Requirements Engineering for Robotic System: A Systematic Mapping Study

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Abstract. *Problem Statement*: Several research efforts have been targeted to support Requirements Engineering (RE) in general software systems for the last two decades. However, to the extent of our knowledge, there is no framework to support RE in robotic systems domain. *Goal*: We aimed to systematically identify and analyze the existing research progress and directions that influence the elicitation, analysis and negotiation, specification, validation and management of requirements in robotic systems domain. *Method*: We used Systematic Mapping Study (SMS) method for identifying and analyzing 38 peer-reviewed studies. Our review has (i) taxonomically classified and (ii) systematically mapped the methods, modelling styles and process which support some RE phases. *Results and Conclusions*: According to the selected studies, we realize that all RE phases are addressed by one or more methods, modelling styles and process. In general, the elicitation and specification phases received greater attention from the academic community whereas validation, analysis/negotiation and management phases still require more attention. Furthermore, we note that only two studies mention all phases of the ER process but such studies do not describe in detail how RE phases should be performed.

Keywords: Robotic Systems, Requirements Engineering, Systematic Mapping Study.

1 Introduction

Robotic systems are being increasingly integrated in several aspects of everyday life. These systems range from critical mission [1] to infotainment and home service tasks [2]. Robotic systems are expected to assist or replace their human counterparts for efficient and effective performance of all sorts of tasks such as industrial operations [3] or surgical procedures [4]. A robotic system is a combination of some parts – *hardware* for system assembling and *software* for system operations – that must be integrated to enable a robotic system's function as expected. In order to support the vision of a robotic-driven world, academic research [1][5], industrial [6] and open source solutions [7] are striving to provide cost-effective and efficient solutions of robotics systems. Researchers [23] and practitioners [6] are increasingly focusing on exploiting software engineering methodologies to abstract complexities and enhance efficiency for modelling, developing, maintaining and evolving robotic systems cost-effectively [8].

The first step towards development of a robotic system is to determine its requirements which are descriptions of how the system should behave and the constraints associated with its operation [11]. Normally, the requirements definition of a system occurs through a process called Requirements Engineering (RE). This process refers to the activities to defining, documenting and maintaining the system requirements [11]. The phases involved in RE vary widely, depending on the type of system, application domain, development process, technical mature, organizational culture, among other factors. According to Kotonya and Sommerville [11], the RE process must include the following phases: elicitation, analysis and negotiation, specification, validation and managements. Since robotic systems often rely on special-purpose hardware and operating software, the requirements engineering for these systems usually involves both *hardware* and *software* requirements.

Since the early 2000's, there has been a continuous stream of reported research on techniques (e.g. methods, modelling styles and processes) to support the several phases of RE process for robotic systems domain. However, to the extent of our knowledge, there is no specific framework to carry out RE process for robotic systems domain. Therefore, it is a timely effort to analyze the collective impact of existing research on RE for robotic system domain. The main goal of this Systematic Mapping Study (SMS) is identify and analyze the existing techniques and research progress that influence the phases on RE process for robotic systems domain. For doing so, we decided to conduct this research by following the guidelines reported in Petersen et al [9] to investigate the state-of-the-art of RE process for robotic systems domain. The key contributions of this study are: (i) The systematic identification and analysis of the existing research, pinpointing the techniques which support the five phases of RE process; and (ii) The classification of the existing research, providing a body of knowledge for deriving new hypotheses to be tested and identifying the areas of future research.

According to the 38 selected studies for this SMS, we noticed that all phases of the RE process for robotic systems are addressed by one or more techniques. In general, the elicitation and specification phases received greater attention from the academic community whereas validation, analysis & negotiation and management phases still require more attention. Furthermore, we observed that only two studies provided fully support to RE process, implying the need to further investigate a set of modelling styles, methods and process that address all phases of the RE process on robotic system domain. Finally, the results of this SMS benefit (i) Researchers who are interested in knowing the state-of-the-art of RE process for robotics systems domain and (ii) Practitioners who may be interested in understanding the techniques for address any phase of RE process on robotic systems domain.

The remainder of this paper is organized as follows. Section 2 briefly introduces robotic systems, RE and existing secondary studies related to this research. Section 3 describes the research methodology used. Section 4 reports an overview of the selected papers, classifying them taxonomically. Based on this classification, various requirements engineering techniques and approaches for robotic software are presented in Section 5. Validity threats are showed in Section 6. Finally, Section 7 presents key conclusions and future works from this research.

2 Background and Related Studies

In this section, we briefly introduce robotic systems (Section 2.1) and requirements engineering (Section 2.2). We also discuss some existing secondary studies (Section 2.3) related to this Systematic Mapping Study (SMS).

2.1 Robotics Systems

Robotic system is a combination of hardware and software components as two distinct layers that can be integrated to build a robot [6]. The hardware components (e.g. sensors and robotic arms) enable the assembly of a robot [26]. Hardware components are controlled and manipulated by Control Layer that is essentially a collection of drivers (as system specific code) to interact with the hardware as depicted in Fig. 1. For more complex functions of a robot, specialized software is provided for integration and coordination of hardware components to manipulate the robotic behavior. In Fig. 1, this refers to as Application Layer that utilizes the control layer to support robotic operations. For example, considering a home service robot [10], the control layer provides a driver that enables access to a robotic arm. Depending on specific requirements, a software system at application layer must be provided. Such software system is expected to rely on drivers from control layer to enable the movement of arm for home service robot at certain degrees of precision and/or avoiding any obstacles.

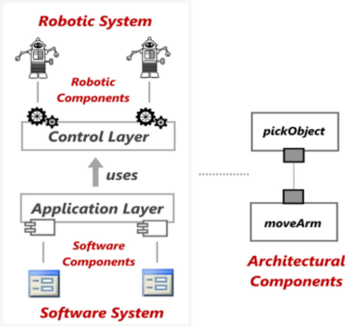

Fig. 1. A reference model for robotic system.

Since robotic systems often rely on special-purpose hardware (Robotic System) using software components (Software System), the first step towards development of robotic systems is to define its software and hardware requirements. The requirements are descriptions of how the system should behave and the constraints associated with its operation [11]. Normally, the requirements definition occurs through a process called Requirements Engineering (RE) which will be described in detail in the next section.

2.2 Requirements Engineering

The Requirements Engineering (RE) process is composed by several phases: Elicitation, Analysis & Negotiation, Documentation, Validation and Management [11]. The *requirements elicitation* phase involves understanding the application domain, the specific problem to be solved, the organizational needs and constraints and the specific facilities required by the system stakeholders. The *requirements analysis and negotiation* are concerned with establishing an agreement on the high-level statement of requirements elicited from stakeholders. The *requirements specification* provides a detailed list of agreed set of requirements which are complete and consistent.

The *requirements validation* is the final stage of RE. The aim of this phase is to check the final draft of a requirements document to certify it represents an acceptable description of the system to be implemented. The inputs to the validation process are the *requirements specification*, organizational standards and implicit organizational knowledge. The outputs are a list of requirements problems and agreed actions to address these problems. In addition to these phases, Kotonya and Sommerville [11] also emphasize the need to manage requirements. The *requirements management* is the process of managing changes in systems' requirements (e.g. software and system requirements). Therefore, this process supports others RE and system development activities. Besides, it is carried out in parallel with other RE activities and continues after the first version of the requirements document has been delivered.

2.3 Related Studies

We found two types of secondary studies related to our study. The former is related to studies in software engineering for robotics domain and the latter is related to studies in requirements engineering for others domains. Following, we briefly discuss these studies:

Software engineering for robotics – (i) Oliveira *et al*. [24] have reported a systematic review of Service-Oriented Development of Robotic Systems based on 39 primary studies published from 2005 to 2011. Their review reports the solutions that support design, development and operation of robotic systems based on software services using service oriented approaches. (ii) Pons *et al.* [12] have conducted another systematic review of Software Engineering Approaches for Robotics based on 67 studies published from 1999 to 2011. They highlight the prominent trends of software engineering techniques for robotic software. The review highlights the application of component based, service oriented as well as model driven development of robotics as the emerging research trends. (iii) Heineck *et al* [25] investigated how model driven development (MDD) techniques have helped the field of Robotics. They conducted a systematic literature review seeking to identify approaches and their main technical features, as well as the types of specific requirements, behavioral and social issues. Finally, (iv) Ahmad *et al* [13] also used SMS method for identifying and analyzing 56 papers published from 1991 to 2015. This review taxonomically classified the existing research and systematically mapped the solutions, frameworks, notations and evaluation methods to highlight the role of software architecture in robotic systems.

Requirements engineering for other domains - (i) Demerval *et al.* [14] conducted a systematic literature review (SLR) to identify the primary studies on the use of ontologies in RE. We then identified the main RE phases addressed, the requirements modelling styles that have been used in conjunction with ontologies, the types of requirements that have been supported by the use of ontologies and the ontology languages that have been adopted. (ii) Martins and Gorschek [15] conducted a review by selecting 151 papers published between 1983 and 2014. Their paper aimed to investigate which approaches have been proposed to elicit, model, specify and validate safety requirements in the context of Safety-Critical Systems (SCS). Finally, (iii) alves *et al* [16] conducted a literature review and assessed 49 studies, dated from 1990 to 2009. Their paper focused on RE within software product line engineering (SPLE) and had the following goals: assess research quality, synthesize evidence to suggest important implications for practice, and identify research trends, open problems, and areas for improvement.

3 Research Methodology

Despite a multi-disciplinary and continuously growing research for more than one decade, there was no effort to systematically select, analyze, and report the peer-reviewed research on the progression, maturation and emerging trends on requirements engineering for robotic system domain. Therefore, we decided to conduct a Systematic Mapping Study (SMS) following the guidelines reported in Petersen *et al* [9] aiming at providing a more comprehensive mapping and review of methods, process and techniques that address several phases of requirements engineering on robotic systems. Following sub-sections provide the details of research methodology depicted in **Fig. 2**.

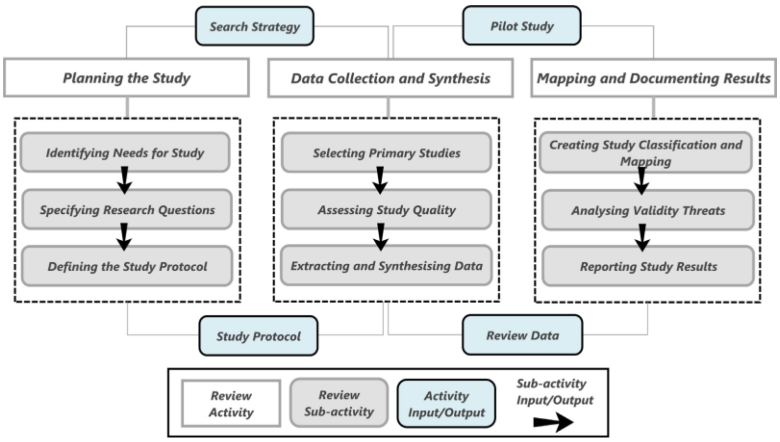

Fig. 2. Overview of the research methodology for SMS [9].

Related to *planning the study*, it is noteworthy that we conducted pilot studies in order to verify the feasibility of this research. During this activity, we established the main considerations of the research (i.e. needs for study, research questions and study protocol). In *data collection and synthesis*, we performed the activities of selection and evaluation of the studies, as well as the data extraction. Part of these activities was done with the automated support provided by Start tool [17]. More details on this activity will be described in **Section 3.2**. Finally, *mapping and documenting the results* activity was concerned with (i) classifying and mapping the selected studies and (ii) presenting the main results. Further details on this activity will be described in **Sections 4.1** and **4.2.**

3.1. Research Questions

Before conducting the SMS, we ensured that a similar study to our review had not been conducted or published. Therefore, we searched IEEE Xplore, Engineering Village, Science Direct, ACM, Google Scholar and Scopus to identify the relevant secondary studies (i.e. SLR, SMS or Survey). Specifically, based on the literature identification with the search string, none of the publications that we retrieved were aimed at answering the outlined research questions below that had motivated our mapping study.

Table 1. Research Questions.

RQ	Description	Motivation
RQ1	What is the publication frequency on RE for robotic system domain?	In this question, we investigate the frequency of published research aiming at reflecting its temporal progression.
RQ2	What phases of the RE process has been supported for robotic system domain?	This question provides a starting point to understand what phases of the RE process have been supported by methods, process and requirements modelling styles in the context of robotic systems domain.
RQ3	What requirements modelling styles have been supported for robotics system domain?	The answer to this question allows the identification of main requirements modelling styles (e.g., scenario-based, goal-oriented, textual requirements) used in the five phases on RE process for robotic system domain.
RQ4	What types of requirements have been supported?	This question intends to identify what is the distribution of the studies with respect to the types of requirements (i.e. functional, non-functional or both).
RQ5	What types of contributions support the phases on RE process?	This question intends to classify the contributions by its type, for instance, model, tool, process and method proposed in the study.
RQ6	How these contributions are validated?	This question helps to analyze how these contributions are validated in terms of research method, for instance, case study, survey and controlled experiment.

It is important to mention some initial Research Questions were formulated for accomplishment of our pilot study. Then, we refined these RQ's to identify challenges and innovative solutions as the possible dimensions of emerging and future research on RE for robotic system domain. By analyzing the past and existing solutions, these RQ's can be helpful to point out the solutions that have proposed in the past and their contribution to the development of existing solutions as well as to identify areas of active research.

3.2. Searching the Primary Studies

After specifying the RQs, we followed the steps to collect and synthesize the data from **Fig. 2**. Following the mapping study protocol, we performed three steps (i) *selection of primary studies*, (ii) *screening and assessment of the studies*, and (iii) *data extraction for synthesis*. **Fig. 3** shows the search process of the primary studies used for this study.

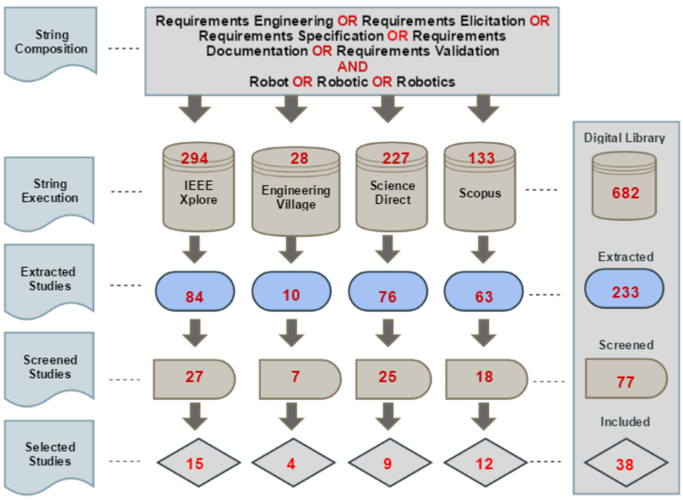

Fig. 3. Summary of the literature search process with search string.

We limited our search to the peer-reviewed literature from years 2005 to 2016, obtaining *682* studies in the primary search process (*String Execution*). We chose this period due to a preliminary pilot study in which we did not find relevant studies for this research before the year of 2005. Aiming at identifying and selecting the studies to be reviewed, the search string was customized for each of the searched databases for effective search [19]. We chose four databases (i.e. IEEE Xplore, Engineering Village, Science direct and Scopus) to support this SMS due to these databases are more recurrent in our related studies. After this String Execution, we focused on title, abstract and keywords; therefore, it resulted in a high number of studies that were not relevant, which we refined with secondary search process (*Extracted studies*), limiting the extracted studies to *233* in total. The selection process of extracted studies was performed with the automated support provided by Start tool [17].

Then, we needed to screen the extracted studies to ensure to remove (i) duplicate studies, (ii) non English language literature, (iii) non peer-reviewed and nonpublished research and, (iv) any study representing an entire book. After the execution of this process *(Screened studies),* we selected *77* studies. Finally, we focused on assessing the technical rigor of contents presented in screened studies. The decision to exclude or proceeding to the final selection was based on an examination of study titles and a preliminary review of the abstracts, conclusions and any other relevant part of the remaining studies aiming at verifying if the study was related to RE for robotic systems. Based on this selecting, the number of studies was reduced to 38 *(Selected studies)*. We provided a full list of selected studies in *Appendix A* of the supplementary material of this SMS available in [17].

4 Classification and Mapping

In the **Section 4.1,** we will provide an overview of the selected studies for this research. In addition, we have identified and analyzed the predominant research themes using a well-known qualitative data analysis approach called thematic analysis [21]. This analysis will be showed in **Section 4.2** and enabled us to taxonomically classify the main themes of the existing research.

4.1. Results Overview

In this research part, we will present some details (at high level) of the selected studies. Due to space limitations, more complete information can be obtained by consulting the supplementary material online available in [17]. The results presented bellow represent a brief information summary which will be described in the following topics:

Industrial or academic - The minority of the studies (39%; 15 studies) are considered academic. This amount shows there is interest of the academic community in researching the subject and that most of the methods, processes and models used in RE for robotic domain need academic validation for later use in the industry. However, it is worth noting that a considerable amount of the studies were conducted in an industrial setting (61%; 23 studies), indicating that, even though the concept of robotics is widespread within the academic RE community, its use also has been significantly investigated in industry.

Conferences and journals – Aiming at guiding researchers and practitioners in the field of requirements engineering applied to the robotics domain, we have verified the main sources of publication related to this area. In these sources of publication we can find about 30% all selected studies. Thus, we can highlight the following sources and the amount of publications found: Robotics and Computer-Integrated Manufacturing (3), International Conference on Software Engineering (2), International Design Engineering Technical Conferences (2), International Symposium on Systems Engineering (2) and International Conference on Rehabilitation Robotics (2).

Main Research Centers - According to selected studies in this research, we can identify the main research centers related to the area of requirements engineering applied to robotic systems. Next, we point out the main countries as well as the number of studies developed.

It is important to mention that 33 studies were developed in these countries, representing about 85% of all considered studies. The United States accounts for (6) works, i.e. more than 15% of selected studies. This country is followed by United Kingdom (5), Germany (4) and Sweden, Spain, Italy and France with three (3) studies, respectively. Finally, we can mention Brazil, Korea and Japan with two (2) studies each one.

Application Domain - The domain of a robotic system defines: the environment which a system operates under some specified conditions (to satisfy some requirements) [23]. A typical example is *health and care* domain in which robots devices are developed to monitor patients´ health state, to assist in rehabilitation or to support laparoscopy. This domain is most representatives with 10 studies, representing about 25% of all selected studies. Other relevant domain is *industrial automation* in which robots are developed to support cleaning services, vacuum pump and welding tasks and industrial production cell. This domain consists of 7 studies, representing 17.5% of all considered studies. Others domains were catalogued in our study such as *Avionics and aerospace*, *critical mission, automotive and generic.*

Hardware or software - As previously discussed, a robotic system is composed of hardware and software components. Thus, during its design and development it is interesting to analyze these two components at the same time. According to the 38 selected studies, we noticed that most of them (22 studies, representing more than 50%) are concerned with defining *hardware and software requirements* concomitantly. Next, the studies that were mainly concerned with the definition of *software requirements* are composed of 15 studies, representing about 40% of the sample of selected studies. Finally, only 1 paper has as priority concern the definition of *hardware requirements*, representing 3% of the sample considered.

4.2. Taxonomy of the Research Themes

The taxonomy in **Fig. 4** provides a systematic identification, naming and classification of various research themes based on theirs similarity or distinctions. By analyzing relevant study [11][20] and following some of the guidelines from ACM Computing Classification System, we derived the following categories:

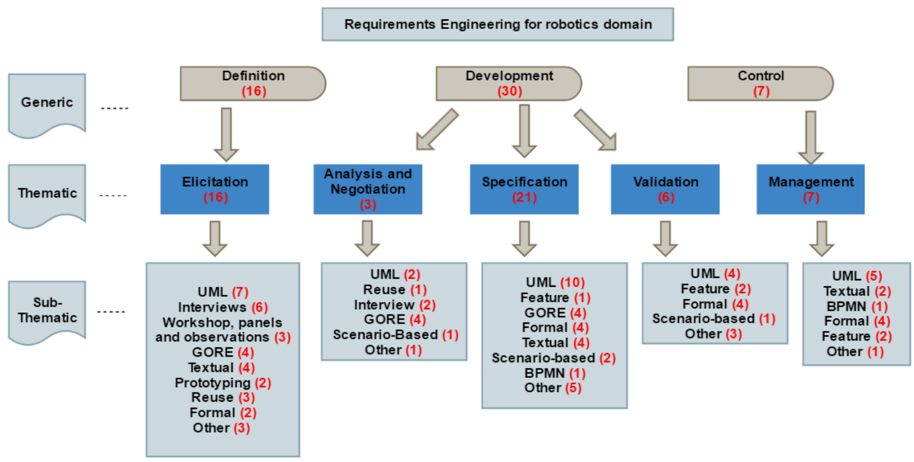

Fig. 4. A taxonomy of research themes on RE for robotic systems domain.

Generic Classification that highlights the role of activities to support the phases of requirements engineering on robotic systems. The generic classification is used to organize the results into three distinct areas. Specifically, in the context of **Fig. 4**, we will generically classify RE process in the following groups: (i) definition, (ii) development and (iii) control.

Thematic Classification extends the generic classification by adding details based on the primary focus of research in a collection of related studies to identify and represent the recurring research themes [21]. We categorized the aforementioned generic groups according to the RE process defined by previous study [11]: elicitation, analysis and negotiation, specification, validation and management.

Sub-thematic classification provides the main techniques (i.e. methods, requirements modelling styles and process) that provide support to the various phases of the requirements engineering process for the robotic system domain. With this classification, we intend to provide the academic community and industrial practitioners with a list of the most recurrent techniques in each RE phases. From this, future research can be carried out in order to set up a framework to support the entire RE process according to system type, application domain, development process, technical mature, organizational culture, among other factors.

Overlapping themes may occur in the above taxonomy. Some studies could be classified to more than one theme or sub-theme whether their contributions were relevant to multiple (sub-) themes. We referred to such cases as thematic and sub-thematic overlaps. Exemplifying case of *themes overlap:* the study [S13] could be classified under the *Specification* and *validation* themes since this study provide support for both RE phases at the same time. Exemplifying case of *sub-themes overlap:* the study [S36] performs *Elicitation* based on UML and Reuse at the same time. Thus, this study contributes with two techniques concomitantly for the same RE phase.

5 Discussion

In this section, we will answer our research questions (RQ1–RQ6). First, we highlight the publication years and types of the selected studies (**Section 5.1**). Second, we will analyze the RE phases described on selected studies (**Section 5.2**). Third, the main modelling styles used on several RE phases will be exposed (**Section 5.3**). Then, we will show which types of requirements have been supported (**Section 5.4**). Finally, the contributions types will be explained in **Section 5.5** whereas the methodological validation of these contributions will be described in **Section 5.6**.

5.1. Publication Frequency on RE for Robotics Domain (RQ1)

The **Fig. 5** shows the years and types of publications reviewed in order to answer RQ1. It shows the relation between the total numbers of studies (y-axis) published during individual years (x-axis) since 2005 to 2016. Each bar of **Fig. 5** shows a relative distribution of the different types of publications (Journal and Conference). For example, the bar relative to year 2006 represents a total of 03 studies [S7, S12 and S16] published (publication distribution as: Conference Papers: 01, Journal Paper: 02) in that year.

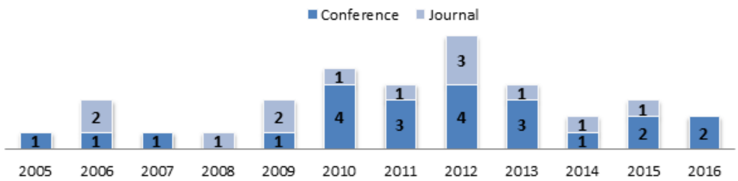

Fig. 5. Overview of the publication years and types.

The oldest studies (such as [S22], [S5] and [S10]) were focused on requirements specification phase using UML models, textual notation and interviews techniques. The most recent studies (such as [S9], [S24] and [S27]) were focused on specification and elicitation phases using SysML models, GORE (KAOS and I*) and formal techniques. There were 23 studies published from 2009 to 2015, representing about 60% of all selected studies. These studies represent the major research progression in the timeframe considered for this research.

5.2. RE Phases Addressed in Robotics Domain (RQ2)

The purpose of RQ was to identify which RE phases had been supported in robotic systems. We categorized these phases according to *thematic classification* (**Section 4.2**) which is composed of the following steps: elicitation, analysis and negotiation, specification, validation and management (**Table 2**). It is worth noting that a study could have addressed more than one RE phase, thus the sum of percentages can be greater than 100%.

Table 2. RE phases on Robotics Systems.

Phase	Studies	Count	%
Elicitation	[S9, S17, S5, S11, S2, S24, S18, S36, S28, S30, S1, S3, S29, S16, S23, S21]	16	42,1
Analysis & Negotiation	[S35, S36, S23]	3	7,8
Specification	[S28, S30, S1, S3, S29, S16, S23, S21, S14, S38, S32, S34, S12, S6, S27, S20, S22, S25, S37, S33, S13]	21	55,3
Validation	[S35, S7, S4, S8, S13, S19]	6	15,8
Management	[S10, S26, S7, S4, S8, S37, S33]	7	18,5
Entire process	[S31, S15]	2	5,3

In summary, the results shown in **Table 2** indicate that all RE phases are minimally covered by the selected studies. The predominant RE phase that we identified was Specification (55.3%), followed by Elicitation (42.1%), Management (18.5%), Validation (15.8%) and Analysis and Negotiation (7.8%). The *Specification* phase is addressed by more than 50% of the studies. In fact, to some extent, this result was expected, since this is one of more important phases of RE process. *Elicitation* phase also encompasses a great number of the studies (about 40%). Furthermore, 18 studies (almost 50% of selected studies) covered both *Elicitation* and *Specification* phases in the same study, indicating the interest of using some method to specify any RE artefact or activity but also to conduct some analysis or reasoning on requirements.

The *Management* phase is also significantly representative in the selected studies. This result was somewhat expected due to particularities of robotic domain. We noticed 7 studies (18.5%) provide support to this RE phase. *Validation* or *Management* phases were supported by 13 studies (about 35%). Among all 38 selected studies, only two [S15, S31] addresses minimally all phases of RE process. Although most of the RE phases are supported by some techniques, we note that there are little studies that perform completely, even in a minimal way, the *entire process* of RE. This result suggests there is a need to be further investigated the support for the entire RE process on robotic systems domain.

5.3. Requirements Modelling Styles (RQ3)

The purpose of this RQ was to identify the types of requirements modelling styles used on RE for robotic systems. The classification of the styles was made after the data extraction of the studies, i.e., during the extraction, plain text data about the software requirements modelling styles used in the study was captured. Next, in the syntheses step of this review, the categories presented in **Table 3** were defined according to the distribution of the studies.

Table 3. Summary of requirements modelling styles.

Phase	Studies	Count	%
Feature model	[S4, S7, S28]	3	7,5
Textual	[S22, S12, S10, S36, S6, S3, S29]	7	18
Formal	[S14, S19, S1, S9, S15, S20]	6	15
GORE	[S30, S1, S9, S15, S24]	5	12,5
Scenario Based	[S11, S34, S23, S22, S9]	5	12,5
BPM	[S32, S37]	2	5
Models (UML, SysML)	[S35, S15, S21, S18, S27, S33, S16, S26, S20, S8, S19, S23, S22, S2, S24]	15	37,5
Volere and IEEE	[S25, S13]	2	5
Other	[S17, S5, S38, S32, S13, S35, S13, S8]	8	20

The results of RQ show that we identified a great variety of requirements modelling styles which supported some RE phase. An interesting result obtained in the research is that about 60% of selected studies used more than one requirements modelling style - concomitantly - to perform a same phase of the RE process. This indicates that there is a notion of complementarity between requirements modelling styles, and it is often necessary to use more than one in order to carry out any phase of the RE process. Aiming at facilitating, we divided the analysis according to the *categories* proposed in this study (see the **Fig. 5**). These categories will be discussed in more details below:

The *Models category* is the most frequent type of RE modelling style addressed by the studies. This category encompasses studies that use UML and SysML diagrams to support the modelling, for instance, use case models, activity models, sequence diagrams, statecharts models and class diagrams. Furthermore, this category includes studies which address all five RE phases (see **Fig. 5**), emphasizing mainly the specification and analysis phases. *Textual requirements* category is also one frequent type of RE modelling style addressed by the studies. The majority of studies are concerned with requirements elicitation, specification, and management of requirements, as can be seen in **Fig. 5**. It also encompasses studies that specify requirements documents using a requirements document template (e.g., Software Requirements Specification—SRS according to Volere and IEEE standard).

The *Scenario-based category* is also expressive in the studies; it encompasses 5 studies and includes requirements styles such as use case diagrams and ScenarioML models. The studies within this category were used in some RE phases, including analysis and negotiation, specification and validation phases. The *Goal-oriented models category* also contains 5 studies and includes papers which use, for instance, the i* framework, the KAOS approach and the NFR framework. The studies within this category addressed, in total, three RE phases, but with more frequency in the elicitation and specification phases. Feature models category is represented by four studies, using ontologies in the context of software reuse (e.g., software product lines - SPL and model driven development - MDD).

In summary, we can note that there is a great diversity of requirements modelling styles associated with each phase of RE process. We identified nine (9) modelling styles, in which four more frequent in the RE phases were discussed. Due to space limitation, we will not discuss in depth the other requirements modelling styles. Furthermore, as presented in **Fig. 5**, the specification phase was addressed by almost all modelling styles, except for BPM category. Similarly, the specification and management phase was met by great part of styles. Note that, the analysis and validation phases were much less considered by the studies, only the UML and Scenario-based addressed such phase.

5.4. Requirements Types (RQ4)

This research question aims to identify how RE process for robotic systems domain concerning the requirement types. Three categories were used: *functional requirements* (FR), *non-functional requirements* (NFR) in order to facilitate the analysis. The former define the system's functionality whereas the latter emphasize system's qualities (e.g. performance and maintainability) and constraints under which a system is required to operate. Additionally, we used the category *both* for studies which addressed functional and non-functional requirements, concomitantly. The **table 4** summarizes the results:

Table 4. Requirements types.

Domain	Studies	Count	%
Functional	[S19, S10, S20, S15, S6, S7, S33, S14, S23, S18, S35, S27, S32, S5, S26, S34, S38, S22, S24, S9, S11]	21	55,3
Non-Functional	[S28, S8, S4]	3	7,9
Both	[S31, S1, S37, S16, S13, S30, S36, S25, S21, S17, S29, S2, S3, S12]	14	36,8

The results indicate that, in general, *functional* and *non-functional* requirements are addressed by the studies. As expected, the great amount of the studies only deal with *functional* requirements – FR (more than 50%), followed by the studies which only consider *non-functional* requirement - NFR (about 8%). The use *non-functional* requirements is still underexplored although it is well known in the RE community that combined definition of FR and NFRs is important for the success in robotic systems domain. However, it was addressed by less than half of the studies (about 37%) included in this SMS. Concluding, the use of *non-functional* requirements may be further explored in the elicitation, specification, analysis, validation and management phases on RE process for robotic systems domain.

5.5. Contribution Type (RQ5)

This question intends to classify the contributions by its type. In the context of this research we used the following contribution types: model, tool, process and method. It is noteworthy that there is no consensus in the literature regarding these concepts. Thus, we will present the concepts of the types of contribution that will be used in this research: (i) a *model* can be defined as a representation or abstraction of the activities characterized in a RE process. (ii) *method* is the procedure, technique or way of doing some activity in the RE process. (iii) a *tool* provides (semi-)automated support for some method or model. Finally, (iv) a *process* is characterized by a well-defined and documented set of activities (e.g. methods and models) that are systematically applied to perform any phase of RE process.

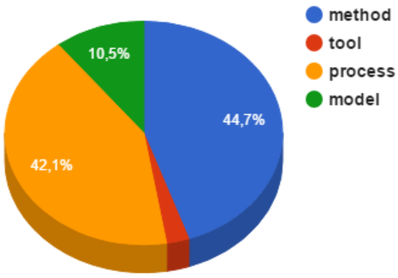

Fig. 6. Contribution types of selected studies.

The **Fig. 6** shows an overview of the contributions types related to RE process for robotic system domain. The *method* contribution (17 studies) constitute majority of the studies, followed by *process* (16 studies), *model* (4 studies), and *tool* (1 study). The results indicate there is academic community interest at researching *methods* to carry out the phases of the RE process. This suggests that there is a gap in terms and "how to carry out" the RE phases on RE process. In addition, the number of studies concerned with *process* contribution was relatively large. It should be noted that these studies focused only on the use of the *process* to perform isolated RE phases (e.g., *elicitation* and *specification*). As previously mentioned (**Section 5.2**), few studies have been concerned with the application of a *process* that supports all phases of the RE process, concomitantly.

5.6 Methods for validating contributions (RQ6)

This RQ analyzes how the contributions are validated in terms of research method. For doing so, we classified the selected studies based on the following categories: *controlled experiment, case study, survey research, ethnography* and *action research*. It is important to mention the previously mentioned categorization was defined in the study of Easterbrook *et al*. [22]. Additionally, we have defined two extra categories: *illustrative scenario* and *not applicable*. The former is appropriate for papers that just evaluate their contributions using simple examples. The latter refers to the papers that do not present any kind of validation in the study. The **Fig. 7** shows an overview of the methods used to validate the contributions concerning in the RE process for robotic system domain.

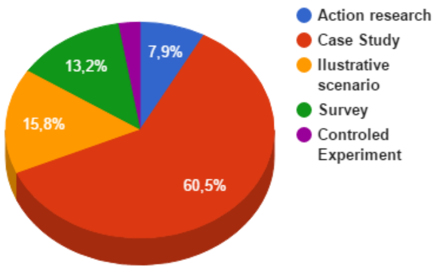

Fig. 7. Methodology of the selected studies.

In summary, *Case Study* (23 studies) constitute majority of the studies, followed by *illustrative scenario* (6 studies), *survey* (5 studies), *action research* (3 studies) and *controlled experiment* (1 study). An interesting aspect that we might note, is that the studies are significantly concerned in conducting empirical researches (e.g., case study and controlled experiment) to validate their proposals. Furthermore, we can highlight the results found in this study suggest that there are empirical evidences to state benefit RE activities in the development of robotic systems. However, the strength of these evidences is somewhat limited to the context (e.g., artefact used, RE phase(s) addressed and so on) on which the studies were performed.

6 Threats to Validity

We followed the guidelines for conducting SMS described in [9][19]. Like any other empirical study, SMS can also have limitations that must be considered for analyzing the potential impact of the validity threats to its findings. We discuss three types of validity threats associated with distinct activities of this SMS.

Threats related to identification of primary studies - In the literature search strategy (**Section 3.2**), we aimed to retrieve as many relevant studies as possible to avoid any possible literature selection bias. We faced a challenge in determining the scope of our study as the notion of "requirements engineering" means different things to different research communities including software engineering, robotics and others. Therefore, to cover them all and avoid any bias, we searched the literature based on relevant terms and combined them in our search string. While this search strategy and search string composition significantly increases the search work [18], it enabled us to find a comprehensive set of the relevant study.

Threats related to quality of studies and data extraction consistency - The results and quality of this study are based on the quality of the studies that have been reviewed. This means that if the quality of the primary studies is low, the claims and their supporting evidence are unlikely to be strong and reliable. Therefore, it is vital to (i) minimize the threats regarding the quality of selected studies and to ensure (ii) a consistent representation of data extracted from these studies. The ideal scenarios may strictly adhere to the guidelines in [19], however, the quality metric can be subjective based on the objectives of SMS and the consensus among researchers.

Threats related to data synthesis and results reporting - The final type of threat corresponds to the bias or a lack of systematic approach to synthesize and report the results. We tried to mitigate this threat by conducting a pilot study. A limited number of researchers and their expertise (software and requirements engineering) may have an internal bias on the style and reporting of results. The threat to the reliability of data synthesis and reporting has been mitigated based on discussion and peer review of the extracted data by the researchers, having a structured template for data synthesis, and several steps where the scheme and process were refined and evaluated. Whilst we followed the guidelines from [9] to conduct the study, we had deviations from the ideal approaches based on the requirements of this research. We believe that the validity of the study is high, given the use of a systematic and recommended procedure and a pilot study to refine the scope of review.

7 Conclusion and Future Work

The goal of this Systematic Mapping Study (SMS) was to identify and analyze the published studies that reports techniques (e.g. methods, processes and modelling styles) to support any phase of Requirements Engineering (RE) process for robotic systems. The results of the classification and mapping of the existing research have been provided in terms of structured tables and illustrative figures aims to systematize and disseminate the knowledge about RE process for robotic systems domain. The taxonomical classification provides a holistic overview of the overlapping and distinct research themes and their sub-themes that emerged and progressed over considered timeframe (2005–2016). Furthermore, It is noteworthy this SMS complements the existing research in terms of the systematic reviews related to *SE for robotics* [24][12][13][25] and *RE for other domains* [14][15][16].

We can mention more than 60% of selected studies were performed on *industrial* environment. There were 23 studies published from 2009 to 2015, representing about 60% of all selected studies. *Health and care*, *industrial automation* and *generic robotic devices* are relevant application domain. The most research effort (about 80%) is concentered in a few *countries* such as USA, UK, Germany, Sweden, Spain, Italy and France. We noticed that most of studies (22, representing more than 50%) are concerned with defining *hardware and software requirements*, concomitantly. The results also indicate that, in general, *functional* and *non-functional* requirements are addressed by the studies. However, both requirement types were concomitantly addressed by less than half of the selected studies (about 37%) in this SMS. Regarding the five RE phases, we noted that each one received support by one or more techniques. In general, the *elicitation* and *specification* phases received greater attention from the academic community whereas *validation*, *analysis & negotiation* and *management* phases still require more attention. Furthermore, we have noticed only two studies provided fully support to RE process, implying the need to further investigate. Concluding, we detected that there is a great diversity of requirements modelling styles associated with each phase of RE process, being *models*, *textual requirements*, *scenario-based* and *goal-oriented* more frequent, in this order. Furthermore, we can highlight the results found in this research suggest that there are empirical evidences to state benefit on some techniques to perform RE phases in the development of robotic systems.

As future work, we intend to further investigate some of the research directions presented in this paper by elaborating new research questions on RE process for robotics systems. For example, we could look closely at the requirements modelling styles that support the various phases of the RE process. In addition, we can analyze more in depth which are the most relevant NFR related to each application domain, providing an especial catalogue of NFR. Moreover, we intend to continue this systematic review, extending the number of selected studies by query other relevant study databases (e.g. ACM and Compedex). We hope from the increase of the sample of studies, we can reconfirm the main findings of this SMS or even point out new ones. Finally, the results of this SMS benefit *(i) researchers* who are interested in knowing the state-of-the-art of RE process for robotics systems; and *(ii) practitioners* who may be interested in understanding the techniques for address any phase of RE process on robotic systems. Accordingly, we also hope to receive some feedbacks from the academic community and industrial practitioners to help us in future directions of research.

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