An Investigation into Reference Architectures for Mobile Robotic Systems

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***Abstract*—Currently, robotic systems have been more and more required for a diversity of new products, such as in domestic robots and in robots for dangerous environments. As a consequence, an increase in the complexity of these systems is observed, requiring also considerable attention to their quality and productivity. In another perspective, reference architectures have emerged as a special type of software architecture that achieves well-recognized understanding of specific domains, facilitating the development, standardization, and evolution of software systems. In this perspective, reference architectures have also been proposed for the robotic domain and they have been considered an important element to the development of systems for that domain. However, there is a lack of work that present an panorama about these architectures; furthermore, there exists no support to choose a reference architecture when developing or evolving robotic systems. Thus, the main contribution of this paper is to present a panorama about reference architectures of the robotic domain, in particular, for mobile robots. It is worth highlighting that we used the systematic review technique to identify and investigate these architectures. We have found that these architectures have in general become consolidated and have already contributed to the industry during the development of robotic systems. Besides that, results of our investigation could support the decision about which architecture to adopt aiming to develop a new software. Also, our analysis could help to create new reference architectures. However, there are still important perspectives of research that need to be investigated.**

***Keywords*-*robotic system*; *robot*; *reference architecture*; *systematic review*.**

I. INTRODUCTION

The field of Robotics has presented an increasing growth in the last years, impacting various sector of the society and opening new, important application areas [1]. A number of different types of robots has been developed and used and, in particular, mobile robots have currently detached by their relevance and range of applications. Good examples of mobile robots are vacuum cleaners, vigilant robots, and mappers, including robots developed to be operated in dangerous environments, sometimes, not accessible by human beings. Furthermore, according to Graaf et al. [2], in the next years, the market for these robots is forecasted to exponentially grow and they will have more and more important roles. In this perspective, the complexity of these mobile robots has been increasing, creating a considerable challenge for their development. Thus, both academic and industrial research have focused on their development, aiming at achieving quality in such systems and timely delivery [2]. It is also worth highlighting that robots are basically composed by mechanical devices (such as sensors and actuators) and software systems (i.e., robotic systems) and the development of these systems have been perhaps the major challenge.

In another perspective, software architectures have been increasingly investigated as the main artifact that plays a pivotal role in determining system quality, forming the backbone of any successful software-intensive system [3]. More specifically, a reference architecture has achieved the status of a special type of software architecture that captures the essence of the system architectures of a given domain, i.e., it encompasses the knowledge about how to design, standardize, and evolve the system architectures of a specific domain. Considering the relevance of reference architectures, various application domains have proposed, used, and reused the knowledge contained in such architectures. It is worth highlighting that these architectures have been sometimes developed by consortia that involve academy and major industrial players (such as manufacturers and suppliers). Thus, reference architectures have been considered as a quite important element to improve productivity and quality of the software systems.

Regarding robotic domain, several reference architectures have been also proposed for the development and evolution of mobile robots [4], [5], [6]. Each reference architecture has its particular characteristics; besides that, they have been successfully used in specific projects. However, in the most cases, robotic systems for mobile robots have been almost always developed and evolved without using reference architectures, i.e., these systems are not taking advantage of the knowledge contained in such architectures in order to be more easily developed and evolved. This fact can be the result of the difficulty to select an more adequate architecture. Thus, a detailed, comprehensive panorama about these architectures will be in fact important. However, there is a lack of such panorama about reference architectures for the robotic domain.

In this scenario, the main contribution of this paper is to present a broad panorama of the reference architectures for robotic systems, as well as an more detailed investigation among these architectures. In the context of this work, we have focused in reference architectures for mobile robots. It is important to say that in order to find these architectures, we adopted and conducted a systematic review [7], i.e., an efficient and effective technique to summarize, assess, and interpret all evidence related to a specific question, topic area, or phenomenon of interest. Besides that, we complemented our investigation using additional documents related to each reference architecture found. As main results, we have observed, in the last years, an increase in the number of reference architectures for robotic systems. These facts have evidenced a real interest by both academy and industry. Moreover, our investigation could be considered as a valuable element during the selection of a more adequate architecture for the design and evolution of robotic systems for mobile robots. Moreover, our results could be used as a start point to the proposal of new reference architectures for mobile robots domain. Finally, this work could make it possible to identify interesting and important research topics for further investigations.

This paper is organized as follows. In Section II, we present an overview on mobile robots and reference architecture, since these topics are important to understand our analysis. In Section III, we present the methodology used to systematically identify reference architectures. In Section IV, we describe each reference architecture found. In Section V, we present a comparison among these architectures. In Section VI, we discuss about the achieved results. Finally, in Section VII, we summarize our contributions and discuss perspectives for further work.

II. BACKGROUND

The field of Robotics encompasses several types of robotic applications, such as robotic arms for assembly lines, household robots, and military robots. In this context, an important type is mobile robots, which also are basically composed by software and hardware projects. The software implements the robotic control system (i.e., robotic system), which is responsible for analyzing the sensor signals, planning and decision-making, and control of actuators. In parallel, the hardware is responsible for the physical implementation of sensors, actuators (responsible for robot's movement and actions), and data processing (the basic components for partial or total autonomy of the robots) through the use of an embedded processor. In particular, sensors are the hardware components responsible to give the robot the "vision" of the world, representing different senses, such as vision and hearing, and allowing the robot to interpret the environment. Otherwise, actuators enable the robot to interact with the environment, allowing the robot to move and perform actions, such as picking or pushing objects.

Regarding robotic system, it enables the robot to develop essential, complex, and intelligent activities. For instance, it also determines the robot autonomy level, from teleoperation to autonomous behavior. Thus, the main activities performed by a robot are: *navigation*, *localization*, and *mapping*. *Navigation* is the act of controlling the movement of the robot from an initial position to a target position. The task of navigation is usually implemented through the use of a control architecture which represents how the robot behaves. *Localization* consists of estimating the position of the robot in the environment. This activity is essential and basic for the robot navigation. If a robot determines exactly its position, it will be capable of planning a path to its destination and will fulfill adequately the tasks allocated to it [8]. *Mapping*, i.e., the act of getting data on the environment and the construction of maps, is an estimation problem which is a major task for the development of autonomous mobile robots. A correct map of the environment is fundamental to find the most efficient path. Through the map, the robot checks the possible paths that lead to the desired position and the obstacles that must be avoided [9].

In another perspective, considering the relevance of reference architectures, a diversity of them for various domains can be found, such as for automotive (e.g., the AUTOSAR [10]), and commerce (e.g., Microsoft Reference Architecture for Commerce [11]). They have served as an important basis for the software systems development, since these architectures have proved their efficiency regarding improvement in productivity during software development. Reference architectures have also been built for different purposes [12]: (i) improvement of interoperability among different components of software systems; (ii) standardization of software systems of a given domain or of a company; and (iii) reuse of knowledge from domain experts regarding development of systems for that domain.

In this context, the robotic community has also noticed that the establishment of reference architectures for robotic systems of mobile robots is also quite interesting. Thus, several architectures can be also found. However, selecting a more adequate architecture aiming at using this one as basis of the development of new robotic systems, as well as evolution of existing systems, is still a hard task. There is not a complete panorama of these architectures and also information or guidelines that support selection of such architectures. This scenario has therefore motivated this work.

III. FINDING THE REFERENCE ARCHITECTURES

In order to specifically find reference architectures which could be applied to the development of robotic systems for mobile robots, we performed an exhaustive search conducting a systematic review. Our systematic review was conducted from December/2011 to January/2012, following the process proposed by Kitchenham [7]. In short, this process presents three main phases: (i) Phase 1 - Planning: In this phase, the research objectives and the review protocol are defined. The protocol constitutes a pre-determined plan that describes the research questions and how the systematic review will be conducted; (ii) Phase 2 - Conduction: During this phase, the primary studies are identified, selected and evaluated according to the inclusion and exclusion criteria established previously. For each selected study, data are extracted and synthesized; and (iii) Phase 3 - Reporting: In this phase, a final report is formatted and presented.

In short, we established one research question: "Which existing reference architectures could be applied to develop robotic systems to mobile robots?" We then identified the main keywords — "reference architecture", "robot", and "unmanned ground vehicle" — and we established a search string considering these keywords and their possible synonymous: `((``reference architecture'' OR ``reference model'') AND (``robot'' OR ``robotic'' OR ``unmanned ground vehicle'' OR ``UGV'' OR ``intelligent vehicle''))`. We added "reference model" in the search string, since it is sometimes used to refer to reference architecture. We also added "intelligent vehicle" to refer to mobile robots. Finally, to find the works (also primary studies in the systematic review context), we used main publication databases: ACM Digital Library [13], IEEEXplore [14], ISI Web of Knowledge [15], and Scopus [16]. As a result of our search in these databases using the search string, a total of 409 primary studies were discovered. Removing the repeated studies, we had 371 unique studies. The title and abstract sections of each study were read and a total of 14 studies were selected for further reading. Next, these studies were read in full and, finally, seven reference architectures that are applicable to mobile robots were identified: 4D/RCS [17], ACROSET [18], AIS [6], JAUS [5], Robot Teleoperation [4], Servicebots [19], and SMAS [20]. For the selection of these architectures, we considered reference architectures that filled three main requirements: (i) the architecture presents a set of pre-defined functionalities that could be contained in robotic systems; (ii) the architecture explains the interaction among these functionalities; and (iii) the architecture permits the derivation of software architectures and their respective systems. It is important to say that these requirements are essential to reference architectures, if it is intended in fact to use them to the robotic system development.

It is important to say that the objective of the systematic review was then to identify all reference architectures applicable to mobile robots. Furthermore, a second search for specific information of these architectures was conducted considering additional documents, such as the web sites, books, papers in conferences and journals, and any other documents that could support to conduct our analysis.

IV. DESCRIPTION OF THE REFERENCE ARCHITECTURES

Based on the seven reference architectures that are applicable to the mobile robots, we conducted a detailed investigation on each one and developed a comparison among them. In Table I, each reference architecture is presented together with name and type of the mobile robots. Below, we present an overview of each reference architecture.

The **4D/RCS** reference architecture provides a theoretical foundation for designing, engineering, integrating, and testing intelligent software systems for unmanned vehicle systems [17]. It consists of a multi-layered multi-resolutional hierarchy of computational nodes, each containing elements of sensory processing (SP), world modeling (WM), value judgment (VJ), and behavior generation (BG). From high levels to low levels, the reference architecture contains functionalities that permit goal definition, going to perception, cognition, and reasoning, involving sensors and actuators. According to its author, this architecture enables precise and fast responses in lower levels while it formulates plans and abstracts concepts in higher levels.

The **JAUS** [21] reference architecture uses a message passing protocol to provide interoperability among subsystems and components that compose systems resulting from this architecture [5]. JAUS presents a service-oriented approach to enable distributed command and control of these systems. The reference architecture provides information about how to enable online interoperability of unmanned systems and their components. For that, JAUS defines a set of basic services which are required by most higher level components, and they are defined in JAUS Core Service Set (JSS Core).

The **ACROSET** is a component-oriented reference architecture for teleoperated service robots [18]. Its main characteristic is the reuse of components from different systems. The reference architecture is composed by subsystems: *Coordination, Control and Abstraction Subsystem* (CCAS); *Intelligence Subsystem* (IS); *User Interaction Subsystem* (UIS); and *Safety, Management and Configuration Subsystem* (SMCS). The CCAS abstracts and encapsulates the functionality of the physical devices of the robots. This subsystem is composed by virtual components that can be implemented in either software or hardware. Besides that, in order to deal with operator-driven, semi-autonomous systems, the IS was inserted in this architecture. This subsystem permits to have different types of user (and even an autonomous subsystem). The UIS is responsible for interpreting, combining, and arbitrating among orders that may come simultaneously from different users. Finally, the SMCS presents two main functionalities: (i) the monitoring of functionalities from other subsystems; and (ii) management and configuration of the initialization of the application.

The **Servicebots** reference architecture was designed to service robots operating in indoor environments [19]. In this context, service robots are those supposed to perform tasks (like mail delivery, tourist guide, etc) in buildings of a whole variety of characteristics [19]. The reference architecture is composed by three subsystems that use the IT (Information Technology) backbone (i.e., the local area

Table I
REFERENCE ARCHITECTURES FOR MOBILE ROBOTS

Name	**Type**
4D/RCS [17]	Unmanned ground vehicles
JAUS [5]	Unmanned systems
ACROSET [18]	Teleoperated service robots
Servicebots [19]	Indoor service robots
SMAS [20]	Situated multi-agent systems
Robot Teleoperation [4]	Robots with many controllers
AIS [6]	Adaptive intelligent systems

network) to communicate and complete the task; these three subsystems or types of robots are: *servicebots*, *fixbots*, and *softbots*. The type *servicebots* is a robot capable of driving autonomously only with sensorial information in an average complex environment (e.g., corridors). The *fixbots* present sensor and actuators distributed all over the environment, having their own intelligence and communication channel. The *softbots* refer to the software agents executing various tasks for the requesting user, fixbot or servicebot. Thus, the reference architecture is concerned with performance, configuration, problem, human-interface, and security management.

The **SMAS** reference architecture provides a blueprint for architectural design of multi-agent system applications [20]. It is composed by two subsystems: the *agent* and the *application environment*. The first one comprises three modules: (i) perception through getting information from the environment; (ii) decision making, selecting the agent action; and (iii) communication, responsible for interactions with other agents. The second subsystem comprises seven modules: (i) representation generator, perceiving the environment; (ii) interaction, dealing with agents' influences in the environment; (iii) communication service, collecting messages and delivering messages to the appropriate agents; (iv) observation, observing the deployment context; (v) synchronization, monitoring domain-specific parts of the deployment context and keeping the corresponding representation in the state of the application environment up to date; (vi) dynamics, maintaining processes in the application environment that happen independent of agents or the deployment context; and (vii) translation of influences and messages into low-level interaction primitives with the deployment context, and low-level formatted messages into messages for agents.

The **Robot Teleoperation** reference architecture is concerned with robots having different controllers [4]. To achieve the objective, the reference architecture was proposed according the definition of Bass [22]. Thus, a domain analysis was made to identify the set of components, followed by the domain design to make the generic design, where patterns and common models could be used. The main identified components were: *graphical representation*, *collisions detection*, *user interface*, *communications* and, the most important, *controller*. To specify how the different components are going to interact, two architectural styles were selected: (i) client-server, used in the interactions between *graphical representation* (client) and *collisions detection* (client) with *controller* (server); and (ii) communicating processes, used in the interactions between *user interface* and *communications* with *controller*, because all of them can take the initiative to send data.

Finally, the **AIS** reference architecture is a heterogeneous mixture of common architectural styles [6], permitting the creation of various adaptive intelligent systems. It is divided hierarchically into layers for different sets of computational tasks. Properties of pipe and filter style architectures are provided by the layers and relations among them. Thus, the reference architecture has two layers (or levels): the *physical level*, responsible for action and perception in external behaviors; and the *cognitive level*, responsible for more abstract reasoning activities (e.g., planning, problem solving, etc). The components comprising each layer are organized in a blackboard style, allowing a range of potentially complex behaviors, since basic functionalities provided in each level can work together to perform more complex functionalities.

After investigating each reference architecture, a comparison among them was developed, aiming at providing information in order to better support selection of one or more architectures when developing new robotic systems or evolving existing ones. Also, we expect this analysis supports the proposal of new reference architectures, since we present a set of main features present in the analyzed architectures. Moreover, the comparison will not point out which reference architecture is better, because each one has its specific requirements and application environment.

V. ANALYSIS OF THE REFERENCE ARCHITECTURES

Regarding analysis of the reference architectures, we also adopted the systematic guidelines proposed by systematic review. For this, we defined three perspectives and compared these architectures: context of application, maturity, and functionalities. To the first perspectives, we analyzed each reference architecture determining if they were developed in an *academic* context or in a *industrial* context. The result of this analysis is presented in Table II. We observed that both industry and academy are interested in proposing reference architectures.

Considering other domain where the success of a reference architecture depends on involvement of the industry, we can observe that reference architectures for mobile robots present good perspective of success, since more than half of the architectures present efforts from industry. Besides that, if selection of an architecture is necessary, it is more interesting to select architectures that have efforts from industry.

Table II
CONTEXT OF DEVELOPMENT OF THE REFERENCE ARCHITECTURES

Reference Architecture	Development Context
4D/RCS	Industrial
JAUS	Industrial
ACROSET	Industrial
Servicebots	Academic
SMAS	Academic
Robot Teleoperation	Industrial
AIS	Academic

Thus, 4D/RCS, JAUS, ACROSEFT, and Robot Teleoperation could be first considered. However, each architecture has its characteristics and knowledge aggregated; hence depending on the purpose of the robotic system to be develop a specific architecture could be more adequate than another one.

Aiming at determining the maturity level of the architectures (i.e., how much they are evaluated), we established three levels: (i) Architectural instantiation: the reference architecture was only instantiated, i.e., the design of robotic systems was developed, but no implementation is presented; (ii) Implementation: at least a robotic system was implemented based on the reference architecture, through, for instance, a case study; and (iii) Use in real situation: the reference architecture is in fact already used in real situations, in particular, in the industry. This fact shows a higher level of maturity of the architecture. Table III shows the result of our investigation. As result, we have observed that reference architectures for mobile robots are in general mature, since three architectures present implementation of robotic systems based on the architecture; besides that, the most of them (i.e., four architectures) have been already used in the industry. Therefore, 4D/RCS, JAUS, ACROSET, and Robot Teleoperation seem to be the best choices to be considered in the adoption of a reference architectures, considering their maturity.

Table III
MATURITY LEVEL OF THE REFERENCE ARCHITECTURES

Reference Architecture	Maturity Level
4D/RCS	Use in real situation
JAUS	Use in real situation
ACROSET	Use in real situation
Servicebots	Implementation
SMAS	Implementation
Robot Teleoperation	Use in real situation
AIS	Implementation

The analysis of the last perspective was the most difficult to be conducted, since we needed to determine a set of functionalities that comprise all reference architectures and, frequently, we found sub-functionalities inside other one. Thus, we defined 10 functionalities and indicated, for each reference architecture, if each functionality is present partially, completely, or not explicitly present. The result of this investigation is presented in Table IV, where an "X" indicates a functionality completely present, an "X*" refers to a functionality partially present, and a blank space indicates functionality not present. Therefore, these architectures have presented a range of functionalities, partially or completely, and, in general, ACROSET seems to be the most complete architecture. Furthermore, our investigation could provide important information to guide the selection of a more adequate reference architecture. For instance, if functionality "Decision judgement" is required in the robotic system to be developed, it is interesting select ACROSET than other architectures. Besides that, this table provides important information about which functionalities could be inserted in the architectures in order to become them more complete. Considering the set of functionalities identified in this work, "owners" of these architectures could have a direction about how to evolve their architectures, if desired. This set can also support the proposal of new reference architectures, since they can be considered as a basic set of functionalities because they are present in a significant number of reference architectures. Moreover, each functionality can be explored in depth, if necessary. In order to use these architectures, a detailed study could be necessary to understand specific points of them.

It is important to highlight that these results do not indicate if a reference architecture is better than another one. Besides that, there exists also functionalities or aspects of reference architectures which were not discussed in this work, because they are not important for mobile robots.

VI. DISCUSSION

The investigation presented in this work intends to support selection of reference architectures for new projects, to the evolution of existing ones or to the proposal of new reference architectures; thus, productivity and quality of the mobile robotic systems could be possibly improved. In general, robotic domain presents good perspectives regarding reference architectures, mainly because industry have been involved in the establishment of such architectures. Regarding their documentation, in general, these architectures are well-documented; however, several of them, for instance, that presented in [18] and [4], could present a more comprehensive representation, if it is intended an adequate dissemination of their architectures. In this perspective, these architectures will have more chances to provide an effective contribution to the robotic area.

Besides that, it was clear the potential of these architectures, since they permit to derive as many components.

Table IV
FUNCTIONALITIES CONTAINED IN THE REFERENCE ARCHITECTURES

Functionality	**Reference Architecture**						
	4D/RCS	**JAUS**	**ACROSET**	**Servicebots**	**SMAS**	**Robot Teleoperation**	**AIS**
Sensorial processing	X	X	X	X	X*	X*	X
Controlling	X	X	X	X	X	X	X
Collision detection	X	X*	X*	X*		X	X*
World mapping	X*			X*			X
Action planning	X	X*	X*	X*	X		X
User interfacing		X	X	X	X*	X	
Communication	X	X		X	X	X	X*
Security		X	X	X			
Decision judgement			X			X*	X*
Multi-robotic interaction	X*	X*		X	X		X*

However, we noticed that some reference architectures, in particular [19], could have their components and functionalities presented in more detailed way.

Based on our investigation, new topics of research can be identified. Thus, the most important ones that we have observed are:

- Establishment of a general, unique, and complete reference architecture for mobile robotic systems, containing possibly all functionalities, constraints, other important information related to robotic system development. This architecture could facilitate therefore the development of any robotic systems;
- Proposal of mechanisms (such as frameworks and components already implemented, as well as support tools) to easily use the reference architectures, since architectures found in this work do not provide in general an adequate automated support; and
- Proposal of complete guidelines to use the reference architectures for mobile domain, since most studies make it more succinctly. However, there are other studies presenting well-specified, detailed guidelines, including the entire architecture. Thus, it is possible to identify this topic as a trend in reference architectures for robotic systems.

Regarding the limitation of this work, other sources of information could be used, possibly resulting in more reference architectures to be studied and, as consequence, achievement of a more comprehensive investigation. In another perspective, we considered only reference architectures applicable to mobile robots; however, this experience could be extended to other types of robots, such as production line robots. Furthermore, the conduction of a systematic review involving a new research area — in our case, mobile robotic systems — is not easy, since there is not a consensus in concepts/terms used by different reference architectures; thus, sometimes, it was necessary to infer a conclusion to make some decisions.

VII. CONCLUSION AND FUTURE WORK

The main contribution of this work is to present an panorama of the reference architectures which could be applied in the development of mobile robotic systems. In general, good initiatives can be found, including architectures that have been used in the industry context. Furthermore, besides our suggestion of future research topic in this area, we believe that this investigation could contribute to the robotic community to open other research fields in mobile robots and related areas.

Motivated by the achieved results, we intend to conducted a detailed, comprehensive investigation involving other types of robotic systems, for instance, production lines robots, intending to contribute to a more effective development of robotic systems.

In a parallel work, we are proposing a new reference architecture aiming at the development of multi-robotic systems for indoor service robots. Thus, we hope that the emerging field of robotics can be supported by our reference architecture.

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