Telematics and Informatics 38 (2019) 118–132

Contents lists available at ScienceDirect

Telematics and Informatics

journal homepage: www.elsevier.com/locate/tele

Analyzing the software architectures supporting HCI/HMI processes through a systematic review of the literature

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ARTICLE INFO

Keywords:
Human-Computer Interaction
Human-Machine Interaction
Software Architectures
Systematic Literature Review

ABSTRACT

Many researchers have dealt with Human-Computer Interaction or Human-Machine Interaction by building or designing software architectures that facilitate the users' interaction or recognize users' inputs to the generate proper responses. Many studies include these approaches in different research areas: from research in healthcare to mobile environments, robotics, etc. Interaction is seen as a critical concept, and the work for its improvement is a crucial factor for many platforms, systems, and business domains. The goal of this manuscript is to present a systematic review of the literature to identify, analyze and classify the published approaches to support or enhance Human-Computer Interaction or Human-Machine Interaction from the perspective of software architectures. The method followed is the systematic review following the guidelines related to Systematic Literature Reviews methods such as the one proposed by Kitchenham and other authors in the field of software engineering. As results, this study identified 39 papers that included software architectures to improve or analyze Human-Computer Interaction or Human-Machine Interaction. Three main approaches were found on software architectures: layered architectures, modular architectures, and architectures based on software agents, but they lacked standardization and were mainly ad-hoc solutions. The primary interfaces covered were those related to Graphical User Interfaces (GUIs) and multimodal/natural ones. The primary application domain detected were in multimodal systems. The main purpose of most of the papers was to support multimodal interaction. Some conclusions achieved are that the generic solutions to support or analyze HCI/HMI processes are still rare in the literature. Despite many works dealing with this topic and its issues and challenges, it is necessary to keep on improving the research in this area through the application of standard techniques and solutions, exploring new ways of analyzing and interpreting interaction, escaping from ad-hoc solutions or evaluating the solutions proposed.

1. Introduction

Software Architectures (SA) are not a new thing in Computer Sciences. There are many authors who have defined and pushed forward the study of this concept (Bass, Clements, and Kazman, 2013; Kruchten, 2004). According to (Bass et al., 2013) a software architecture can be defined as "[…] the set of structures needed to reason about the system, which comprises the software elements,

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https://doi.org/10.1016/j.tele.2018.09.006
Received 10 May 2018; Received in revised form 31 August 2018; Accepted 24 September 2018
Available online 06 October 2018
0736-5853/

relations among them, and properties of both". Also, the Human-Computer Interaction and Human-Machine Interaction concepts and research areas have been developing for a long time. The Association for Computing Machinery (ACM) defines Human-Computer Interaction (HCI) as "a discipline concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them" (Hewett et al., 1992). Other authors, such as Alan Dix, define HCI as "the study of the way in which computer technology influences human work and activities" (Dix, 2009). Moreover, Human-Machine Interaction (HMI) has been defined in the past as "how we as humans interact with machines, and we define a machine as any mechanical or electrical device that transmits or modifies energy to perform or assist in the performance of human tasks" (Cannan and Hu, 2011). Despite these definitions, the term is currently assumed in the same way as the HCI, with the only exception that it is associated mostly to robotics and industrial applications and machines (Cannan and Hu, 2011; Hewett et al., 1992; Hoc, 2000).

Both areas, one typically related to software engineering, and the other to fields such as perception, psychology, design, user research, etc. seem to be separated, but researchers have made many efforts to merge them in order to build better systems. Thus, (Tran et al., 2008) state that "the architectural design of interactive systems is the object of many pieces of research since the eighties". Following the idea of the combination of both fields, (Seffah et al., 2005) comment that: "one of the common communication breakdowns between software engineers and usability professionals is the lack of strategies to inform the early design of software architectures with usability principles, which helps avoid late (and expensive) architectural changes to accommodate user experience requirements". What is more, in more complex environments such as software ecosystems, the user, and his or her human factors are included as part of the whole, considering it as important as any other software component or restriction (García-Holgado and García-Peñalvo, 2016, 2017). According to (García-Holgado and García-Peñalvo, 2016), "the users are components of the ecosystem, they establish information flows with other components and they are affected if the ecosystem evolves", we can consider that their usage and interaction with other (software) components in the system are as important as the interaction between the software components. It may result in considering the HCI process/characteristics to be at the same level as the other components or parts of the (eco)system when designing or developing a system.

Theoretically, combining both fields (SA and HCI/HMI) would contribute to the building of better systems that should include the best from both the systems and user-centered designs. As many authors claim (Bosch and Juristo, 2003; John and Bass, 2001), the software architectures should enclose the fundamental structure and ideas of the system, in order to offer the desired quality based on sound design decisions. This quality could be related to any part or goal of the system, such as structural quality, presentation quality, etc. (Seffah, 2015). It has been proven that system features can have an impact on the usability of the system, even if they are logically independent of the UI and not necessarily visible to the user. For example, Bass observed that even if the presentation of a system was well designed, the usability of a system could be significantly compromised if the underlying architecture and designs did not have the proper provisions for user concerns (Bass et al., 2001). We propose that the software architecture should define not only the technical issues needed to develop and implement functionality but also dialogs with the users.

Following all those ideas, the subject of this paper is the conjunction between software architectures and HCI/HMI processes: how can software architectures support HCI/HMI processes? How could software architectures help, improve, analyze, intervene or contribute to HCI/HMI processes? In the case of this paper, we will deal with these questions from the published literature in these research fields. To accomplish these goals, we conducted a systematic literature review following the guidelines proposed by (Kitchenham et al., 2009; Kitchenham and Charters, 2007).

The work is organized as follows. Section 2 presents the systematic review methodology, including its different aspects and steps required. Section 3 presents the results of the systematic review regarding the content of the selected literature. Section 4 discusses the findings in the process, commenting on the different solutions and approaches found in the literature and outlines the threats to the validity of the study. Finally, the 5th and last section includes some brief conclusions on the research.

2. Materials and methods

Some authors (Kitchenham and Charters, 2007) have emphasized that an evidence-based approach to software engineering is an important research issue. Finding evidence by reviewing the literature on a specific topic could be addressed using methodologies such as systematic literature reviews and mapping studies (Kitchenham et al., 2011). In this context, the primary purpose of a systematic review is to identify, evaluate and interpret the available studies in the literature that consider the research questions proposed by the authors. A second purpose could be to gather evidence to identify gaps and research opportunities in the area of interest. This paper is organized using the main activities proposed by Kitchenham: planning, conducting and reporting the study.

2.1. Review planning

When designing the processes of review and planning, we identified the different objectives, the protocol to follow and other relevant details. Below is provided an explanation of the different relevant aspects for the review.

2.2. Research questions (RQ)

- RQ1: What are the trends in software architectures that support or analyze Human-Computer Interaction?
- RQ2: What are the trends in software architectures that support or analyze Human-Machine Interaction?
- RQ3. Are there significant differences in the trends of software architectures that support or analyze HCI to those applied to HMI?

- RQ4: What kind of software architectures have been proposed to support or analyze Human-Computer Interaction?
- RQ5: What kind of software architectures have been proposed to support or analyze Human-Machine Interaction?
- RQ6: Are there significant differences in the software architectures proposed to support or analyze HCI to those applied to HMI?

Based on the research questions, we used the PICOC method proposed by (Petticrew and Roberts, 2008) to define our review scope:

- Population (P): The target group for the investigation. In this study: Software architectures
- Intervention (I): specifies the investigation aspects or issues of interest for the researchers. In our case, those aspects or issues that provide support or analyze HCI/HMI processes.
- Comparison (C): the aspect of the investigation with which the intervention is being compared to. No comparison intervention has been planned in our study.
- Outcomes (O): the effect of the intervention. We seek Software Architectures proposals and real-world experiences.
- Context(C): the setting or environment of the investigation. In our case, they are those environments related to HCI/HMI (in the industry, academia, etc.).

2.3. Inclusion and exclusion criteria

The following inclusion and exclusion criteria were used to answer the different questions posed. The different criteria used to include or exclude a paper were organized into five inclusion criteria (IC) and five exclusion criteria (EC):

- IC1: The papers had a software architecture-based solution AND
- IC2: The presented solution was applied to HCI OR HMI fields AND
- IC3: The presented solution supported OR analyzed HCI OR HMI processes AND
- IC4: The papers were written in English AND
- IC5: The papers were published in peer-reviewed Journals, Books, Conferences or Workshops

The exclusion criteria were established as the opposite to the IC. If any of the papers retrieved do not met the IC, it will be excluded.

After that, we chose the databases to perform the search. The selection was accordingly to the following requirements: the database is capable of using logical expressions or a similar mechanism, allows full-length searches or searches only in specific fields of the works, is one of the most relevant in the research area of computer science and finally, but extremely important, the database is available for us (through our institution, etc.).

Sources: The search was conducted in the following electronic databases: Web of Science, Scopus, IEEE Xplore, ACM Digital Library and Springer Link

2.4. Query string

To create the search string, we identified the main terms from the research questions, the PICOC and the possible alternative spellings and synonyms. Based on the identified terms, and using logical operators for the search, the query designed was:

(“*software architectur**” *AND* ((*HCI OR* “*Human-Computer Interaction*” *OR* “*Human Computer Interaction*”) *OR* (*HMI OR* “*Human-Machine Interaction*” *OR* “*Human Machine Interaction*”)))

As additional details, the search was not restricted by publication date or other filters. The unique filter applied was in the Springer Link database, where we avoided all “Preview only” papers, as these papers were not accessible for us.

2.5. Review process

After the search, the selection of papers to be used for the literature review was performed following these steps:

1. All the raw-results were collected in a GIT repository (Cruz-Benito, 2017) and a spreadsheet (https://goo.gl/QK5Qrd), removing all the duplicates across the databases.
2. The resultant papers were analyzed based on the title and abstract and the inclusion/exclusion criteria. In those cases where the title and abstract were not sufficient to decide, the authors quickly assessed the entire content of the paper. The resultant candidate papers were added to another sheet of the spreadsheet document (https://goo.gl/4xweXc).
3. The papers were read in detail and analyzed following the previously-posed research questions. The selected papers passed a quality assessment checklist (see Table 1), and the information was collected in another spreadsheet (https://goo.gl/cYBfyp). Besides the papers selected in this manner, the authors also considered papers collected within the references of those that potentially could be interesting for the review process. It raised another three papers to be included in the review.

Following these steps, the following results were obtained (Fig. 1):

Table 1
Quality assessment checklist.

Question	Score
1. Are the research aims related to software architectures & HCI/HMI clearly specified?	Y/N/partial
2. Was the study designed to achieve these aims?	Y/N/partial
3. Are data presented on the evaluation of the proposed solution?	Y/N/partial
4. Are data presented on the assessment regarding the human part of HCI/HMI?	Y/N/partial
5. Is the software architecture clearly described and is its design justified?	Y/N/partial
6. Are the devices involved clearly specified? Are their functions within the software architecture justified?	Y/N/partial
7. Do the researchers discuss any problems with the software architecture described?	Y/N/partial
8. Is the solution based on a software architecture tested in a real context?	Y/N/partial
9. Are the links between data, interpretation and conclusions made clear?	Y/N/partial
10. Are all research questions answered adequately?	Y/N/partial

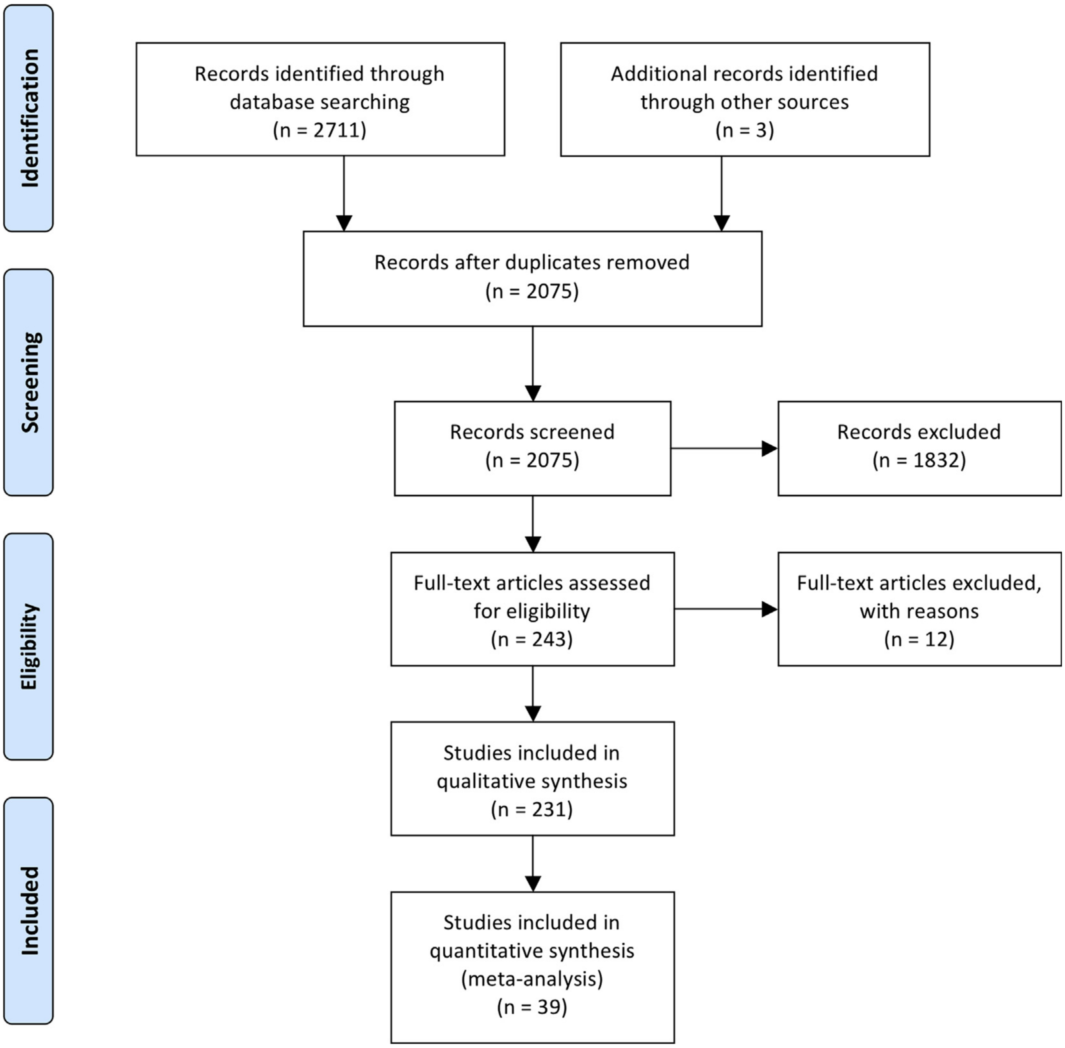

Fig. 1. Steps and results of review process. Reported as proposed in the PRISMA Statement (Moher et al., 2009).

1. Querying the databases (identification phase): 2711 papers retrieved (217 from Web of Science, 395 from SCOPUS, 56 from IEEE Xplore, 403 from ACM Digital Library, 1640 from Springer Link).
2. Remove duplicate studies (screening phase): 2075.
3. Selected papers after reviewing titles and abstracts (eligibility phase): 243 (11.71% of the papers retrieved). B) Inclusion and review of papers after checking the primary paper references: 3
4. Papers selected after reading the full text (phase of final papers inclusion): 39 (1.88% of the total papers considered, 15.85% of the

Table 2
Summary of review findings on the main interfaces/systems presented in HCI papers.

Reference	Graphical User Interface	Laser Pointer	Touch display/ interface	Camera	Microphone	BCIs (Brain-Computer interface)	Motion tracking sensors	Mouse, Keyboard & Joystick	Force pressure sensors & Haptics	Smartphone/mobile devices/tablet	Gaze trackers	Wearables
Vega-Barbas et al. (2015)							X					
Chaczko et al. (2015)				X			X		X			
Mackin et al. (2012)			X	X								
Biel et al. (2010)										X		
Jacquet et al. (2009)	X		X	X	X		X			X		
Dimakis et al. (2009)	X			X	X		X					
Seffah et al. (2008)	X											
Capilla et al. (2014)	X									X		
Tiefenbacher et al. (2014)	X		X									
Calandra et al. (2013)	X		X		X						X	
Caruso et al. (2013)	X		X			X				X		
Pittarello (2011)	X									X		
Folmer and Bosch (2008)												
Jacquet et al. (2007)				X								
Marsic and Dorohonceanu (2003)	X			X	X			X		X	X	X
Nigay and Coutaz (1995)	X							X				
Bass et al. (2001)												
Jalaliniya et al. (2015)										X	X	X
Wang and Canedo (2014)	X									X		
König et al. (2010)	X	X			X					X		
Olmedo et al. (2015)	X				X			X				
de Alencar et al. (2014)										X		
Rego et al. (2014)				X	X	X	X	X	X			
Malandrino et al. (2010)										X		
Bongartz et al. (2012)	X				X		X			X		X
Sutcliffe et al. (2011)	X											

papers read). The analysis performed to achieve this number of paper was only based on their content, and without concerning bibliometric measurements (number of citations, journal source) or other aspects.

As shown in the guidelines proposed by (Kitchenham and Charters, 2007), we formulated a quality checklist to assess the individual studies and avoid subjectivity. These checklists are used to assist in the selection process of the papers. The customized quality assessment checklist developed is based on the checklist suggested in (Kitchenham and Charters, 2007). Other works on systematic reviews of the literature (Neiva et al., 2016) have also customized their quality checklists based on the suggestions given in (Kitchenham and Charters, 2007).

In the third step of the review, as described above, the papers were read in full, and their quality was evaluated using the quality assessment checklist formulated (Table 1). The answer for each one of the 10 questions could be scored with 1 point if the answer was "Yes", 0.5 points if the answer was "Partial" or 0 if the answer was "No". Using the table each paper could obtain a score from 0 to 10 points. The first quartile mark (Q1 = 7.5 points) was used as the cutoff score for a paper to be included. If a paper scored less than 7.5, we excluded it from our final list to avoid low-quality works according to the assessment checklist.

3. Results

Regarding RQ1, in the case of the user interfaces (Table 2), most systems and architectures used GUIs as the contact point with the user (15/26 papers, 57.69%), followed by mobile devices, smartphones or tablets that were the primary physical interface presented (12/26 papers, 46.15%). Table 3 shows the main findings on the logical support provided by the software architectures. The primary goal for the software architectures in the selected papers was related to improving usability (34.62% of the papers), followed by the support of multimodal interaction (26.92%) and information fusion from multiple sources (26.92%).

Under the scope of trends, the topic of the interfaces used was focused on mobile technology and GUIs (Table 2). Most papers from 2009 onwards (11/19 – 57.89% – papers published in those years) were related to smartphones, mobile devices, and tablets as input sources for user interaction. Furthermore, GUIs were included in 57.69% of publications across all years (1995–2015). Despite this, in recent years (2014 and 2015) fewer papers were found dealing with GUIs (5/9, 55.56%, of papers published in 2014–2015) as other terms and interfaces became interesting for the researchers such as the so-called natural interfaces. The other input sources and interfaces were more balanced across the entire time span of publications. Other short-trends appeared, such as the case of two papers that dealt with BCIs, published in 2013 and 2014, respectively. In the case of the support provided by the software architectures, there were no clear trends in general. The only specific trend that could be observed was that all the software architectures that were focused on supporting the interaction with non-classical devices or systems were published in 2015. Related to other kinds of support provided by the architectures, there are recurrent subjects like seeking for the improvement of usability (10/21 papers published between 2001 and 2014) or information fusion from different sources (common in papers from 1995 to 2015), but they do not represent a trend *as is*.

In the case of RQ2, Tables 4 and 5 show the different interfaces or interaction systems found in the HMI-related papers, as well as the support provided by each software architecture outlined. In general, most of the papers referred to robotic systems that use different input sources for human interaction (7/13 papers, 53.85%). Also, most of the architectures were designed to support interaction via two primary interfaces: GUIs (61.54% of the papers) and/or multimodal interfaces intended to recognize users' gestures or body (53.85% of papers). In the case of the support, the main one provided by the software architectures was related to supporting the recognition of multimodal interaction (7/13 papers, 53.85%). In the other cases, the support provided was related to: helping in recognizing users' feelings, behaviors, or interests using mostly ad-hoc techniques (30.77% of papers), helping in the application of information fusion techniques (23.08%), supporting the application of statistical techniques to analyze interaction (15.38%) such as Hidden Markov Models, using artificial intelligence/neural networks methods to analyze interaction (7.7%) or supporting personalization in the human-machine interaction (7.7% of the papers).

Related to the trends: there was a clear trend in interfaces working with multimodal interfaces and systems. From the point of view of the interfaces involved, most papers from 2011 dealt with multimodal challenges in several ways: 7/13 (53.85%) of total papers –77.78% of the papers published since 2011– used multimodal interfaces such as gesture and body recognition system, speech inputs –for example, only one dealt with speech input before 2011– or pressure sensors (1/13 of the papers). Regarding the support that software architectures provided to the HMI processes, the multimodal interaction recognition was also the trending topic from 2011. In this case, the same papers that used multimodal interfaces –77.78% of the papers published since 2011; 53.85% of all papers in HMI category–, dealt with software architecture in charge of recognizing the multimodal interaction. Regarding other trends, it should be noted that software architectures focused on recognizing feelings, behavior or interests between users were trendy between 1997 and 2011 (3 papers out of the 5 published in that time span discussed this). With respects to other interfaces or support provided by the software architectures presented in Tables 4 and 5, the remaining contents were not grouped into particularly exciting trends, since most of them were commented in the papers without constituting them as a definite trend.

Related to both previous questions, we answer question RQ3. Concerning the interfaces mentioned in each paper that studied HCI and HMI, it was observed that the GUIs were highly relevant, as more than 50% of the papers in each area covered GUIs as the primary interaction interface for the architectures presented. The main difference in their trends was that in the case of HCI-related papers, the primary interfaces were related to mobile devices (smartphones, tablets, etc.), while in HMI the main interfaces were those related to recognizing users' gestures or body position. In the case of HCI papers, the interfaces that collected users' gestures also appeared (under the motion tracking and camera terms). In the case of HMI papers, mobile devices did not appear per se. In HMI papers the term GUI appeared, but not in mobile devices, although it was present in desktop computers, in embedded systems, etc.

Table 3
Summary of review findings on the logical support provided by the software architecture to the interaction process in HCI papers.

Reference	Support non-classical interaction devices or systems	Context-aware	Fusion input information from multiple sources	Multimodal interaction support	Improve usability	Adaptability	Enhance user collaboration	Evaluate interaction/gestures	Analyze user behavior or profile	Accessibility	Assistive services	Communicate software and hardware systems between user and external operators
Vega-Barbas et al. (2015)			X								X	
Chaczko et al. (2015	X		X	X								
Mackin et al. (2012												X
Biel et al. (2010)					X							
Jacquet et al. (2009)			X	X					X			
Dimakis et al. (2009)		X		X								
Seffah et al. (2008)					X							
Capilla et al. (2014)					X							
Tiefenbacher et al. (2014)								X				
Calandra et al. (2013)				X								
Caruso et al. (2013)					X					X		
Pittarello (2011)		X										
Folmer and Bosch 2008)					X							
Jacquet et al. (2007)			X	X								
Marsic and Dorohonceanu, 2003)			X		X	X	X					
Nigay and Coutaz (1995)			X	X								
Bass et al. (2001)					X							
Jalaliniya et al. (2015)	X											
Wang and Canedo (2014)					X							
König et al. (2010)												
Olmedo et al. (2015)	X											
de Alencar et al. (2014)						X						
Rego et al. (2014)			X	X								
Malandrino et al. (2010)		X										
Bongartz et al. (2012)						X						
Sutcliffe et al. (2011)					X							

Table 4
Summary of review findings on what are the main interfaces/systems presented in HMI papers.

Reference	Robotic system	Multimodal interface (gestures and body recognition input)	Multimodal interface (speech input)	Multimodal interface (pressure sensors, haptics, etc.)	Other sensors (humidity, temperature, etc.)	Graphical User Interface	Brain Computer Interface (BCI)
Alonzo et al. (2015)	X	X		X		X	
Bozzon et al. (2007)						X	
Pires et al. (1997)			X			X	
Tessadori et al. (2012)						X	X
Bigdelou et al. (2012)		X				X	
Kim et al. (2006)	X					X	
Parsons et al. (1997)	X				X		
Heigemeyr and Harrer (2014)							
Mayer et al. (2013)		X				X	
Burger et al. (2012)	X	X	X				
Moshkina et al. (2011)	X	X	X		X		
Srinivasan et al. (2015)	X	X	X		X		
Veloso et al. (2017)	X	X				X	

Table 5

Summary of review findings on the logical support provided by the software architecture to the interaction process in HMI papers.

Reference	Interaction analysis using Artificial Intelligence techniques	Interaction analysis using statistical techniques	Feelings, behavior, interest recognition	Information fusion	Personalization	Multimodal interaction recognition
Alonzo et al. (2015)						X
Bozzon et al. (2007)					X	
Pires et al. (1997)			X			
Tessadori et al. (2012)						
Bigdelou et al. (2012)		X		X		X
Kim et al. (2006)			X			
Parsons et al. (1997)	X					
Heigemeyr and Harrer (2014)				X		
Mayer et al. (2013)						X
Burger et al. (2012)		X		X		X
Moshkina et al. (2011)			X			X
Srinivasan et al. (2015)			X			X
Veloso et al. (2017)						X

Table 6
Summary of review findings on software architecture definition in HCI papers.

Reference	Theoretical proposal/study	Architecture based on modules and components	Architecture based on agents	Layered architecture	Architecture based on web services	Uses ontologies to define software behavior or services	Defines communication protocols or structures
Vega-Barbas et al. (2015)		X			X		X
Chaczko et al. (2015)				X	X		
Mackin et al. (2012)					X		X
Biel et al. (2010)	X				X		
Jacquet et al. (2009)			X				
Dimakis et al. (2009)			X				X
Seffah et al. (2008)	X						
Capilla et al. (2014)	X			X			
Tiefenbacher et al. (2014)				X			X
Calandra et al. (2013)		X					X
Caruso et al. (2013)		X					
Pittarello (2011)		X			X		
Folmer and Bosch (2008)				X			X
Jacquet et al. (2007)			X				
Marsic and Dorohonceanu (2003)			X				
Nigay and Coutaz (1995)			X				
Bass et al. (2001)	X						
Jalaliniya et al. (2015)		X					
Wang and Canedo, 2014)				X			
König et al. (2010)		X					X
Olmedo et al. (2015)		X					X
de Alencar et al. (2014)						X	X
Rego et al. (2014)		X					
Malandrino et al. (2010)		X			X		X
Bongartz et al. (2012)		X			X		X
Sutcliffe et al. (2011)	X						

Among the less trendy interfaces, similarities such as the appearance of BCI systems in both fields were found.

When discussing the support provided by the software architecture to the HCI/HMI processes, as previously explained, in the field of HCI-related papers there were no clear trends (most of the types of supports appeared a few times or were constant over the time). Moreover, in the HMI-related papers, there was a clear trend: 77.78% of the papers dealt with the recognition of multimodal interaction.

Lastly, in the case of software architectures, even though it will be commented in depth below, we can highlight some common trends in HCI and HMI papers: in recent years, layered architectures became relevant for the researchers in the field of software architectures. In HCI papers they became popular in 2014–2015; in contrast, in HMI they were broadly used since 2007 and are continuously used nowadays. As for the other approaches and structures presented, there were fewer coincidences: in both cases, software architectures based on components and modules or in agents were presented, but with no evident coincidence in the time regarding their popularity. Also, in HMI papers the software architectures based on web services did not appear, while in HCI papers, there was an increasing trend in recent years (2015 mostly).

To answer RQ4, Table 6 outlines the main findings on how software architectures in the selected papers were defined. As a result of the review, we found that most of the architecture proposals were based on modules and components –generally isolated– (in 38.46% of the papers). Regarding the composition, the other preferred structures were those based on layers (19.23%) or agents (19.23%).

Regarding other aspects, there was a clear trend regarding the use of web services to articulate the communication between internal software entities or external systems (26.92% of the papers). 42.3% of the HCI-related papers reviewed presented the communication protocols or data structures employed in the software architectures. Another aspect to highlight is that 5/26 of the papers (19.23%) were theoretical proposals or research studies in the field of software engineering. For that reason, they did not provide architectures explicitly but provided handy explanations on how the software architectures affect different aspects related to HCI (most of them discussed how structural aspects could help improve usability, etc.). Finally, the last feature extracted from the reviewed papers was that only one of them (3.85%) used ontologies to define the software architecture behavior or services.

In the case of RQ5, Table 7 presents the main findings related to the question. In this case, we found that most of the architectures were based on modules or components (53.85%) and these were mainly under the scope of monolithic architectural designs. Moreover, there were other papers (6/13, 46.15%) that presented layered architectures where the different parts were not framed within modules or simple components. In both approaches sometimes appear (3 proposals, 23.08%) coordinator entities that manage all the architecture and regulate the interaction between the different components or layers. Only in one case, the architecture was designed in a layered manner ready to be used in a distributed environment using APIs and other web-based network protocols (Bozzon et al., 2007). Regarding the information flows and protocols used by the architecture to communicate with the internal or external software entities/stakeholders, only 6 out of the 13 (46.15%) proposed architectures specified their communication protocols, data formats, etc. Also, in general, the papers did not present traditional architectures (PAC, PAC-Amodeus, MVC, etc.) as the basis for their proposal, but they presented ad-hoc approaches.

Lastly, we compared RQ4 and RQ5 to answer RQ6. There were some coincidences in the structures, composition and design presented in the papers. Both in HCI and HMI-related papers, architectures composed by modules or components, based on agents, layered ones, etc. were presented. Also, in HCI software architectures that established their activity and communicated with each layer, agent or component using web services were presented. In the case of HMI papers this issue was not widely covered (only one paper mentions it).

Also, in the case of HCI-related papers, there were some theoretical studies (in the field of software engineering) that tried to standardize different common issues or deal with particular problems from a logical and pattern perspective. In the HMI papers, there were no theoretical approaches, as these papers were more focused on giving practical applications to their context and challenges.

Table 7
Summary of review findings on software architecture definition in HMI papers.

Reference	Architecture with a coordinator entity	Architecture based on modules or components	Layered architecture	Distributed architecture	Define the communication protocols?
Alonzo et al. (2015)			X		
Bozzon et al. (2007)			X	X	X
Pires et al. (1997)		X			
Tessadori et al. (2012)		X			
Bigdelou et al. (2012)		X			X
Kim et al. (2006)		X			X
Parsons et al. (1997)		X			
Heigemeyr and Harrer, 2014)		X			X
Mayer et al. (2013)	X		X		
Burger et al. (2012)			X		
Moshkina et al. (2011)	X	X			
Srinivasan et al. (2015)	X		X		X
Veloso et al. (2017)			X		X

Also, the software architectures that appeared in the HCI category had more complex architectures that comprised more components, behaviors, and uses, while in HMI the architectures were simpler and mainly had the purpose of dealing with multimodal challenges mostly from a physical perspective. Following this idea, in general, the papers related to HCI had richer descriptions of their software architectures, communication protocols, etc., than those present in the HMI category.

It could be remarked that most of the architectures presented (at least those that appeared in practical papers) were ad-hoc and did not follow well-known models or approaches that were previously present in the literature. Exceptions were three papers in the HCI category that worked with previously-defined architectures such as PAC-Amodeus (Nigay and Coutaz, 1995), MARIA framework (Bongartz et al., 2012) and with KUP models (Jacquet et al., 2009).

4. Discussion

The dominance of research papers related to multimodal interaction reflected that gathering, analyzing and interpreting several inputs or interaction sources in real time or as a whole is still a problem for many systems and interactive environments. Even more since the mainstreaming of natural interfaces, voice commands, gestures and another kind of multimodal interactions in the daily life of users. We detected that had been published a massive amount of work in this area, but there is still room for more improvements in the combination of input sources through the enhancement of information fusion algorithms, multi-input, and multi-purpose architectures, new software patterns designed to support HCI, etc. Related to this, and from the HCI/HMI, we observed a lack of interaction analysis as the primary purpose of papers. In the case of theoretical papers, they approached this problem through the use of patterns, but they did not provide real-time solutions to enhance usability or define adaptability to the users' profiles or behaviors. Related to the techniques found, we miss the usage of AI-related techniques or advanced statistical methods in this subject. Only 3 papers use this kind of approaches to analyze the interaction; the other few works found dealt with the analysis based mainly on heuristic rules. As shown in other application fields, that modern data-driven or AI-driven approaches could enhance the research and provide better results. Also, in other cases, the interaction analysis is not present as it should. In this sense, we identify an important gap between academia and the pure engineering/industry work in this area. Many approaches followed in the industry nowadays are related to analyze the users' interactions within their different systems to provide proper feedback, to analyze behavior to ad-targeting users, etc. We agree that some of the goals pursued by the industry are not aligned with those from the academia, but we believe that the academia can provide new valuable approaches to make this kind of analysis better, more efficient, more responsible to the user and ethically adequate, etc.

From the software architectures, in general, the proposals found were not based on traditional well-known/well-tested proposals. Most papers used custom solutions that were not designed to be reusable or generic for some purposes. The exceptions were: the paper (Nigay and Coutaz, 1995) that based their proposal on the PAC-Amodeus (Nigay and Coutaz, 1993), the chapter by (Jacquet et al., 2009) that was based on their previous work on the KUP model for multimodal interaction (Jacquet et al., 2007) and the work by (Bongartz et al., 2012) that used the MARIA model-based framework (Paterno et al., 2009). Regarding the communication between components/layers and other systems, we would like to highlight that most systems used typical data structures encapsulated in files such as XML, CSV or JSON, and not many proposals relied on web services, APIs or microservices as in other research areas. Also, we want to remark that many papers did not provide any kind of –or proper– evaluation or assessment of the support or analysis provided by the software architecture; they only included brief reports about tests or minimal experiments/experiences with users.

From application fields, albeit many papers do not include research designed for particular fields of application, we want to present some examples of papers focused on a specific field of application. To do this, we would like to put the example of how software architectures have been used to support, analyze or improve HCI in the field of education or training. We found 5 papers out of the 39 papers selected (12,82%) which deal with the relation of software architectures supporting, enhancing or analyzing the HCI/HMI to improve learning or training processes in multiple ways. Those papers are the following.

In the context of smart learning environments, (Chaczko et al., 2015) present a way to enhance these environments through the use of software architecture (in this case described as middleware) that controls and manages all the different interfaces and resources available, such as haptic interfaces, cameras, and gesture/body trackers, etc. The middleware they used manages the network communication, integration of all inputs from different devices, etc., to combine all the interactions and gather them into a combined mode to be tracked and used within the smart learning environment software platform. Regarding the evaluation of the proposal, the authors presented some preliminary experiments to report on how the software architecture with the gestures or body recognition as the input, could work.

In the context of mobile applications to engage users in learning, (Pittarello, 2011) describes a conceptual model and a software architecture on how to provide context-awareness to engage emotional users with mobile applications. To pursue this goal, the software architecture and conceptual model worked with different inputs from the user (the interaction, information from sensors, etc.) that allowed for the adaptation to different views in mobile applications and websites. The author presents some preliminary results in a case study related to a website that narrated different aspects and stories about San Servolo island, with 6 users who had a background in Fine Arts.

In the field of users' interaction with robots and machines to learn or train, we found two papers: on the one hand (Kim et al., 2006) present an interactive software architecture for service robots that aimed to manage the robot's interaction with the environment and especially with humans. This software architecture is based on different modules governed by a "planner" module that manages the different robot motions. The software architecture has been tested in a tour-guide robot that operates at the National Science Museum of Korea. Moreover, on the other hand, (Mackin et al., 2012) present a software architecture designed to connect hardware and software efficiently, to be used by astronauts during their training. This connection was not intended to exchange information between different hardware or software components or even with the user, but to enable new efficient interaction manners between users and devices in a unique context such as Desert RATS field-testing. The devices presented in the case study simulated those that astronauts have used in space missions and presented some issues and challenges that were inherently different in the case of goals, interaction or tasks.

Finally, in the field of serious games, (Rego et al., 2014) define interaction models for the use of 3D contents in serious games. In the paper, the authors proposed several natural and multimodal user interfaces in rehabilitation, similar to those offered by different devices such as Kinect, eye gaze trackers, joysticks, etc. Using these devices and the natural interaction that is linked to them, researchers defined a system that tracks and aids users in home rehabilitation for different cognitive and motor disabilities, implementing different strategies related to serious games to foster the users' motivation. As for the architecture, the authors proposed a layered architecture with different modules within each layer. Each component is responsible for different issues related to the recognition of gestures, interaction, gamification, etc., and communicates with each other component or layer to collaborate in helping users to complete the rehabilitation tasks. The authors tested their approach and different usability tests with 20 healthy users, with some positive results.

As a coda, we want to note some brief comments about the threats to validity. Since as other authors (Neiva et al., 2016) mentioned that in this kind of literature reviews, the results presented "may have been influenced by certain uncontrollable limitations". One of the main threats to the validity of this kind of investigation is the authors' bias to certain aspects in papers or subjects. In this case, some strategies –such as the quality assurance checklist (Kitchenham and Charters, 2007)– used to mitigate this bias were applied. Also, the number of researchers involved in the selection of papers could be considered a bias. To reduce this bias, the first author was the primary reviewer, and the other two authors reproduced each step taken in the whole process to ensure its validity. Also, the different resources provided –such as the spreadsheets or the public GIT repository (Cruz-Benito, 2017) that contained the results from databases as well as other resources used in this research– were intended to reduce or remove any bias and make the whole process reproducible for the reviewers and readers. In the case of the search string, authors previously evaluated some papers to monitor the results and validate the search string, so it could be assumed as a kind of evidence to ensure the query correctness. Regarding the databases used, all the central relevant digital libraries and databases in the field of computer science were included. Thus, one of the main typical threats to validity that usually arise in systematic literature reviews was eliminated. Other databases such as Google Scholar could have been included in this research study, but we only considered those that indexed ensured contrasted quality contents. Other of the essential threats to validity is related to the trust in the conclusions, discussion and general results achieved. The Systematic Literature review is considered a reliable method to review the existing literature and get an in-depth knowledge of the area of study. Albeit of that, the different terms used for the query, the different criteria used, the authors' bias (as commented previously) or other parts of the process can compromise the validity of the results and reduce the trustiness of the discussion and conclusions achieved. In this case, we have been as much rigorous as possible with the process and methodology to mitigate this threat. We have used foundational terms to perform the query; we have used well-known inclusion, and exclusion criteria (at least in the field of software engineering), a traceable quality assessment checklist, all the materials have been reviewed by all the authors and are publicly available, etc. So, we believe that our results deserve enough confidence according to the corpus of papers retrieved, filtered and selected during the process and considering the methodology followed.

5. Conclusions

In this paper, a systematic review to identify, classify and analyze software architectures that support HCI/HMI processes was presented. For this, all the publications related to this knowledge area were examined in an unbiased way. During the review process of the papers, 2711 papers from 5 different databases were found initially, but this number was reduced, using different criteria and quality assessments, to 39 papers, which were deemed to be the most relevant for this research. Considering the content of the papers, we detected that the different software architectures designs and implementations observed, the main trends were related to modular software architectures, layered architectures or architectures based on software agents to conduct the software behavior, features or methods. Regarding the interfaces analyzed, the most common ones were those related to GUIs. It must be noted that the manner in which to use multimodal and natural interfaces was a standard issue in the papers, and much research effort was devoted to this subject. There were a lot of resultant papers that dealt with multimodal interaction in many ways, offering different solutions and proposals. Moreover, on the work conducted by the authors, we detected the existence of many different implementations and proposals for dealing with HCI/HMI from the software architectures, but there was a lack of formal proposals and standardization: most of the papers presented custom and ad-hoc solutions to different problems. Also, regarding the methods for conducting or evaluating interaction, there were no common methods, but different common algorithms or heuristic rules adapted to these problems were found. In general, we also detected a lack of adaptive systems or systems that analyzed user interaction based on current trends such as artificial intelligence, etc. As a result, we believe that more studies focused on the interaction itself and how we can benefit it from the systems and their software should be conducted, emphasizing the standardization of techniques and approaches.

For the future work, we plan to apply the knowledge gained to articulate a set of patterns and good practices in the support, analysis, and enhancement of HCI/HMI processes by the software architectures. We found in the literature some work on this sense, but we think that the current approaches, devices, and environments raise new challenges to be tackled from the software engineering and the User-Centered Design perspective.

Acknowledgments

This work has been partially funded by the Spanish Government Ministry of Economy and Competitiveness throughout the DEFINES project (Ref. TIN2016-80172-R) and PROVIDEDH project (PCIN-2017-064).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tele.2018.09.006.

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