Institute of Mathematics and Computational Sciences - ICMC
University of São Paulo - USP

A Systematic Review on Service-Oriented Robotic Systems Development

Lucas Bueno Ruas Oliveira, Fernando Santos Osório
and Elisa Yumi Nakagawa

{buenolro, fosorio, elisa}@icmc.usp.br

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Abstract

The robotics is emerging as one of the most prominent research areas for next years. Robots have been supporting from simple domestic tasks to complex and dangerous activities, such as surgeries on human beings and underwater exploration. However, there are great challenges for robots to be developed in a more mature fashion. To face these challenges, researchers have investigated the use of Service-Oriented Architecture (SOA) aiming at providing better integration, flexibility and scalability to robotic systems. SOA is a architectural style which has been sucessfully applied in different domains. Many studies have reported researches involving the use of SOA during robotic systems development. Nevertheless, there are no studies providing an updated, broad and fair overview about the development of those systems. This report aims at presenting a detailed and analytical view about the systems, implementation technologies and software engineering guidelines developed for robots based on SOA. For this, we conducted a systematic review, which is a technique coming from Evidence-Based Software Engineering. As the main results, we observed a recent increase in the number of works reporting systems, technologies and development environments for SOA-based robots. Furthermore, we identified interesting and important perspectives for future research.

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Chapter 1

Introduction

The SOA has arisen as a successful architectural style to develop software systems. It has been recently focus of considerable attention not only of the industry but also of the academy. In SOA, software functionalities are packaged in independent, self-contained and well-defined modules, called services, which are the basis to compose more complex service-oriented systems (Papazoglou and Heuvel, 2007). SOA intends to contribute with low coupling systems, promoting reuse and productivity in software development (Papazoglou et al., 2008). Recently, the SOA characteristics have been attracting researchers and developers of different domains, even out of the traditionally web-based business applications. One of these domains is Robotics, which is claimed as one of the most prominent research areas in the next years. As reported by Tomatis (2011), many experts have predicted that the 21st century will be the century of robotics.

In fact, Robotics has drawn increasing attention in recent years. Robots are already in use worldwide as either simple domestic devices (iRobots, 2011) or complex autonomous agents (NASA, 2011). Despite its relevance, there are still great challenges for robotic systems to be developed productively and in a mature way. To mitigate these issues, SOA has been adopted as a solution for providing more flexible, reconfigurable and scalable robotic systems, so that they can be developed as a set of distributed and independent software modules (Berná-Martínez et al., 2006b). It may also facilitate integration of heterogeneous devices and different robotic systems (Chen et al., 2008). Therefore, companies and research groups have been investigating and supporting the development of service-oriented robotic systems, i.e., robotic systems based on SOA (Straszheim et al., 2011; Jackson, 2007). In this context, studies reporting the initiatives to develop such systems can be found (Jansen et al., 2006; Remy and Blake, 2011; Alnounou et al., 2010). Nevertheless, as far we are concerned, there is no complete and detailed view of the systems, implementation technologies, and software engineering guidelines developed for robots based on SOA. A study involving a broad and fair analysis of this research topic seems to be relevant, considering the impact that would have on the development of service-oriented robotic systems.

The main objective of this paper is to present a detailed panorama of how robotic systems based on SOA have been recently designed, implemented, and used. We have adopted and applied the systematic review technique (Kitchenham et al., 2004a), that allows for a complete and fair evaluation of a topic of interest. As the main results of our systematic review, we have observed that in the last years there has been an increase in the number of studies reporting on the development of robotic systems based on SOA, as well as a growing interest in technologies that support their development. These facts evidence a real interest by both academy and industry. Furthermore, this panorama makes it possible to identify interesting and important research topics for investigation.

The remainder of this paper is organized as follows. Chapter 2 presents an overview of topics related to this work. Chapter 3 describes the systematic review conducted and discuss its results. Chapter 4 discusses the threats to validity of the systematic review. Chapter 5 presents a mapping of the research area investigated. Finally, Chapter 6 presents our conclusion and future work.

Chapter 2

Background and Related Works

Since SOA, robotic systems and systematic review technique are basis of this work, in this chapter, we present ab overview about them.

2.1 Service-Oriented Architecture - SOA

SOA has been recently disseminated as a new, promising architectural style to organize software systems. It introduces the concept of business service (or simply service) as a fundamental unit to design, build, and compose service-oriented software systems (Papazoglou et al., 2008). A service usually provides business functionalities which are independent of the context and the state of other services (Papazoglou and Heuvel, 2007). For the services to work properly, SOA requires the establishment of mechanisms for the communication among services, or through a direct communication or using broker (i.e., a mediator among the services). Besides, to build service-oriented systems, a highly distributed communication and integration backbone is important. This functionality can be provided by the Enterprise Service Bus (ESB), which represents an integration platform to support a wide variety of communication patterns over multiple transport protocols and deliver value-added capabilities for the SOA applications (Papazoglou and Heuvel, 2007).

Through the composition of simple services, more complex service-oriented systems can be built in a more productive and agile way (Papazoglou and Heuvel, 2007). In other words, SOA aims at cooperation of low coupling services to create dynamic and flexible business processes. Service composition is therefore considered one of the most promising characteristics of SOA. In this context, concepts, such as service orchestration and service choreography (Peltz, 2003) are important. To ensure the quality and interoperability among services, contracts can be used as a formal agreement to specify the relation between a service and its clients, expressing each part's rights and obligations (Dai et al., 2007).

According to Kreger (2003), web services (WS-*) seem to be the preferred implementation technology to realize SOA. Based on open and pervasive standards and using infrastructures, such as HTTP (W3C, 2012b), SOAP (W3C, 2012c), and XML (W3C, 2012a), web services aim to maximize service sharing, reuse, and interoperability. Besides WS-* standards, a different type of service abstraction has appeared: Representational State Transfer (REST) (Fielding, 2000). REST is an emerging technology which rediscovers the original design principles of the World Wide Web (WWW) to provide a new abstraction for publishing information and giving remote access to application systems. Using REST, systems can be directly mapped to the interaction primitives found in the HTTP standard protocol, making it easy to publish existing Web applications as services by replacing HTML pages with data payloads formatted in XML (Pautasso, 2009).

2.2 Robotic Systems

Robots can play a key role in our lives in the near future (Alnounou et al., 2010). Nowadays, robots have already been used in different and important areas, such as in industry (Veiga et al., 2009), aware houses (Ha et al., 2005), hospitals (Waibel et al., 2011), and even spacial missions (NASA, 2011). In fact, there are numerous areas in which robots can be applied. However, there are still problems which the industry and robotics researchers should face to develop robotic systems in a mature and productive way. Furthermore, limitations, such as processing capability, storage, development flexibility, and knowledge acquisition are challenging topics in robotics. Aiming at solving these issues, researchers have considered using SOA as a basis for robotic systems development. It use would allow robots to be designed as a set of reusable functionalities which are platform-independent and physically distributed. The SOA architectural style has been used to support the interaction not only among robots (Majedi et al., 2008), but also between robots and their environments (Kim et al., 2005).

Due to the increasing number of studies on the development of service-oriented robotic systems, researches that investigate and provide an overview of this topic can already be found (Jansen et al., 2006; Remy and Blake, 2011; Alnounou et al., 2010). Jansen et al. (2006) provide an in-depth survey of the approaches that span robots use of the Web, such as information acquisition, query formation, and information delivery and management. In a similar context, Remy and Blake (2011) present a brief survey of some technologies available to develop robotic systems based on SOA. In a broader analysis, Alnounou et al. (2010) discuss the suitability of different architectural styles to develop robotic systems, including SOA. Although these studies have put forward an overview of the development of service-oriented robotic systems, they are based only in the authors' experience. Moreover, they have addressed only specific uses of SOA, not covering the area as a whole. To the best of our knowledge, there are no systematic studies which provide a broad, trustful and replicable assessment regarding the systems, implementation technologies and software engineering guidelines developed for robots based on SOA.

2.3 Systematic Review

It has been observed that as a research area matures, there is almost always an increase in the number of reports and results made available. During the study of a new knowledge area, researchers usually conduct a bibliographical review (almost always an informal review) to identify publications related to a specific subject. However, this type of review does not use a systematic approach and does not offer any support to avoid bias during the selection of the publications that will be analyzed. Thus, the use of mechanisms to summarize and provide overview about an area or topic of interest becomes important

(Petersen et al., 2008). In particular, systematic review has been widely investigated and adopted in the Evidence-Based Software Engineering (EBSE) Kitchenham et al. (2004b). A systematic review provides a comprehensive and systematic evaluation of research using a predefined search strategy to minimize bias (Kitchenham and Charters, 2007). In other words, it makes possible systematically to obtain literature review and it is used to summarize, assess, and interpret the relevance of all evidence related to a specific question, topic area, or phenomenon of interest. An individual evidence (for instance, a case study or an experimental study reported in a publication/paper) which contributes to a systematic review is called *primary study*, while the result of a systematic review is a *secondary study*. Systematic review has already been applied for different topics of interest, such as Software Architecture (Oliveira et al., 2010; Williams and Carver, 2010; de Boer and Farenhorst, 2008), Software Testing (Engstrom et al., 2010; Endo and Simao, 2010), Requirement Elicitation (Davis et al., 2006), and Robot Assisted Surgery (Shah et al., 2007). Considering its relevance, in this work we will use systematic review to explore the research area of service-oriented robotic systems.

Chapter 3

Systematic Review Application

In order to conduct this systematic review, we followed the process proposed by Kitchenham (2004). In short, this process presents three main phases: (i) Phase 1 - Planning: In this phase, the research objectives and the systematic review protocol are defined. The protocol constitutes a pre-determined plan that describes research questions and how the systematic review will be conducted; (ii) Phase 2 - Conduction: During this phase, primary studies are identified, selected, and evaluated according to the inclusion and exclusion criteria previously established. For each selected study, data are extracted and synthesized; and (iii) Phase 3 - Reporting: In this phase, a final report is organized and presented. The next sections present these three phases in details.

3.1 Phase 1 - Planning

In this phase, we established the systematic review protocol. For this, we specified: (i) research objectives; (ii) research questions, range, and specificity; (iii) sources selection criteria; (iv) studies definition; and (v) procedures for studies selection.

3.1.1 Research Objectives

The main objective of this systematic review is to identify primary studies that report the development of service-oriented robotic systems, i.e., robotic systems that are designed based on SOA. Furthermore, this review aims at obtaining a comprehensive overview of technologies and methodologies used to develop such systems.

3.1.2 Research Questions

Aiming at finding possibly all primary studies to understand and summarize evidences about the use of SOA in the development of robotic systems, the following research questions (RQ) were established:

- **RQ1:** How has service-orientation been applied to the development of robotic systems? This question aims to identify the abstraction level, such as sensors/actuators, actions or the whole robot, on which services have been developed;

- **RQ2:** What is the most common way of interaction among service-oriented robotic systems? The main objective of this question is to identify how services interact in the robotics domain. This interaction could be made, for example, between: sensor–robot, robot–robot, robot–back-end or robot–external services;

- **RQ3:** What implementation technology has been mostly used to develop service-oriented robotic systems? The aim is to verify which implementation technology, such as SOAP and REST, is mostly used to develop service-oriented robotic systems;

- **RQ4:** What are the development environments and tools that support the development of service-oriented robotic systems? The objective is to identify development environments and tools used to develop robotic systems based on SOA;

- **RQ5:** Is SOA applicable to all types of robots? This question aims at identifying if SOA is a viable solution for all robotic systems and their operational situation. Otherwise, in what area or context has SOA been mostly applied to robotic systems; and

- **RQ6:** How has Software Engineering been applied to the development of service-oriented robotic systems? This question aims at identifying the software engineering knowledgement, such as processes, activities, methods, and techniques used during the development of service-oriented robotic systems.

A well formulated research question is generally composed and analyzed according to different viewpoints, which define range and specificity. Thus, we have defined the PICO (Population, Intervention, Comparison and Outcomes) for our systematic review. Population identifies the population group observed by the intervention; Intervention refers to what will be observed in the context of the systematic review; Comparison defines what is compared in the context of the systematic review; finally, the intervention results are expressed by the Outcomes. The PICO of our systematic review is presented as follow:

- **Population:** Researchers and developers of robotic systems that make use or are interested in using SOA as a basis for the design of their systems;

- **Intervention:** The intervention of this systematic review is represented by service-oriented robotic systems, their projects, and the methodologies used during their development;

- **Comparison:** In our case, it is not applicable; and

- **Outcomes:** An overview of the studies proposed in the literature that report on the use of SOA during the development of robotic systems. We also expect to identify the domains for which these robots have been built, as well as the procedures, methods, and technologies that support their development.

3.1.3 Sources Selection

In order to establish the search strategy, we defined: source selection criteria; sources list; studies language; and keywords and their related terms:

- **Sources selection criteria:** Three types of sources were considered in this systematic review:
  - Publication databases: Aiming at establishing which publication database would be used to find the primary studies, we have adopted the following criteria (Dieste et al., 2009): *content update* (publications are regularly updated); *availability* (full text of the papers are available); *quality of results* (accuracy of the results obtained by the search); and *versatility export* (a mechanism to export the results of the search is available);
  - Related works: we also considered those studies cited as related works in the relevant primary studies found in the publication databases; and
  - Specialist: we have also considered studies suggested by a specialist of the robotics domain. Although the indication of studies by a specialist can be considered as bias, we have adopted this source aiming to not lose any important evidence.
- **Sources list:** The publication databases selected for our systematic review are shown in Table 3.1. According to Dybå et al. (2007), these databases are efficient to conduct systematic reviews in the context of Software Engineering. Furthermore, *Scopus* has been added, since it is considered the largest database of abstracts and citations (Kitchenham and Charters, 2007);

Table 3.1: Selected publication databases

Source	Location
ACM Digital Library	`www.portal.acm.org`
Compendex	`www.engineeringvillage.com`
IEEE Xplore	`www.ieeexplore.ieee.org`
ScienceDirect	`www.sciencedirect.com`
Scopus	`www.scopus.com`
Springer	`www.springerlink.com`
Web of Science	`www.isiknowledge.com`

- **Studies language:** Only primary studies written in English were considered in this systematic review. English was adopted because most of research in Computer Science have been reported in this language;
- **Keywords:** The main keywords were "*Service Oriented*" and "*Robot*", with the following related terms:
  - **Service Oriented:** "*Service-oriented*", "*Service based*", "*Service-based*", "*Service Orientation*" and "*SOA*";
  - **Robot:** "*Robotic*" and "*humanoid*".

It is worth mentioning that the acronym "*SOC*", which refers to the term "*Service-Oriented Computing*", has not been considered as related term. This decision was made based on the fact that this acronym also refers to other non-related terms, such as "*State of Charge*", "*Stochastic Optimal Control*", "*System-on-chip*", and "*Society*", causing a considerable increase in the number of primary studies to be evaluated. In fact, the keywords chosen must be simple enough to bring many results and, at the same time, rigorous enough to cover only the desired research topic; and

- **Search string:** We applied the boolean OR operator to link the main terms and their related terms. All these terms were combined using the boolean AND operator. Thus, the final search string was:

```
("Service Oriented" OR "Service-oriented" OR "Service Based" OR
        "Service-based" OR "Service Orientation" OR SOA)
            AND (Robot OR Robotic OR humanoid)
```

3.1.4 Studies Definition: Inclusion and Exclusion Criteria

Another important activity of the systematic review planning is to define the Inclusion Criteria (IC) and Exclusion Criteria (EC). These criteria make it possible to include primary studies that are relevant to answer the research questions and exclude studies that do not answer them. Thus, the inclusion criteria of our systematic review are:

- **IC1:** The primary study proposes or reports on the design and development of a service-oriented robotic system;
- **IC2:** The primary study proposes or reports on a new technology for developing service-oriented robotic systems; and
- **IC3:** The primary study proposes or reports on a process, method, technique, reference architecture or any software engineering guideline that supports either the design or the development of service-oriented robotic systems.

The exclusion criteria established are:

- **EC1:** The primary study reports on the development of a robotic systems without using SOA;
- **EC2:** The primary study presents contributions in areas other than Robotics;
- **EC3:** The primary study does not report on the design or development of service-oriented robotic system;
- **EC4:** The study is a previous version of a more complete study about the same research; and
- **EC5:** The primary study is a table of contents, short course description, tutorial, copyright form or summary of an event (e.g., a conference or a workshop).

3.1.5 Procedures for the Studies Selection

In our systematic review, the selection and evaluation of primary studies was be performed in three steps:

- **First selection:** Initially, the search string will be customized and applied to each publication databases, previously listed in Table 3.1. For this, the title, abstract and keywords of all primary studies available will be considered. As a result, a set of primary studies possibly related to the research topic will be obtained. Based on this set, the title and the abstract of each primary study will be read the inclusion and exclusion criteria will be applied. Thus, the study will be selected as relevant or not. The introduction and the conclusion sections of each primary study might also be considered when necessary. After this analysis, if a study has been selected, it will be read in full.

- **Second selection:** In this step, each primary study selected will be read in full and analyzed again according to inclusion and exclusion criteria. In addition, the related works cited by these studies will be evaluated intending to cover the whole research area. This additional selection might be a great source of evidence, since an included study often presents related works in the same research area. If the decision about the inclusion or exclusion of a study is not clear, this study will be analyzed by two reviewers. When a disagreement occurs, discussions will be conducted; and

- **Data Extraction and Synthesis Method:** In order to extract data, we plan to build data extraction tables related to each research question. These tables should synthesize results to facilitate the drawing of conclusions. To summarize and describe the set of data, statistical synthesis method and meta-analysis might be used.

3.2 Phase 2 - Conduction

Our systematic review was conducted by three people (a software engineering researcher, a robotics researcher, a systematic review specialist) from September/2011 to December/2011 and according to the systematic review protocol presented in Section 3.1. In this section, we describe the details of each conduction step.

3.2.1 First Selection

In this step, we adapted the generic search string defined in the protocol according to the specificity of each publication database. The selection of primary studies was then performed by searching for all primary studies that match the adapted search string. As a result, 619 studies were obtained. Once a primary study can be obtained in more than one database (or search engine), before starting reading we filtered the obtained studies, excluding those repeated. After filtering, 254 studies were obtained. To support the organization of the primary studies we used JabRef[1], an open source reference manager

[1] `http://jabref.sourceforge.net/`

system which allows storing information on the primary studies (for instance, title, authors, booktitle, and abstract), as well as set the exclusion/exclusion criteria applied to select each primary study. Details of the search conducted in each database are described as follow.

ACM Digital Library:

The search in the ACM Digital Library was performed on September 20 and six studies were obtained. Due to limitations of this database, the search string needed to be divided into two substrings. The first substring was designed to find studies whose abstract comprehends words that match the terms defined. As a result, five studies were obtained. In the second substring, the terms were searched for in the title of studies, which resulted in one study. The defined search strings are presented in Table 3.2. Right column (# PS) presents the number of studies obtained by each search string.

Table 3.2: Search strings and the number of studies in ACM Digital Library

Search string	# PS
(Abstract:(("Service Oriented" OR "Service-oriented" OR "Service Based" OR "Service-based" OR "Service Orientation" OR SOA) AND (Robot OR Robotic OR humanoid)))	5
(Title:(("Service Oriented" OR "Service-oriented" OR "Service Based" OR "Service-based" OR "Service Orientation" OR SOA) AND (Robot OR Robotic OR humanoid)))	1

It is worth noting that ACM Digital Library does not provide a functionality to export the abstract and the bibtex file of the obtained studies. However, we kept this database as a publication source, since it indexes a great amount of relevant studies.

Compendex:

The search in the Compendex was performed on September 20 and 192 studies were returned. The search was conducted in the abstract, title and keywords. The result was filtered by language, considering only studies written in English. The defined search string is presented in Table 3.3.

Table 3.3: Search strings and the number of studies in Compendex

((("Service Oriented" OR "Service-oriented" OR "Service Based" OR "Service-based" OR "Service Orientation" OR SOA) AND (Robot OR Robotic OR humanoid)) WN KY), English only

IEEE Xplore:

Similarly to ACM Digital Library database, the search string applied to IEEE Xplore needed to be splitted into two substrings, since it does not allow searching in the abstract and title in the same string. In the first string we performed the search considering the abstracts and 72 studies were obtained. Besides that, 22 studies were obtained in the search considering the titles of primary studies. The search was performed on September 20. The defined search strings are presented in Table 3.4. Right column (# PS) presents the number of studies obtained by each search string.

Table 3.4: Search strings and the number of studies in IEEE Xplore

Search string	# PS
("Abstract":"Service Oriented" OR "Abstract":"Service-oriented" OR "Abstract":"Service Based" OR "Abstract":"Service-based" OR "Abstract":"Service Orientation" OR "Abstract":SOA) AND ("Abstract":Robot OR "Abstract":Robotic OR "Abstract":humanoid))	77
(("Document Title":"Service Oriented" OR "Document Title": "Service-oriented" OR "Document Title":"Service Based" OR "Document Title":"Service-based" OR "Document Title": "Service Orientation" OR "Document Title":SOA) AND ("Document Title":Robot OR "Document Title":Robotic OR "Document Title":humanoid))	22

The studies retrieved by more than one search string were discarded, avoiding repetition. Thus, a total of 76 single primary studies were obtained.

ScienceDirect:

The search in the ScienceDirect was performed on 20 September. In this database, we searched for primary studies using the abstract, title, and keywords and total of four studies were retrieved. The defined search string is presented in Table 3.5.

Table 3.5: Search strings and the number of studies in ScienceDirect

TITLE-ABSTR-KEY(("Service Oriented" OR "Service-oriented" OR "Service Based" OR "Service-based" OR "Service Orientation" OR SOA) AND (Robot OR Robotic OR humanoid))

Scopus:

On Septembed 21 we performed the search in Scopus and 230 primary studies were retrieved. This was the publication source that returned the largest number of studies. It is important to highlight that Scopus is a search engine and indexes primary studies from other publication databases. On the other hand, this characteristic may cause an overlapping of studies, since we adopted other databases covered by Scopus. However, we decided to include databases covered by Scopus, because not all primary studies contained in those databases are indexed by this search engine. The defined search string is presented in Table 3.6.

Another important issue regarding Scopus is that it returns a considerable amount of conference proceedings and invited talk descriptions, which do not provide any evidence for the systematic review. A set of 27 conference descriptions and invited

Table 3.6: Search strings and the number of studies in Scopus

TITLE-ABS-KEY(("Service Oriented" OR "Service-oriented" OR "Service Based" OR "Service-based" OR "Service Orientation" OR SOA) AND (robot OR robotic OR humanoid))

talk descriptions was retrieved by Scopus, representing 11,7% of all studies obtained from this source.

Springer:

The search in Springer was conducted on September 20. Given the limitations of this database, the generic string needed to be divided into three complementary substrings. The defined search strings are presented in Table 3.7. Right column (# PS) presents the number of studies obtained by each search string.

Table 3.7: Search strings and the number of studies in Springer

Search string	# PS
ab:(("Service Oriented" or "Service-oriented") and (Robot or Robotic or humanoid))	9
ab:(("Service Based" or "Service-based") and (Robot or Robotic or humanoid))	1
ab:(("Service Orientation" or SOA) and (Robot or Robotic or humanoid))	3

Since the use of complementary strings may retrieve repeated studies, we filtered the search result and two repeated studies were excluded. Thus, a total of 11 primary studies were obtained.

Web of Science:

The search in Web of Science was performed on September 21 and a set of 80 primary studies was obtained. Since this database does not allow searching by abstract, the search was performed using the title and 'Topic'. Those fields were selected to obtain the same breadth of search used in other databases which we considered in our systematic review. The defined search string is presented in Table 3.8.

Table 3.8: Search strings and the number of studies in Web of Science

Topic=(("Service Oriented" OR "Service-oriented" OR "Service Based" OR "Service-based" OR "Service Orientation" OR SOA) AND (Robot OR Robotic OR humanoid)) OR Title=(("Service Oriented" OR "Service-oriented" OR "Service Based" OR "Service-based" OR "Service Orientation" OR SOA) AND (Robot OR Robotic OR humanoid))

After reading the title, abstract and, when necessary, the introduction of each primary study obtained, 72 studies were selected to be read in full. Table 3.9 presents the distribution of criteria applied to each primary study evaluated during the first selection.

The columns #PS indicate the number of primary studies classified in each inclusion and exclusion criterion, respectively. Similarly, the columns %PS indicate the percentage of primary studies classified in each inclusion and exclusion criterion. It is important to note that some primary studies were classified based on more than one criterion.

Table 3.9: Criteria applied during the first selection

Inclusion criteria			Exclusion criteria		
IC	# PS	% PS	EC	# PS	% PS
IC1	52	20.47%	EC1	55	21.65%
IC2	16	6.30%	EC2	84	33.07%
IC3	6	2.36%	EC3	19	7.48%
			EC4	–	–
			EC5	43	16.92%
TOTAL	72	28.35%	TOTAL	182	71.65%

In the first selection, most of the studies were included by IC1. Besides, EC2 was the most applied exclusion criterion. No study was excluded by EC4, since a full reading is necessary to determine if a primary study is a previous or less complete version of a same research.

Table 3.10 summarizes the total of primary studies obtained in each database, the number of studies included, the number of studies included exclusively by one database, the precision rate[2], and the rate index[3]. For instance, from IEEE Xplore, we obtained 76 studies. After the application of selection criteria, 39 studies were selected. Thus, the precision rate was 0.513% (i.e., 39/76) and the rate index was 0.541% (i.e., 39/72).

Table 3.10: Search sources and primary studies obtained and included after the first step

Database	Obtained	Included	Exclusive	Precision Index	Rate Index
ACM Digital Library	6	0	0	0	0
Compendex	192	63	0	0.326	0.875
IEEE Xplore	76	39	1	0.513	0.541
Science Direct	4	2	0	0.500	0.026
Scopus	230	67	6	0.291	0.930
Springer	11	6	2	0.545	0.083
Web of Science	80	41	1	0.512	0.569

It is important to observe that Scopus was the most efficient source, since it provided 93.00% (0.930 of rate index) of all included primary studies in Step 1. Otherwise, ACM Digital Library did not contribute with any relevant primary study to our systematic review. In addition, we can point out that all studies obtained in the Compendex were also obtained in Scopus, i.e, there was an overlap of Scopus on the studies indexed by Compendex. The Science Direct contributed with only two primary studies, which were obtained by other included databases, such as Scopus. Thus, for this systematic review, only Scopus, IEEE Xplore, Web of Science, and Springer would be enough to obtain all studies included in the end of this first step.

[2]Ratio between the total of included studies of a database and the total of primary studies obtained by this database

[3]Ratio between the total of included studies of a database and the total of primary studies obtained.

3.2.2 Second Selection

In Step 2, we selected the primary studies through the full reading and the application of the inclusion and exclusion criteria. During this step, five studies were not available (Cesetti et al., 2010a; Crow et al., 2007; Mikulski and Szkodny, 2011; Oswald et al., 2007; Veiga and Pires, 2008) and two studies were written in Chinese (Yin and Yan, 2010; Cai et al., 2010). As previously stated, only papers written in English were considered in our systematic review. Thus, 65 primary studies were evaluated. After the criteria application 36 primary studies were included. We also evaluated other two studies suggested by the specialist (Waibel et al., 2011; Lindemuth et al., 2011). Besides, we looked for the related work (i.e., the main references) of each primary study read in full. Among all related works evaluated, we selected one relevant primary study (Arumugam et al., 2010), which had not been previously identified. This study was found while we were evaluating the paper written by Remy and Blake (2011). As a result, a set of 39 studies was selected as the most relevant to our systematic review. Theses studies were deeply analyzed and their data were extracted in Step 3.

Table 3.11 presents the 39 primary studies included. Column "Type" indicates if the primary study was published in a Journal Article (JA), Technical Report (TR) or in a Conference Paper (CP). Column "Criteria" points out the criteria used to include each study. . Almost all studies were included by the Inclusion Criteria 1 (IC1), i.e., the primary study reports on the design and development of a service-oriented robotic system. Column "Sources" shows the sources where each study was obtained. In this column, we adopted the following abbreviations: Compendex (Co), IEEE Xplore (IE), Science Direct (SD), Scopus (Sc), Springer (Sp), and Web of Science (WS)

Figure 3.1 shows the number of primary studies published per year. It is important to note that only primary studies available until the end of September/2011 were considered in our systematic review. Furthermore, is it observed an increase in the number of primary studies related to the use of SOA in the robotic systems development, indicating a great interest in this research topic. On the other hand, the number of studies on the development of technological infrastructure (i.e., those included by IC2) and software engineering guidelines (i.e., those included by IC3) has not grown in the same way.

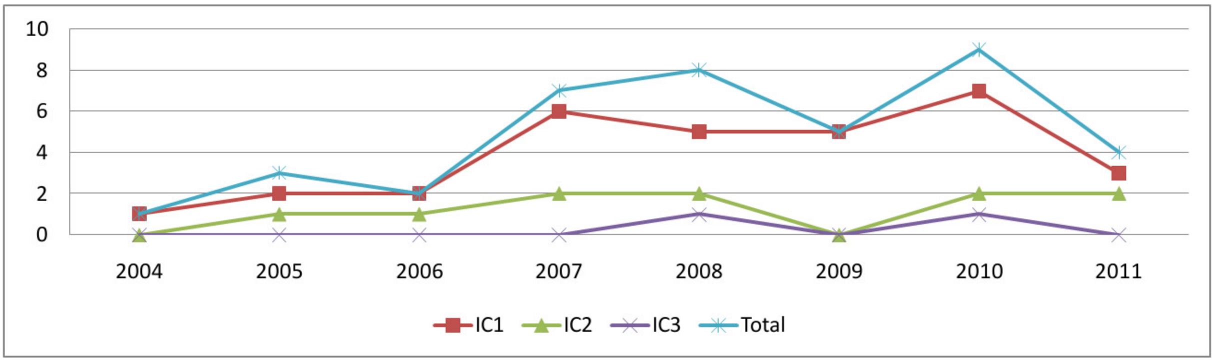

Figure 3.1: Primary studies published throughout the years

Table 3.11: Included primary studies

ID	Author	Year	Type	Criteria	Sources
S1	Ahn et al. (2006b)	2006	CP	IC1, IC2	WS, Sc, IE, Co
S2	Ambroszkiewicz et al. (2010)	2010	JA	IC1, IC2	WS, Sc, Co
S3	Amoretti et al. (2007)	2007	CP	IC1	WS, Sc, IE, Co
S4	Arumugam et al. (2010)	2010	CP	IC2	E9
S5	Awaad et al. (2008)	2008	CP	IC2	WS, Sp, Sc, Co
S6	Barbosa et al. (2009)	2009	CP	IC1	WS, Sc, IE, Co
S7	Berná-Martínez and Maciá-Pérez (2010)	2010	CP	IC3	Sc, IE, Co
S8	Berná-Martínez et al. (2006b)	2006	CP	IC1	Sc, IE, Co
S9	Blake et al. (2011)	2011	JA	IC1, IC2	Sc, IE, Co
S10	Cepeda et al. (2010)	2010	CP	IC2	Sc, IE, Co
S11	Cesetti et al. (2010b)	2010	CP	IC1	Sc, IE, Co
S12	Chen and Bai (2008)	2008	CP	IC1	Sc, IE, Co
S13	Chen et al. (2008)	2008	CP	IC1	WS, Sc, IE, Co
S14	Chen et al. (2010)	2010	CP	IC1	Sc, IE, Co
S15	Chen et al. (2009)	2009	CP	IC1	WS, IE
S16	Coelho et al. (2007)	2007	CP	IC1	WS, Sc, IE, Co
S17	Edwards et al. (2010)	2010	CP	IC1	Sc, Co
S18	Ha et al. (2005)	2005	CP	IC1	WS, Sc, IE, Co
S19	Hongxing et al. (2008)	2008	CP	IC1	Sc, IE, Co
S20	Kim et al. (2005)	2005	CP	IC1	Sc
S21	Kononchuk et al. (2011)	2011	CP	IC2	Sp, Sc, Co
S22	Lee et al. (2008b)	2008	CP	IC1	WS, Sc, IE, Co
S23	Lee et al. (2004)	2004	JA	IC1	WS, Sc, IE, Co
S24	Lindemuth et al. (2011)	2011	JA	IC1	Specialist
S25	Majedi et al. (2008)	2008	CP	IC3	WS, Sc, IE, Co
S26	Mokarizadeh et al. (2009)	2009	CP	IC1	Sc
S27	Narita et al. (2005)	2005	CP	IC2	Sc
S28	Pinto et al. (2010)	2010	CP	IC1	Sc, Co
S29	Prüter et al. (2009)	2009	CP	IC1	WS, Sc, IE, Co
S30	Rahman et al. (2007)	2007	JA	IC1, IC2	WS, Sc, Co
S31	Scotti et al. (2010)	2010	CP	IC1	Sc, Co
S32	Tikanmaki and Roning (2007)	2007	CP	IC2	Sc, Co
S33	Trifa et al. (2008)	2008	CP	IC1	Sc, Co
S34	Tsai et al. (2008c)	2008	JA	IC2	WS, Sc, SD, Co
S35	Veiga et al. (2009)	2009	JA	IC1	WS, SD, Sc, Co
S36	Waibel et al. (2011)	2011	JA	IC1	Specialist
S37	Walter et al. (2007)	2007	CP	IC1	WS, Sc, IE, Co
S38	Wu et al. (2007)	2007	JA	IC1	WS, Sc, Co
S39	Yeom (2007)	2007	CP	IC1	WS, Sp, Sc, Co

Table 3.12 lists the studies excluded by EC4, i.e., they have the same scientific contribution of another primary study already included. Although these studies are related to our research, they were not included to avoid computing the same evidence twice. However, they will be considered in the meta-analysis presented in Chapter 4. Column "RS" presents the ID of the included study (listed in Table 3.11) related to each excluded study.

Table 3.12: Primary studies excluded by EC4

ID	Author	Year	Type	RS	Sources
E1	Ahn et al. (2006a)	2006	CP	S1	WS, Sc, IE, Co
E2	Ambroszkiewicz et al. (2007)	2007	TR	S2	Sc, Co
E3	Berná-Martínez et al. (2006a)	2006	CP	S8	WS, Sc, Co
E4	Du et al. (2011)	2011	CP	S14	Sc, IE, Co
E5	Kim et al. (2006)	2006	CP	S20	WS, Sc, IE, Co
E6	Lee et al. (2008a)	2008	CP	S22	WS, Sc, IE, Co
E7	Lee et al. (2008c)	2008	CP	S22	WS, Sc, IE, Co
E8	Lee et al. (2003)	2003	CP	S23	WS, Sc, IE, Co
E9	Remy and Blake (2011)	2011	JA	S9	WS, Sc, IE, Co
E10	Tsai et al. (2008a)	2008	CP	S34	WS, Sc, SD, Co
E11	Tsai et al. (2008b)	2008	CP	S34	WS, Sc, SD, Co
E12	Veiga et al. (2007)	2007	CP	S35	Sc, Co
E13	Wu et al. (2006)	2006	CP	S38	Sc, Co

Similarly to the analysis performed in Step 2, we summarized the information regarding each database after the final selection. Table 3.13 presents the total of the primary studies obtained in each database, the number of studies included, the number of studies included exclusively by one database, the precision rate, and the rate index. Scopus was by far the most effective search engine for our systematic review, indexing 35 of 36 primary studies obtained from the publication sources. Only primary study S15 was not be obtained from this search engine, as it was indexed by IEEE Xplore and Web of Science. Furthermore, as previously stated, we strongly discourage the use of Compendex together with Scopus. In spite of the good Compendex rate index, all studies obtained from this publication database were also indexed by Scopus.

Table 3.13: Search sources and primary studies obtained and included after full reading

Database	Obtained	Included	Exclusive	Precision Index	Rate Index
Compendex	192	32	0	0.167	0.889
IEEE Xplore	76	20	1	0.263	0.555
Science Direct	4	2	0	0.500	0.055
Scopus	230	35	6	0.152	0.972
Springer	11	3	2	0.273	0.083
Web of Science	80	19	1	0.238	0.528

3.3 Phase 3 - Reporting

In this last phase, we present analytical results of our systematic review. They are based on the data extraction performed in the previous phase. Table 3.14 summarizes the objective of each primary study. In the following sections, we present and discuss the answers for each research question.

Table 3.14: Short description of the objective of each primary study

ID	Objective of the Primary Study
S1	Proposition and use of the UPnP SDK for developing service-oriented robots
S2	Proposal of an environment, description language and protocols to automate the accomplishment of open heterogeneous multi-robot systems
S3	Discussion of a conceptual framework to develop peer-to-peer robotic systems
S4	Definition of a software framework to support the use of cloud computing in robotics
S5	Implementation of a framework and a simulation environment for SOA-based robots
S6	Description of a testbed which has cameras and robots working cooperatively as services
S7	Proposal of a model of integration and management for robotic systems development
S8	Use of sensors and actuators as smart devices for building service-oriented robots
S9	Discussion of SOA usage in the robot development and implementation of a case study
S10	Report the use of MSRS for developing service-oriented robotic systems
S11	Implementation of SOA-based industrial robotic system using the MSRS
S12	Presentation of SOA-based robot concepts and design of two case studies
S13	Design and implementation of a security robot using SOA
S14	Report on the design and implementation of robot as a service in cloud computing
S15	Provision of an insight about the SOC and event-driven paradigm application in robotics
S16	Proposal of a Web Lab built for remote experiments in the field of mobile robotics
S17	Proposal of a framework for integrating robots using the web
S18	Design of a ubiquitous architecture that controls devices and robots in an aware house
S19	Discussion of a middleware that supports the development of service-oriented robots
S20	Use of web services information to support control decisions of robotic systems
S21	Description of a protocol for service-oriented robotic system communication
S22	Use of the SOA to provide more intelligence to robots through external services
S23	Proposal of a service-based architecture for distributed multi-robot interactions
S24	Report on the use of a SOA-based architecture for implementing a marsupial robot team
S25	Design of a SOA-based architectural model for multiple robots interaction
S26	Description of a SOA-based architecture for robot swarms coordination
S27	Proposal of the RoboLink protocol to improve the service reliability among robots
S28	Report on the use of services for developing sensors and unmanned vehicles.
S29	Design of a REST-based architecture for industrial embedded devices, including robots
S30	Proposal of a framework for designing service-oriented robotic systems
S31	Implementation of SLAM algorithm using the SOA and MSRS
S32	Proposal of a Property Service architecture for creating distributed software systems
S33	Implementation of a system suited to support heterogeneous robotic swarms
S34	Design of an ontology-based framework built on MSRS
S35	Design and analyze of the adaptability of SOA-based systems to industrial robotic cells
S36	Discussion of the use of robots in cloud computing
S37	Proposal of a SOA-based infrastructure for distributed acquisition and fusion of sensors
S38	Report on the SOA-based control development of an industrial arm in a production line
S39	Design of a binding architecture for low-level robotic services

3.3.1 RQ1 - Research Question 1

This research question investigates how SOA has been applied during the development of service-oriented robotic systems. Four different categories of services were considered: (i) Sensors and Actuators; (ii) Tasks and Activities; (iii) Knowledge and Algorithms, and (iv)

Whole Robot. Category Sensors and Actuators indicates that services have been applied at the lowest level of the robot infrastructure, i.e., each sensor or actuator is controlled and provides information as an independent service. The second category, Tasks and Activities, means that services are expressed as functionalities, such as monitoring, gaming, seeking and object manipulation. Strategies of localization, path-following algorithms, fusion of sensors approaches, and knowledge acquisition through the web were considered examples of the third category (Knowledge and Algorithms). Category (iv) indicates the studies whose design have considered the whole robot as a single service. In these studies, the use of SOA is more related to the tele-operation (remote operation) of robots. Table 3.15 summarizes these categories and presents the total of primary studies that address each of them. Column "Primary Studies" indicates the studies that addressed each of these categories.

Table 3.15: Service development approaches in SOA-based robotic systems

Abstraction level	Total	Percentage	Primary Studies
Sensors and Actuators	20	51.28%	S4, S7, S8, S9, S10, S11, S12, S13, S14, S15, S17, S19, S21, S23, S28, S31, S32, S34, S35, S37
Tasks and Activities	18	46.15%	S1, S2, S3, S5, S7, S11, S13, S14, S16, S17, S23, S26, S27, S28, S31, S33, S34, S36
Knowledge and Algorithms	14	35.90%	S4, S5, S7, S8, S9, S11, S15, S20, S21, S22, S31, S34, S36, S37
Whole Robot	19	48.72%	S1, S3, S4, S6, S12, S14, S16, S18, S20, S23, S24, S25, S27, S29, S30, S32, S33, S38, S39

There is no clear predominance of a single development approach of SOA in robotics. The application of SOA may bring to robotic system developers the so-claimed platform independence, allowing a better integration among off-the-shelf sensors and actuators (Chen et al., 2008; Berná-Martínez and Maciá-Pérez, 2010; Hongxing et al., 2008; Veiga et al., 2009). This is a central development issue for the productive design of integrable robots. Moreover, SOA provides a better abstraction for functionalities offered by robots (Trifa et al., 2008; Tsai et al., 2008c; Mokarizadeh et al., 2009; Chen et al., 2010). The abstraction ability allows robots to hide their implementation details and facilitates the development of a more complete and collaborative behavior. Although the abstraction level related to knowledge and algorithms has been reported only in 35.90% of the studies, this seems a prominent strategy to provide more processing power and knowledge for robotic systems. Using SOA, demanding algorithms such as SLAM (Strasdat et al., 2010) and Q-Learning (Watkins and Dayan, 1992) may be executed in a distributed way, improving the performance and processing capabilities of robots (Scotti et al., 2010; Waibel et al., 2011). In addition, approaches that use web services as a source for obtaining external knowledge may bring a myriad of new possibilities in the robotics field , such those presented in studies S9 and S20.

The use of the WWW as a source of knowledge for robots is an emerging research topic. The IEEE Robotics Automation Magazine has just published an entire edition regarding web-enabled robots able to use the web (Corke, 2011). In this special issue, both natural language processing and web services were used to obtain relevant data from the web. Studies that have used natural language, such as those proposed by Mozos et al. (2011); Ciocarlie et al. (2011); Tenorth et al. (2011); Roggen et al. (2011), although important, were not included in this review, since they do not make use of SOA.

3.3.2 RQ2 - Research Question 2

RQ2 refers to the interactions among services in robotic systems, i.e., this question investigates the most common ways by which services interact inside and outside a robot in a robotic environment. Based on the selected primary studies, we have identified five ways of interaction in a service-oriented robotic system: (i) interaction of robot control with its sensors and actuators (Robot to Device); (ii) interaction of robot with other robots (Robot to Robot); (iii) interaction of robot with a computer back-end[4] (Robot to Back-end); (iv) the robot accesses external services, i.e., services which are out of its working environment (Robot to ES); and the robot interacts with other environment devices, such as electronic doors, light and temperature controller (Robot to Environment). Table 3.16 shows the ways of interaction addressed by the primary studies.

Table 3.16: Ways of interaction among services in SOA-based robots

Ways of Interaction	Total	Percentage	Primary studies
Robot to Device	14	35.90%	S1, S7, S8, S9, S10, S11, S12, S13, S14, S15, S17, S31, S34, S35
Robot to Robot	8	20.51%	S3, S10, S14, S21, S23, S24, S27, S30
Robot to Back-end	36	92.30%	S1, S2, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S15, S16, S17, S18, S19, S20, S21, S23, S24, S25, S26, S27, S28, S29, S30, S31, S32, S33, S34, S35, S36, S37, S38, S39
Robot to ES	4	10.26%	S9, S20, S22, S36
Robot to Environment	4	10.26%	S15, S18, S20, S23

Most of the robotic systems developed (corresponding to 92.30%) is supported or depends on a computer back-end. It is due to the fact that most of the available robotic infrastructure needs a server which provides the robots as services. Most robots developed in those primary studies are unable to provide their functionalities directly to consumers. Moreover, robots often use the back-end as an alternative to increase their processing capacity. The second most common way of interaction is between the robot control and its devices (i.e., 35.90%). We have also identified studies (10.26%) which investigate the connection between the robot and external services. Those services are used to support robots to make more intelligent decisions (Kim et al., 2005; Lee et al., 2008b; Blake et al., 2011). Furthermore, studies that use SOA to integrate robots with elements of the environment, like in a smart house (S18 and S20), have also been found. Therefore, it is observed that robots are still dependent on external infrastructures to be able to interact as services or use them. Otherwise, the dependency tends to decrease with the improvement robots hardware capabilities.

[4] In this report we considered a computer back-end as computer that remotely supports the processing, the data storage, or the interaction among robots.

3.3.3 RQ3 - Research Question 3

RQ3 addresses the technologies used to implement service-oriented robotic systems. In this research question, we considered the possible protocols, programing languages and frameworks that have been supporting the development of robots based on SOA. Some of these technologies were not initially designed to develop robots as a service or a set of services. However, they were used as innovative initiatives for providing robots according to SOA. Table 3.17 lists all technologies used to implement service-oriented robotic systems. Notice that the technologies presented here might not be classified on a same abstraction level.

Table 3.17: Languages and protocols for the development of service-oriented robotic systems

Implementation technology	Total	Percentage	Primary studies
WS-* (Erl, 2005)	17	43.59%	S3, S7, S8, S9, S10, S11, S12, S14, S15, S16, S18, S20, S22, S25, S26, S38, S39
REST (Fielding, 2000)	11	28.21%	S10, S11, S12, S14, S15, S17, S28, S29, S31, S34, S36
CORBA (Vinoski, 1997)	2	5.13%	S19, S37
UPnP (UPnP Forum, 2012)	3	7.69%	S1, S35, S39
JINI (Waldo, 1999)	1	2.56%	S23
Simple XML	2	5.13%	S2, S6
MeRMaID	1	2.56%	S6
Entish	1	2.56%	S2
RoboCoP	1	2.56%	S21
RoboLink	1	2.56%	S27
Property	1	2.56%	S32
SENORA	1	2.56%	S30
XPERSIF (Awaad, 2008)	1	2.56%	S5
DNR	4	10.26%	S4, S13, S24, S31

Regarding this research question, there is a predominance of the use of web service standards (i.e., WS-*), with 43.59% of the studies, and REST with 28.21%. Together, they represent more than seven of each ten robots developed. Besides, studies that have adapted UPnP (7.69%) and CORBA (5.13%) have also been developed. Although other technologies have also been found, they seem isolated initiatives used only by their authors (for example, S2, S6, S21, S27, S30 and S32). Studies that do not report on the use of any technology are listed in category DNR. Therefore, it is possible to observe that languages or protocols widely accepted in commercial software systems (WS-* and REST) were more used in robotics, instead those specifically designed to fit the robots needs. Although these commercial languages do not ensure aspects such as the message size and real-time constraints, they are easier to be integrated to other types of services and are most widely accepted.

3.3.4 RQ4 - Research Question 4

This research question investigates the environments that have been supporting the development of service-oriented robotic systems. Development environments are recognized as important tools which provide different functionalities to the implementation of service-oriented robotic systems. When associated to simulators, these environments can reduce the cost of a project, since the major part of a robotic system can be developed without physical devices. Table 3.18 lists the development environments that have been used to design service-oriented robotic systems.

Table 3.18: Development environments used to develop service-oriented robotic systems

Development environment	Total	Percentage	Primary studies
MSRS (Jackson, 2007)	7	17.95%	S10, S11, S12, S14, S15, S31, S34
ROS (Straszheim et al., 2011)	3	7.69%	S4, S9, S36
Player/Stage (Gerkey et al., 2003)	2	5.13%	S3, S17
LEGO Mindstorm (LEGO, 2012)	1	2.56%	S8
XPERSim (Awaad, 2008)	1	2.56%	S5
YARP (Metta, 2006)	1	2.56%	S6
Own Environment	2	5.13%	S20, S22
DNR	22	56.41%	S1, S2, S7, S13, S16, S18, S19, S21, S23, S24, S25, S26, S27, S28, S29, S30, S32, S33, S35, S37, S38, S39

Despite their importance, more than a half of the service-oriented robotic systems do not report the use of development environments. Among the development environments, the Microsoft Robotic Studio (MSRS) Jackson (2007) was identified as the most relevant environment available thus far. It is a platform designed specifically to the development of robots based on SOA. This environment is recognized as landmark of service-oriented robotic systems development and has been cited by almost all authors after 2007. However, there has been an increasing interest in the recent Robotic Operating System (ROS) environment Straszheim et al. (2011). Like MSRS, ROS is specifically designed to support the development of service-oriented robotic systems. Although ROS has been less addressed than MSRS, (probably because this environment is just arising), we believe it will be largely used in the next years. ROS is an open source environment free for commercial and research use. Other environments, such as the well known Lego Mindstorm LEGO (2012) and Player/Stage Gerkey et al. (2003) have been adapted to support development and simulation in some studies (S3, S8 and S17). Furthermore, studies that propose own environments can also be found (S20 and S22).

3.3.5 RQ5 - Research Question 5

This research question investigates whether SOA architectural style fits any type of robotic system. For this, we looked for characteristics which could influence the suitability of SOA for developing robotic systems, such the environment and the robot type. Moreover, we investigated the context in which service-oriented robotic systems had been applied. Table 3.19 shows the characteristics addressed by each primary study. Column "Domain" presents the areas of service-oriented robotic systems reported in the primary studies.

Column “Application” classifies the studies according to their purpose of use, i.e., for academy or industry. Column “Environment” presents if the service-oriented robotic system was developed for indoor or outdoor environments. In column “Class”, we classify a robot, according to its mobility, as ground mobile, aquatic, aerial, and non-mobile. Finally, in column “Type” we specify multiplicity in which service-oriented robots have been developed. Three levels of cardinality were considered: single robot, multiple robots, and robot swarms.

Notice that most of service-oriented robots have been developed with a generic purpose (56.41%), for academy (92.30%), in indoor environments (92.30%), and as ground mobile (79.48%). Studies that present generic purpose are those that regard more to the robot development and technologies used than a possible application domain. Furthermore, these studies have investigated the suitability of SOA for the development of both single and multiple robotic systems. We have also found studies that applied SOA to coordinate and control swarm of robots (studies S26 and S33). We believe that the predominance of the indoor and ground mobile (including non-mobile) robots can be related to physical limitations of the networks. In fact, this result seems coherent, since the availability, reliability, and management of wireless networks are still a challenging topic in robotics. Another important fact to be observed is the emerging interest in providing a robot as a resource in cloud computing (studies S4, S14 and 36). The use of cloud computing in robotics is quite recent and immature, but it seems to be a prominent research topic in the future. Initiatives that aim to provide robot capabilities as services are already available (van de Molengraft, 2011; RobotShop, 2011).

3.3.6 RQ6 - Research Question 6

In this research question we are looking for studies which propose software engineering knowledge to design and implement service-oriented robotic systems. As the development of new types of software systems, the design of service-based robots requires software engineering guidelines to become mature and more productive. Nevertheless, there is a lack of guidelines that support the development process of service-oriented robotic systems. We have found only two studies which propose models to design service-based robots. Study S7 proposed a SOA-based integration model for robotic devices. The design of this model was inspired on the human beings regulatory system. In study S25, the authors propose a generic service-oriented architectural model which can be applied for various classes of pervasive computing applications, including robotics. Apart from theses studies, no other guideline could be found. Thus, there is a need for software processes, methods, techniques, metrics, reference architectures, and reference models which support the development of service-based robots. It is important to highlight that we have not considered concrete architectures of service-oriented robotic systems as a software engineering guideline, since they are not applicable sometimes to the development of other robotic systems.

Table 3.19: Main characteristics of service-oriented robotic systems

ID	Domain	Application	Environment	Class	Type
S1	Generic	Academy	Indoor	Ground mobile	Single
S2	Generic	Academy	Indoor	Ground mobile	Multiple
S3	Generic	Academy	Indoor	Ground mobile	Multiple
S4	Cloud	Academy	Indoor	Ground mobile	Multiple
S5	Generic	Academy	Indoor	Ground mobile	Single
S6	Monitoring	Academy	Indoor	Ground mobile	Multiple
S7	Generic	Academy	Indoor	Ground mobile	Single
S8	Generic	Academy	Indoor	Ground mobile	Single
S9	Generic	Academy	Indoor	Non-Mobile	Single
S10	Generic	Academy	Indoor	Ground mobile	Multiple
S11	Manufacturing	Industry	Indoor	Ground mobile	Single
S12	Generic	Academy	Indoor	Ground mobile	Multiple
S13	Monitoring	Academy	Indoor	Ground mobile	Multiple
S14	Cloud	Academy	Indoor	Ground mobile	Multiple
S15	Generic	Academy	Indoor	Ground mobile	Multiple
S16	Education	Academy	Indoor	Ground mobile	Multiple
S17	Generic	Academy	Indoor	Ground mobile	Multiple
S18	Ubiquitous	Academy	Indoor	Ground mobile	Single
S19	Generic	Academy	Indoor	Ground mobile	Single
S20	Ubiquitous	Academy	Indoor	Non-Mobile	Single
S21	Education	Academy	Indoor	Ground mobile	Multiple
S22	Generic	Academy	Indoor	Non-Mobile	Single
S23	Generic	Academy	Indoor	Ground mobile	Multiple
S24	Monitoring	Academy	Outdoor	Aerial/Aquatic	Multiple
S25	Generic	Academy	Indoor	Ground mobile	Multiple
S26	Generic	Academy	Indoor	Ground mobile	Swarm
S27	Generic	Academy	Indoor	Ground mobile	Multiple
S28	Monitoring	Academy	Outdoor	Aquatic	Multiple
S29	Automation	Both	Indoor	Ground mobile	Multiple
S30	Generic	Academy	Indoor	Ground mobile	Multiple
S31	Generic	Both	Indoor	Ground mobile	Single
S32	Generic	Academy	Indoor	Ground mobile	Multiple
S33	Generic	Academy	Indoor	Ground mobile	Swarm
S34	Gaming	Academy	Indoor	Ground mobile	Multiple
S35	Manufacturing	Industry	Indoor	Non-Mobile	Single
S36	Cloud	Academy	Indoor	Ground mobile	Multiple
S37	Pipe inspection	Academy	Outdoor	Aquatic	Single
S38	Manufacturing	Industry	Indoor	Non-Mobile	Multiple
S39	Generic	Academy	Indoor	Ground mobile	Single

Chapter 4

Threats to Validity

The main threats identified to the validity of this systematic review are described as follows:

Missing of important primary studies:

The search for software systems, technologies, and software engineering guidelines in the field of service-based robots was conducted in several publication databases and search engines. According to Dybå et al. (2007) and Kitchenham and Charters (2007), the publication databases that we have used are the most relevant sources. Aiming at not missing any important evidence, we also considered the specialist suggestion and the related works which were presented in the reference list of the primary studies that we have selected. In addition, no limit was placed on the date of publications. During the search, conference papers, journals, and technical reports were also considered. In spite of our effort to included all relevant evidence in this research, it is possible that primary studies were missed;

Reviewers reliability:

In this systematic review, all reviewers are researchers in the Software Engineering and Robotics areas. Furthermore, none of the robotic systems, implementation technologies or software engineering guidelines were developed by our research group or researchers related to us. Therefore, we are not aware of any bias we may have introduced during the analyses. However, it might be possible that the conclusion about the studies evaluated have been influenced by the opinion of the reviewers;

Specialist suggestion:

Apart from the publication databases, we have considered primary studies suggested by a specialist. We believe that this suggestions has not introduces a bias, since none of the studies considered had been written by our specialist and he/she has never worked in any research developed by the authors of the suggested studies. However, it might be possible that the papers suggestion has been influenced by some previous experience or particular knowledgement;

Data extraction:

Another threat to this review refers to how the data were extracted from the primary studies, since not all the information were obvious to answer the research questions and some data had to be interpreted. In order to ensure the validity of this systematic review, other sources of information were analyzed, i.e., technical reports, web sites, and manuals, in addition to the primary studies analyzed. Furthermore, in the event of a disagreement between the reviewers, a discussion was conducted to ensure that a full agreement was reached; and

Quality assessment:

Since the goal of this systematic review was to identify all available systems, implementation technologies, and software engineering guidelines for SOA-based robots, no quality assessment was performed, as it might restrict the number of primary studies included. We agree that a quality assessment can provide more insights and explanations to the conclusion of this review. Thus, they should be included in a future version of the study.

As it can be observed, we have concerned with the validity of results of our systematic review. In particular, we have dedicated special effort to completely cover this research area as impartial as possible.

Chapter 5

Mapping the Research Area

Additionally to this systematic review, we elaborated a analysis by mapping the included primary studies. The graphs presented in this chapter are important to provide a bird's-eye view of the research area investigated. The primary studies were analyzed according to two viewpoints: author-study and co-authoring. In the author-study graph, the edges connect each study with their authors. The co-authoring graph represents the interaction among the authors and research groups. To support the development of these graphs we used SCI2 tool[1], which provided a large set of clustering and representation functionalities. It is important to mention that the primary studies included (presented in Table 3.11) and excluded by EC4 (presented in Table 3.12) were considered in this mapping, as they are part of the research area and are important to show the relationship among the researchers in this area.

Figure 5.1 shows the author-study graph. The included primary studies are represented by light green nodes and those excluded by EC4 are represented by dark green nodes. The authors are represented by the other nodes. The bigger and more colorized a node, the more studies the researcher has published. Notice that the nodes position does not represent any information. Thus, closest nodes are not more similar than others.

It is observed that most studies were isolated initiatives developed by different research groups, as the majority of groups have published only one or two primary studies. Furthermore, groups that have published two papers usually report the same research. The main researcher in this area are Y. Chen[2], followed by X. Sun and W. T. Tsai. They are the headers of the biggest group (or set of groups) which has been developing service-oriented robotic systems. Several authors and eight studies are connected through these head researchers.

In the co-authoring graph, shown in Figure 5.2, we describe interactions among researchers of service-oriented robotic systems. Each cluster represents one or more research group. In this graph, the edges connect authors who have published together at least one primary study. The stronger the edge, the more intense the interaction between the researchers. In other words, stronger edges represent a large number of studies written in common. Like in the author-study graph, researchers who have published more studies are represented by the bigger and more dark colorized nodes.

[1] `https://sci2.cns.iu.edu/user/index.php`

[2] Yinong Chen, Xin Sun, and Wei-Tek Tsai work in Arizona State University (Tempe, Arizona, USA).

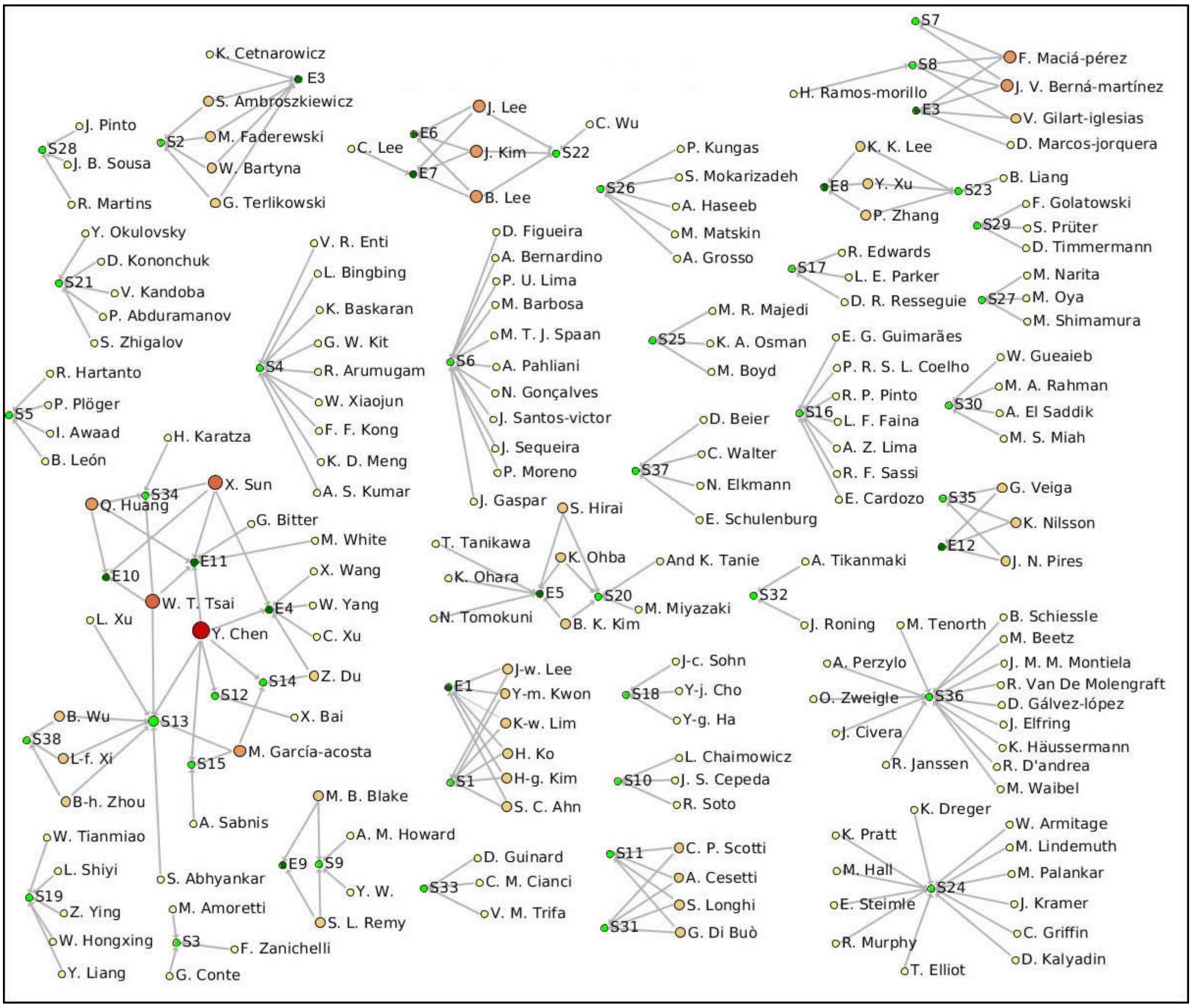

Figure 5.1: Graph of the authors and their primary studies

Notice that more than a half of researchers in this area have published only one study. For example, the clusters at the top of Figure 5.2 indicate that around fifty researchers have published only once. Moreover, clusters which have a two-study interaction often address the same research, i.e., an initial paper and an extended version of the same topic. Only a unique cluster on the bottom right side of the graph indicates a possible interaction among more than one research group. At the end, we can observe that these characteristics evidence a lack of interaction, and even a discontinuity in the development of service-oriented robotic systems. This might be one of the possible consequences of the low number of methods, techniques, processes, software engineering guidelines and other important issues to the development of service-oriented robotic systems.

Although it is not part of the systematic review process, it is important to note that maps, such those graphs presented in this chapter can complement the results of a systematic review. In this case, we were able to gather important information about the interactions among the researchers of service-oriented robotic systems. In addition, the main groups in this research area could be identified.

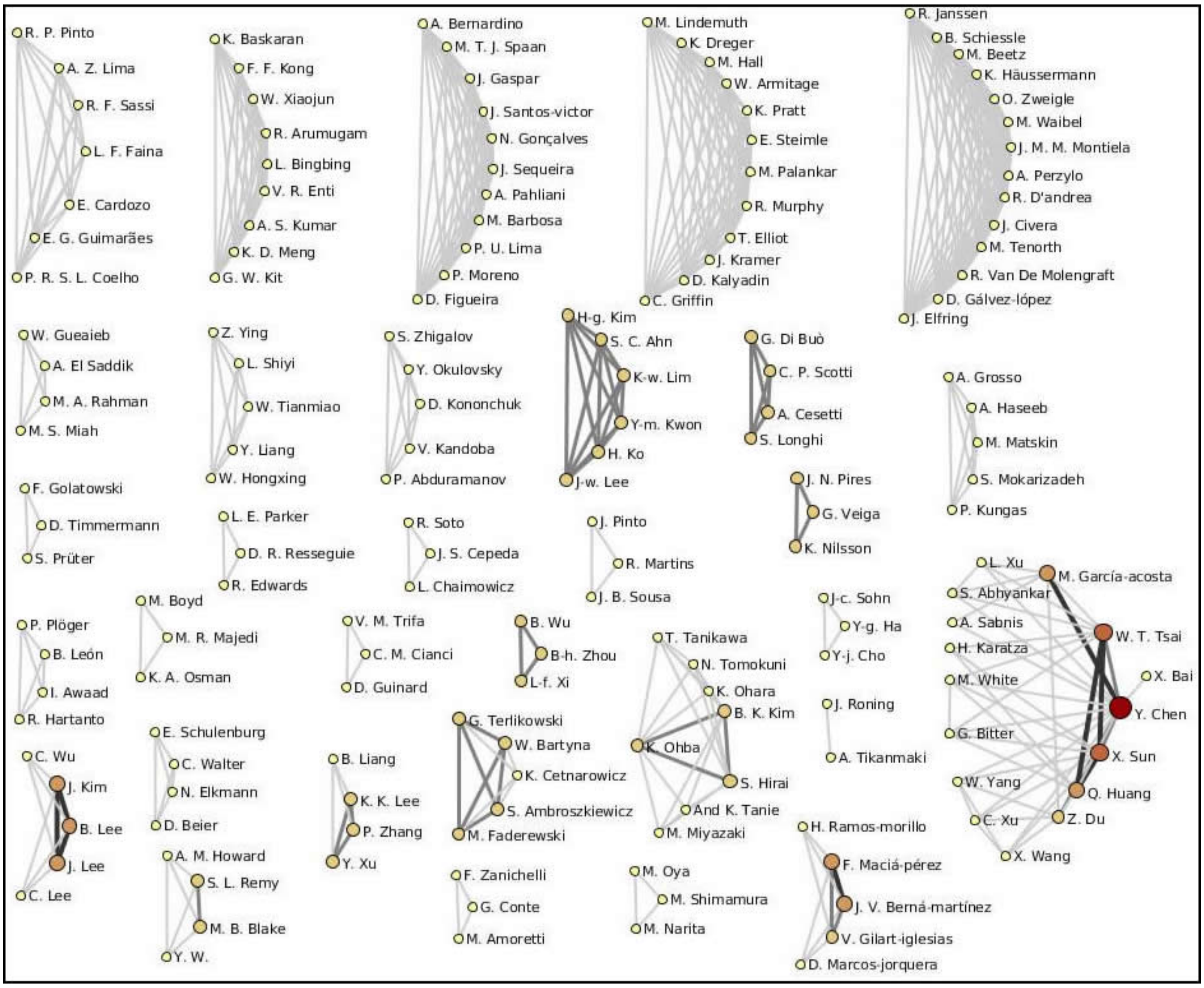

Figure 5.2: Graph of the interaction among authors

Chapter 6

Conclusion and Future Work

The main contribution of this work is the presentation of a detailed panorama on the design, implementation and technologies related to the development of robotic systems based on SOA by means of a systematic review. A bird's-eye view of the research area has also been presented. As the main result, we can conclude that the development of service-oriented robotic systems has been the focus of increasing attention in the last years. Another important contribution of this work is the identification of new research lines. For instance, there is a lack of processes, methods, and architectural guidelines that support the development of service-oriented robots in a productive, and systematic way. Furthermore, tools that support the design phase of the development have not been widely investigated yet. There are still different perspectives that could be investigated, aiming at improving reuse, productivity and quality of service-oriented robotic systems.

Regarding the conduction of the systematic review, we can point out that Scopus is the most efficient publication database. It is also important to highlight that we strongly discourage the use of Compendex and Scopus in the same review, as it may cause a large increase in the number of primary studies obtained, with no significant improvement in the number of included studies. As future work, we intent to make a more complete investigation of the research area and to periodically update this systematic review, aiming to monitor the evolution of this area.

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