include high-quality software engineering journals and proceedings of conferences.

Table 1: Research questions and motivations

Research Question	Description and Motivation
RQ1. What are the requirements engineering problems addressed by the approaches?	The purpose of this question is to identify and analyze the requirements engineering problems addressed by the approaches. It is important because it provides a set of contributions regarding the use of these approaches to address some well-known RE research problems, which can be useful to researchers that might be interested in using some of these RE approaches for embedded systems domain.
RQ2. What phases of the requirements engineering process have been supported?	This question provides a starting point to understand what are the main phases (elicitation, analysis, specification, validation and management) of the requirements engineering process supported by the approaches. It may help to identify which RE phases are attracting more attention to community and which ones deserve a special care.
RQ3. What style of requirements modeling have been supported by the approaches?	The answer to this question allows the identification of main styles of requirements modeling (scenario-based, goal-oriented, textual requirements and so on) that have been supported by the approaches. It may help to identify which requirements styles are attracting more attention to embedded systems community and the strengths and weakness of each style in the embedded systems domain.
RQ4. What type of requirements have been supported by the approaches?	This question intends to identify what is the distribution of the studies with respect to the type of requirements (functional and/or non-functional) addressed. It is important to investigate whether requirements engineering approaches for embedded systems have been used to manage both functional and non-functional requirements.
RQ5. What are the domains supported by the approaches?	The goal of this question is to identify different domains (automation technology, automotive, avionics, energy technology or medical technology) supported by the requirements engineering approaches identified in question 1. It may help to recognize which domain may need more attention with respect to requirements engineering.
RQ6. What are the tools used by the approaches to support requirements engineering for embedded systems?	This question maps the Computer-Aided Software Engineering (CASE) tools used in the approaches that support requirements engineering for embedded systems. It also aims to classify the level of tool support.
RQ7. What challenges /problems are identified in research literature relating to RE for ES?	The purpose of this question is to identify the open problems reported by the studies. This information is useful to identify gaps in current research and suggest areas for further investigation.

The search period starts in 1970 when embedded system was an emergent area. The search period finishes in June 2019. The search was executed in title, keywords, and abstract based on terms presented in Table 2.

Table 2: Terms of the search

#	Related words
(T1)	"requirements engineering" OR "requirements elicitation" OR "requirements specification" OR "requirements management" OR "requirements validation" OR "requirements verification" OR "requirements education"
(T2)	"requirements modeling" OR "requirements modelling"
(T3)	"embedded systems" OR "safety critical systems" OR "real time systems" OR "embedded software" OR "embedded product"
(T4)	”approach” OR ”technique” OR ”framework” OR ”processes” OR ”methods” OR ”tool”

In this paper, we want to collect information about requirements engineering for embedded systems. Therefore, such information can be used by academics and practitioners to improve the requirements process to reduce the risk of undetected errors and deficiencies. Thus, we had focused on terms in RE area, embedded systems, and kind of contribution.

Our procedure for selecting studies consisted of six main steps, as shown in Fig. 1.

Inclusion and exclusion criteria We are interested only in primary studies, that present some contribution to requirements engineering for embedded systems, and that satisfies a minimum quality threshold. The results presented here are important since they take into account the several decades of research about RE for embedded systems.

Secondary studies, short papers ($<$ 5 pages), studies that are not related to research questions, non-peer-reviewed studies, duplicated studies (only one copy of each study was included), non-English written papers, studies that do not discuss requirements engineering in embedded systems development, grey literature, redundant paper of same authorship, and ongoing work were considered exclusion criteria.

Threats to validity We used the four categories of threats presented by [53], which includes threats such as construct, internal, external and conclusion validity threats.

Construct validity: We followed the guidelines provided by [24] to develop a reliable and auditable research protocol. The protocol was validated employing inspection and comparison between already published SLR protocols. The search string of an SLR was evaluated several times to avoid the risk of omitting relevant studies.

Internal validity: During data extraction, subjective decisions may have occurred since some papers did not provide a clear description or proper objectives and results. We conducted the SLR process iteratively to try to mitigate the probabilities due to personal bias on study understanding.

External validity: To mitigate external threats, the search was defined after several trial searches and validated with the consensus of all authors.

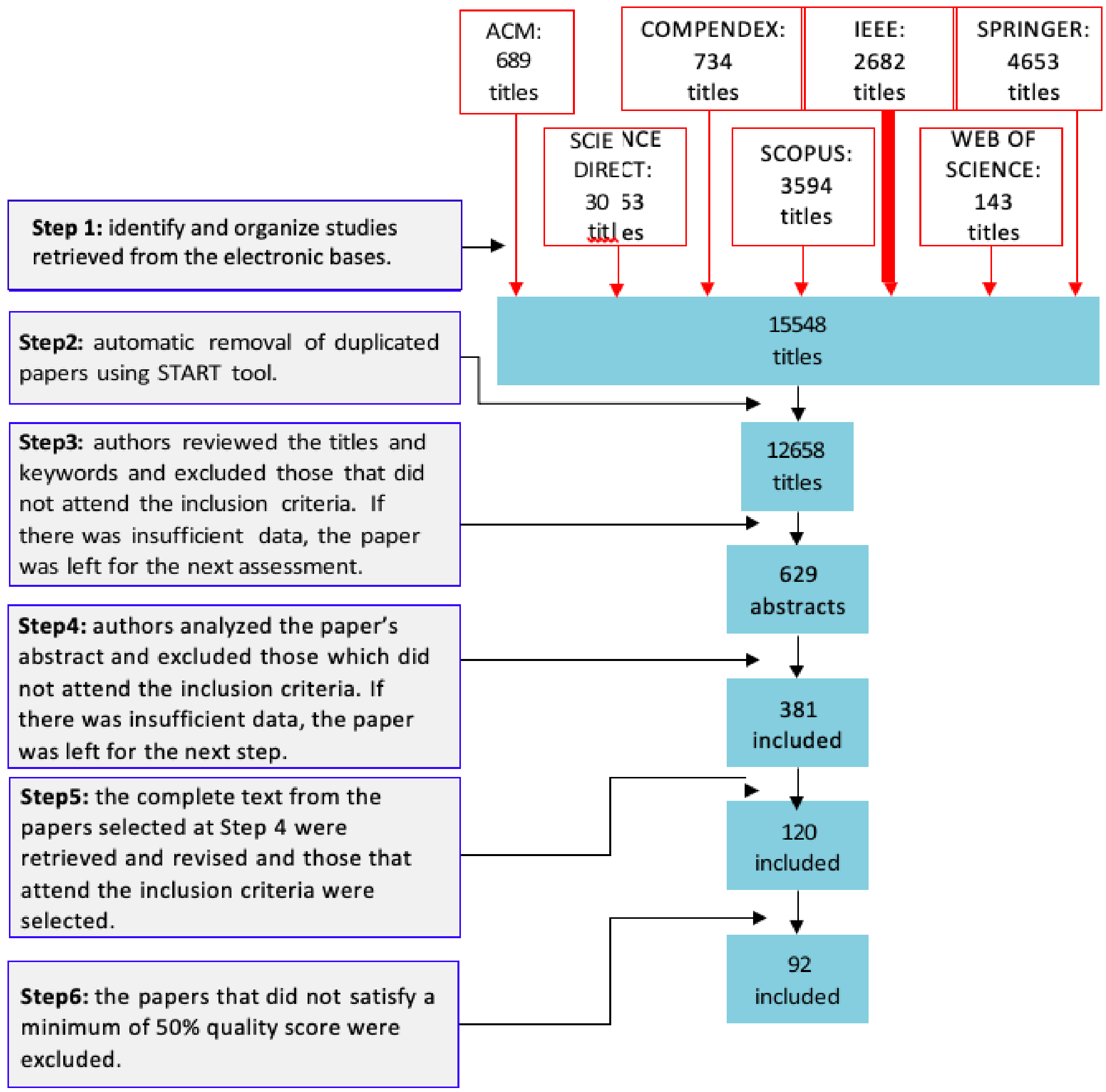

Figure 1: Systematic literature review steps. Adapted from [26]

Conclusion validity: The methodology chosen in [25] already considers that not all relevant primary studies that exist can be identified. It is possible that some studies excluded in this review could have been included. To mitigate this threat, the selection process and the inclusion and exclusion criteria were carefully designed and discussed by authors to minimize the risk of exclusion of relevant studies.

In order to avoid bias and maximize internal and external validity we performed a quality assessment (QA) of the selected studies (See Table 3). All studies were assessed against a set of 12 quality criteria. The quality score in each criterion of the selected studies is available at the following [link]. We considered 50% as minimal score for a study to accepted. The overall quality of the selected studies is acceptable since the mean of quality is 66.32%.

Table 3: Quality assessment criteria

#	Questions	Possible answer
1.	Is there a rationale provided for why the study was undertaken? [19]	Y=1, N=0, P=0.5
2.	Is the paper based on research (or is it merely a lessons learned report based on Y=1, N=0 expert opinion)? [16]	Y=1, N=0,
3.	Is there a clear statement of the goals of the research? [16]	Y=1, N=0, P=0.5
4.	Is the proposed approach clearly described? [2]	Y=1, N=0, P=0.5
5.	The research context was described at an adequate level (industry, laboratory setting, products used and so on)? [2]	Y=1, N=0, P=0.5
6.	How many phases of requirements engineering process does the study supports? [14]	Num of Phases/Total of Phases
7.	Does the approach support more than one domain (automation technology, automotive, avionics, energy technology or medical technology)?	Y=1, N=0
8.	Is the study support by a tool? [14]	Y=1, N=0
9.	Is there a discussion about the results of the study? [14]	Y=1, N=0, P=0.5
10.	Is the limitation of this study explicitly discussed? [15]	Y=1, N=0, P=0.5
11.	Is there a clear description of the open issues related to the study that was carried out?	Y=1, N=0, P=0.5
12.	Does the research also add value to the industrial community? [2] [16]	Y=1, P=0.5

4. Results and analysis

In this section, we present the results and analysis of the selected studies.

Publication year. The analyzed studies in this review were published between 1980 and June 2019. Figure 2 shows that, from 1980 until 2004, the number of publications was almost continuous. We highlight the year 2015, with a total of eleven publications. From 2004 until 2014, we can observe a gradual increase in the number of publications.

Application context. The academic and industrial context were considered in this classification. Forty-nine papers (53.26%) are in the academic category and 43 papers (46.73%) in the industry category. Hence, the industrial community of embedded systems is also very interested in investigating methods, processes, and approaches for requirements engineering.

Research method. In order to classify the research method of the publications, we rely on [14].

The research methods of the majority of the papers are illustrative scenarios (49 papers, 53.26%), followed by case study (37 papers, 40.21%), controlled experiment (3 papers, 3.26%), quasi-experiment (1 paper, 1.08%), survey (1 paper, 1.08%), and not applicable (1 paper, 1.08%). Ethnography and action research were not found in our classification. We can observe that research in the field of RE for embedded systems is focused on small examples and case studies to evaluate contributions while the remaining methods are put aside.

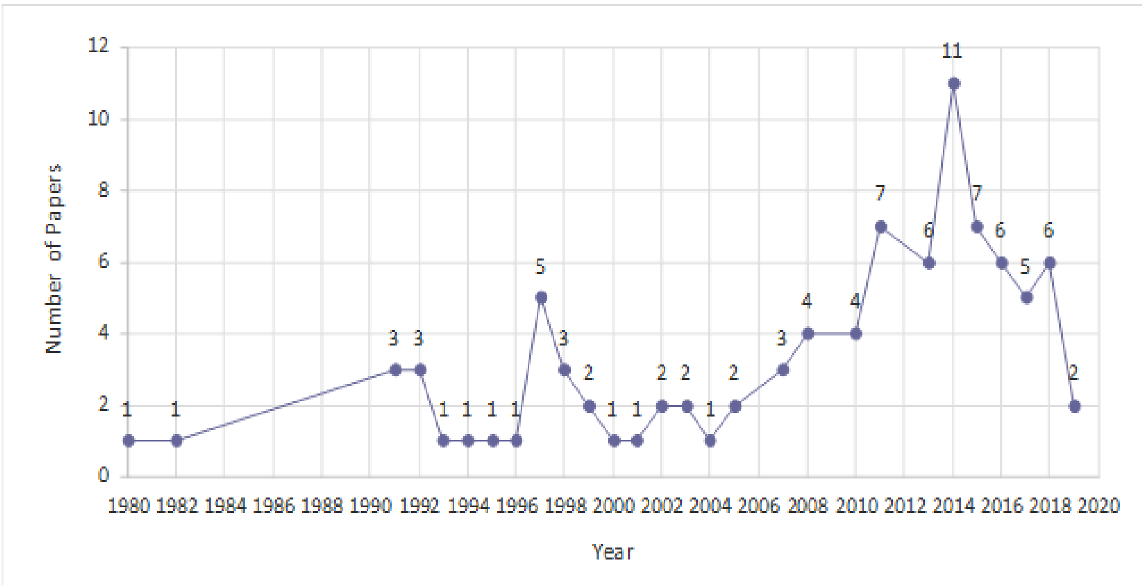

Figure 2: Temporal view of the studies

4.1 RQ1: What are the requirements engineering problems addressed by the approaches?

We reviewed the RE problems considered by the studies. The results of this question are depicted in Table 4. We focused on specific RE contributions for ES, leaving aside the contributions of the studies that fit in general purpose contributions (32.6%, 30 studies). Besides, many studies did not explicitly discuss the goal of their proposals (13.04%, 12 studies).

During this literature review, it was clear that many studies address RE using specifics viewpoint and domain. Thus, the results of this research question were fragmented. In this case, the constant comparison method to create categories for all studies was not possible to be used. The authors discuss specific problems, sometimes related to a particular ES domain, and therefore, our classification included 37 RE problems.

One significant finding is that 42 studies (45.65%) discuss general issues or does not cite the problem they wish to solve, while 50 studies (54.34%) propose specific contributions for embedded systems. This might indicate that requirements engineering for ES still requires more effort.

Table 4: Requirements engineering problems

#	Problems	Studies
	General purpose contribution	30 studies
	It does not cite/Not clear	12 studies
P1	Specification of safety requirements	5 studies
P2	Integration between requirements and architecture	4 studies
P3	Elicitation of safety requirements	4 studies
P4	Specification of timing requirements	3 studies
P5	Specification of real-time capabilities	3 studies
P6	Difficulties to handle safety issues during the development of safety critical systems	2 studies
P7	Integration of safety and security requirements to the overall system	2 studies
P8	Lack of a unified framework for requirements engineering of safety critical systems	2 studies
P9	Lack of a well-defined requirements engineering process for embedded systems domain	1 study
P10	Handling of multiple stakeholders	1 study
P11	Integration between hardware and software	1 study
P12	Improved use case for the requirements elicitation and specification of embedded systems	1 study
P13	Specification of timing behavior and operational system properties	1 study
P14	Elicitation and analysis of security requirements	1 study
P15	Specification of security requirements	1 study
P16	Requirements reuse for embedded systems	1 study
P17	Verification of timing requirements	1 study
P18	Specification of resource requirements	1 study
P19	Physical and non-functional requirements in SPL for embedded systems	1 study
P20	Modeling of functional and non-functional requirements for the domain of embedded systems	1 study
P21	Handling of multiple non-functional requirements on the entire distributed system	1 study
P22	Specification of electronic control unit (ECU)	1 study
P23	Prototyping embedded systems for requirements validation	1 study
P24	System and controller specification	1 study
P25	Control of the physical processes of embedded systems	1 study
P26	Space of system specification	1 study
P27	Detection and correction of behavioral requirements	1 study
P28	Specification of system behavior and software architectures	1 study
P29	Integration of tools used by different stakeholders	1 study
P30	High number of elements available for modeling due to different domain experts	1 study
P31	Elicitation of trustworthiness requirements	1 study
P32	Requirement definition and their verification in the context of distributed embedded system	1 study
P33	Avoid manual intervention for analysis of embedded systems	1 study
P34	Tool support to comply with FuSA Standards	1 study
P35	Secure communication between ground station and data stored on sUAS	1 study
P36	Lack of linguistic techniques to improve specification and analysis of embedded systems	1 study
P37	Monitoring and verification of embedded systems	1 study

The first five problems in Table 4 appeared in 19 studies (20.65%). This indicates the importance that the primary studies give for issues of specification of safety requirements, integration between requirements and architecture, elicitation of safety requirements, and specification of timing, and real-time capabilities. Therefore, these five problems are strong candidates to receive attention from researchers and practitioners in RE for embedded systems.

Another important aspect is that twelve problems (32.43%) are related to the specification phase of the RE process (P1, P4, P5, P12, P13, P15, P18, P22, P24, P26, P28 and P36). There are 17 (18.47%) studies that concern the specification of some ES property such as safety, security, resource, and time, indicating that the specification phase has been investigated.

Only three studies contribute to problems related to hardware, which is part of an ES together with software. Each study address one RE problem (in Table 4, see P11, P19, and P22 - 8.10%). This result indicate that few authors investigate hardware related problems. Other contributions are shown in Table 4.

4.2 RQ2. What phases of the requirements engineering process have been supported?

The phases considered to answer this question were defined according to the RE process established by [27]: elicitation, analysis and negotiation, specification, validation, and management. The predominant phase that we identified was Specification (76.09 %), followed by Validation (42.39%), Analysis and Negotiation (36.96%), Elicitation (27.17%), and Management (17.39%). It is important to note that a study could have addressed more than one phase of the RE process.

An interesting finding is that 28 studies (30.4% of papers included) met both Specification and Validation phases in the same paper, indicating the interest to specify and validate the ES requirements.

4.3 RQ3. What style of requirements modeling have been supported by the approaches?

In order to guide our classification, we used seven requirements style presented in the work of [14], except for Description logic since it was discovered during the classification. The results presented in Table 5 were defined according to the distribution of the studies.

Scenario-based category is the most frequent type of RE modeling addressed by the studies. This category included studies on all RE phases, but most studies are concerned with requirements specification, analysis, and validation of requirements, as can be seen in Fig. 3.

Table 5: Requirements modeling style

Requirements style	Count	%
Scenario-based	25	27.2%
Formal language	22	23.9%
UML	21	22.8%
Textual requirements	18	19.6%
Non-specific	12	13.0%
Description logic	8	8.7%
Feature models	1	1.1%
Problem frames	1	1.1%

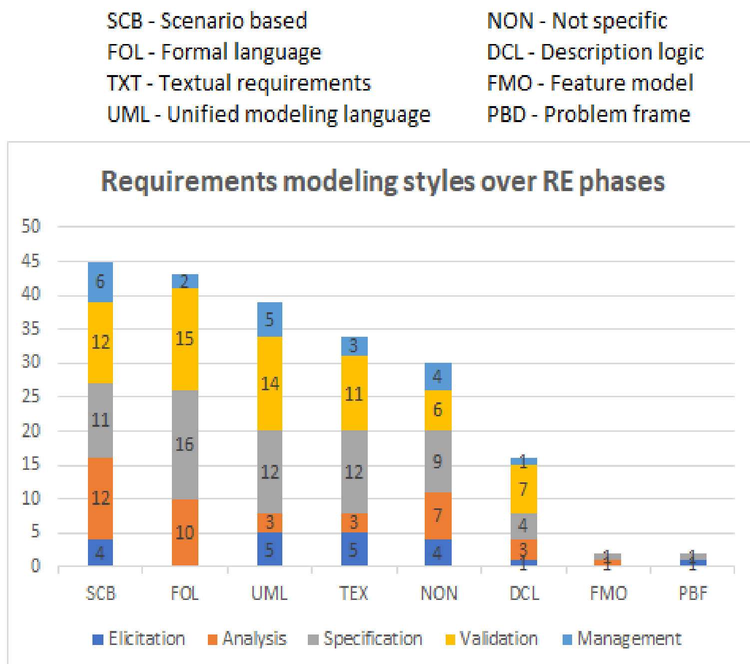

Figure 3: Requirements modeling styles over RE phases

4.4 RQ4. What type of requirements have been supported by the approaches?

The purpose of this research question was to identify what the distribution of the studies with respect to the type of requirements is (functional and/or non- functional) addressed. The categories we used were: (1) functional requirements, (2) non-functional requirements, and (3) both types. Table 6 presents the distribution of the studies within these categories. As expected, most studies (80.4%) addressed functional requirements. Interestingly, (39.1%) of studies considered both functional and non-functional requirements in the same study, indicating their concern with a more complete requirements specification.

Table 6: Functional and non-functional requirements distribution

Type of requirements	Count	%
Functional req. only	38	41.3
Non-functional req. only	18	19.6
Both	36	39.1

4.5 RQ5. What are the domains that the approaches support?

The goal of this question is to identify different domains related to embedded systems identified in our SLR. The results of this research question are of great importance to identify the different domains that are addressed by the studies. Thus, we can cross data and get other kinds of information. It may help to recognize which domain may need more attention concerning requirements engineering. The classification we made to answer this question was based on the analysis of the fields (automation technology, ground transportation, avionics, energy technology, medical technology or agriculture) used by the approaches. It is important to note that ground transportation domain encompasses automotive and train transportation.

Through the results of Table 7, we can see that six different domains were identified. The most frequent domain is *Ground transportation* (37 papers, 40.2%) followed by Avionics (19 papers, 20.6%), Automation Technology (16 papers, 17.4%), Medical Technology (17 papers, 18.5%), Energy Technology (2 paper, 2.2%) and Agriculture (1 paper, 1.1%). An unexpected result was the number of studies that do not address any domain (23 papers, 25%). The studies leave readers free to decide where to apply the approaches. It can be a positive point or a negative one. Positive since we can test in many different domains and get our conclusion or negative because we do not previously know how the approach is applicable to a specific field of embedded systems. Thus, we can waste effort and time.

Another surprise is the number of papers that are related to energy technology domain (2 studies). Hence, we can conclude that little attention is given to the energy technology field even though it is a critical area and in evidence over the last years [46]. Finally, only one study addresses the agriculture domain. As the publication year is recent (2018), this result may indicate a possible domain to be investigated from now on.

Table 7: Embedded systems domain

# ES Domain	Count	%
D1 Ground transportation	37	40.2
D2 Not applicable	23	25.0
D3 Avionics	19	20.6
D4 Automation Technology	16	17.4
D5 Medical Technology	17	18.5
D6 Energy technology	2	2.2
D7 Agriculture	1	1.1

4.6 RQ6. What are the tools used by the approaches to support requirements engineering for embedded systems?

This research question maps the computer-Aided Software Engineering (CASE) tools used in the approaches that support requirements engineering for embedded systems.

Even though we have found 48 tools, the number of papers that do not mention any tool is high (58 studies, 63%).

In fact, it may indicate the need for the development of tools capable of dealing with the elicitation, analysis, specification, validation, and management of embedded systems requirements.

The following tools are used in three studies each: Doors, Simulink, and Uppal. While Matlab, OSATE, Paragon, Artisan Studio, and TASM Tool Set are cited in two studies each. The remaining tools are cited in only one study each, such as Uni-REPM SCS Tool, AutoProof Tool, MBSE Software Capella and Arcadia Method, REMsES, Extended EAST-ADL2 Tool, Signal Matrix Editor, UML tool.

The answer to the research question RQ6 suggests the need for specific RE tools for the embedded systems community. One possible reason of these few numbers of tools can be the fact that they have a wide range of parameters, which interact in different and unpredictable way, thus creating a large and complex design space [39]. An example of this complexity is the fact that in ES domain different stakeholders with different expertise require various tools to perform their work. However, the tools need to integrate the work products generated by each one [3]. Additionally, [20] stated that many tools are not sufficiently open to the tools of other vendors, such as for modeling or traceability. Thus, there is a need for tools with migration capabilities. Besides, [46] argues that the lack of tool support lead to uncertainty about how models should be used in the RE process.

4.7 RQ7. What challenges / problems are identified in research literature relating RE for ES?

The purpose of this question is to identify further research needed in this area. These challenges/problems were extracted from the selected studies, and they are presented in Table 8. We focused on specific RE problems for ES. The problems of the studies that fit in general purpose problems (32.6%, 30 studies) were left aside. Besides, many studies presented just their proposals, but did not discuss challenges/problems on RE for ES. This corresponds to 31.5% of the studies (29 studies).

One important finding is that eight challenges (33.2%) are related to non-functional requirements for ES (O3, O5, O6, O8, O9, O13, O18, and O21). There are 11 (11.9%) studies highlighting the need to handle quality requirements such as timing, safety, reliability, performance, user interface, and others, indicating that NFRs need further investigation. It should be noticed that safety is related to five challenges and timing to 3 problems.

Table 8: Challenges/problems on requirements engineering for ES

#	Research directions	Studies
General open issue.		30 studies
It does not cite/Not clear.		29 studies
01	Apply the proposed approach in industry embedded systems project	[3,8,56], [41,32,36]
02	Apply the proposed approach in different domains	[52,12,48]
03	Specification of timing requirements	[1,17]
04	Refining requirements into specifications taking the environmental assumptions into account	[5,51]
05	Timing requirements verification and tool support development	[11,22]
06	Analysis of hazard and threats, timing, performance, and safety	[55,57]
07	Improve the development process for ensure functional safety requirements	[35]
08	Handling of non-functional requirements such as QoS, safety, reliability, resource and scheduling properties	[30]
09	Specification of safety requirements	[40]
010	Specification and analysis of scenarios for embedded systems	[43]
011	Enhance the IEEE Std 830 and establish a reference Software Requirements Specification for automotive system	[49]
012	Hardware verification and modeling of synchronous and asynchronous components	[18]
013	Measuring requirements stability and reusability in embedded systems domain	[29]
014	Integration of requirements management tools	[5]
015	Simulation execution of practical real-time software in a visual way	[54]
016	Modeling of urgency	[9]
017	Evolution of behavioral requirements and functional design	[13]
018	Specification of user interface for embedded systems	[17]
019	Variability in embedded systems development Complete the language implementation; validate the language	[42]
020	considering 244 FR; transformation of ReSA requirements to formal requirements	[31]
021	Automated verification of the safety and liveness properties	[45]
022	Improvement in geographic location of the Small Unmanned Aerial Systems	[4]
023	Integration of hardware monitoring and verification with the presented software monitor and verification approach	[44]
024	Improvement of the maturity level of requirements engineering	[52]

Seven studies are concerned with the specification phase of the RE process. The challenges O3, O4, O9, O10, and O18 point a concern to investigate the specification of quality requirements, environmental assumptions, and scenarios for embedded systems. Considering that 58 of the studies did not cite any tool support, the finding of O5 and O14 might indicate the need of development of tools capable of verifying timing requirements and dealing with different domain tools. Another important aspect is the need to investigate requirements standards in different domains. Moreover, one study argues the need to enhance the IEEE Std 830 [23] for automotive systems.

The most cited challenge/problem is Apply the proposed study in industry embedded systems project (O1). This challenge was referenced in 6 studies (6.5%), and it is the consequence of the low number of proposals evaluated in the industrial context (46.7%). These results show the need of applying the proposal in practice with real users to assess the extension of the contributions. O2 - Apply the proposed approach in different domains is the second most cited challenge. The goal is to test the proposed solution in different domains, expanding the examples and checking the effects [52,12,48].

In sequel, we have O3 - Specification of timing requirements, O4 - Refining requirements into specifications taking the environmental assumptions into account, O5 - Timing requirements verification and tool support development, and O6 - Analysis of hazard and threats, timing, performance, and safety. Timing requirements and environmental assumptions are necessary for the correct operation of embedded real-time systems [6].

ISO 26262 is an international standard for functional safety of road vehicles. This standard can be used to Improve the development process for ensuring functional safety requirements (O7). It is possible to deal with performance analysis for specification of NFRs in the Handling of non-functional requirements such as QoS, safety, reliability, resource and scheduling properties (O8).

Investigations are also necessary to propose mechanisms to perform the Specification of safety requirements (O9). A possible approach is to derive safety requirements from the results of a systematic analysis of the system. This derivation can be done by formalizing the results of fault tree analysis. Multiprocessor based environments and case maps notation can be used in the Specification and analysis of scenarios for embedded systems (O10).

Difficulties are also faced to Enhance the IEEE Std 830 and establish a reference Software Requirements Specification (SRS) for automotive system (O11). Considering that there are many different SRS for the automotive system, the development of a reference template is a substantial challenge. Introducing hardware at the beginning of the verification infrastructure and considering the use of different interaction paradigms can support the Hardware verification and modeling of synchronous and asynchronous components (O12) respectively.

Measuring requirements stability and reusability in embedded systems domain (O13) is a challenge. The goal is to define a set of criteria for measuring requirements stability and its reusability. A possible solution may be the use of the Requirements Maturity Model (RMM) to evaluate the requirement reuse process.

The contributions presented (see the table with the complete list of contributions in Table 4) can be useful in different contexts. For example, a newcomer (e.g., new student) will be able to identify new research opportunities, and they can become the subject of new research projects.

5 Conclusions

Requirements engineering plays a vital role to help to correctly develop embedded systems. In this paper, we presented a systematic literature review that investigates studies reporting approaches proposed to elicit, analyze, specify, validate and manage requirements for embedded systems. Different aspects of the approaches were examined such as their contributions, RE phases, tools to support their proposals, type of requirements, modeling styles as well as the challenges to be investigated. Our SLR draws on 92 studies, selected out of 12658 over 49 years, through a multi-stage process. An essential aspect of this review is that it does not restrict itself to a particular domain. Thus, the search gives us deeper insights on the state-of-the-art about the content of requirements engineering for embedded systems.

The most relevant findings from this review and their implications for further research are as follows:

Need to include all requirements engineering phases. Most studies only partially address the RE process. In fact, only two studies considered all five phases and only one addressed four phases of the RE process. This indicates that only part of the RE process is met by the studies included in this review, demonstrating that there is a lack of approaches that consider the whole RE process.

Lack of a specific requirements engineering process for embedded systems. The embedded systems community does not present a well-defined, standardized, and known requirements engineering process to guide companies. Hence, there is a need to investigate and develop a specific requirements engineering process by providing inputs, outputs, and work products for correct requirements development and management for the scope of embedded systems.

Need to improve the specification and analysis of timing requirements. Timing requirements are necessary for the correct operation of embedded real-time systems [5]. Hence, the requirements engineering for ES should provide guidelines for the specification, analysis, and verification of timing requirements [11,55].

Need to improve safety requirements. It should be noticed that specification of safety requirements has been treated by some approaches, as depicted in question RQ7. However, safety is related to five challenges (20.8%), which involves specification, analysis, and verification activities. For example, the requirements specification must be suitable to derive safety requirements. Therefore, RE approaches for ES need to provide guidance of safety-related concerns.

Need to improve the specification and analysis of the NFRs. Despite the current contributions to ameliorate the non-functional requirements problem, there are several open issues to be solved. Handling of multiple NFRs such as QoS, safety, and reliability is pointed out by [30] as future work. The difficulty is to select the best possible system configuration based on a set of non-functional requirements. Therefore, RE approaches for embedded systems need to provide a significantly improved account of NFRs concerns.

Need of integration tools. The development of embedded systems requires stakeholders from different expertise. Thus, a tool should be able to organize the specification in a structured manner into several abstraction layers (additional views/expertise). Additionally, it is necessary to develop interfaces to support migrating from well-known requirements management tools such as Doors and RequisitePro. Moreover, the tools should be capable of dealing with elicitation, analysis, specification, validation, and management of embedded systems requirements.

Need to consider RE standards. There are different requirements engineering standards such as IEEE Std 29148:2011 and IEEE Std 830:1998. Nevertheless, RE approaches for ES are not using what has already been done to develop specific RE processes for ES domain. The RE standards provide tasks, activities, practices, goals, and work products that can be tailored to accomplish the RE needs for a specific ES domain.

Need for industry validation. Even though the industrial community of embedded systems is investigating requirements engineering (46.7% of the studies were applied in an industrial context), there is still a need for implementing the studies in real industry projects with real users in order to improve the relevance of the research and to assess to what extent the approach contributes to the RE for embedded systems.

Need to apply the proposed solution in different domains. Fourteen studies (15.2%) applied their solutions in more than one domain. This fact may indicate the need to test with the appropriate indicators, the proposed solution in different domains, expanding the examples and checking the effects [52,12,48]. Hence, it may be necessary to evaluate in a second domain, a solution specially developed for a specific area.

Motivated by the results of this SLR we propose a research agenda for the RE community for embedded systems:

1. How can we develop a RE process to address elicitation, analysis, specification, validation, and management phases?

2. What is the core set of information that should be considered by requirements engineers in the development of embedded systems?

3. What are the main requirements engineering patterns and how they can be used in a RE process for the domain of embedded systems?

4. What are the requirements and constraints need to develop a tool capable of dealing with integration with other tools and that supports all five RE phases?

5. How to measure the feasibility of using requirements engineering approaches in embedded systems?

6. What are the primary non-functional requirements and how they are related to embedded systems specificities?

7. How to improve the maturity level of requirements engineering processes for embedded systems?

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