Robotic frameworks, architectures and middleware comparison

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Abstract Nowadays, the construction of a complex robotic system requires a high level of specialization in a large number of diverse scientific areas. It is reasonable that a single researcher cannot create from scratch the entirety of this system, as it is impossible for him to have the necessary skills in the necessary fields. This obstacle is being surpassed with the existent robotic frameworks. This paper tries to give an extensive review of the most famous robotic frameworks and middleware, as well as to provide the means to effortlessly compare them. Additionally, we try to investigate the differences between the definitions of a robotic framework, a robotic middleware and a robotic architecture.

Keywords Robotic framework · Robotic architecture · Robotic middleware

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1 Introduction

Robots are mechanical or virtual agents that are able to perform tasks by collecting various types of data and interacting with the environment through their effectors. It is obvious that since robots are machines (in a wider sense), they are incapable of human-like intellectual capabilities such as thinking, taking initiatives or improvise. On the contrast, robot capabilities are limited to their programmers’ software that in many cases consists of a large variety of modules from kinematic models or PID controllers to high level functionalities, such as navigation strategies or vision based object recognition. It is apparent that programming a complex robot from scratch is an unfeasible task for two reasons. First of all a team comprised of scientists specialized in many different areas is needed and second, great effort must be applied in joining the separate software modules for the whole robotic system to work fluently. For that reason, a large variety of robotic frameworks, middleware and architecture proposals exist, aiming at not reinventing the wheel, but providing a solid basis for any robotics developer to build on and perform in an effective way their experiments.

2 Nomenclature

A Robotic framework is a collection of software tools, libraries and conventions, aiming at simplifying the task of developing software for a complex robotic device. In most of the cases, the use of a robotic framework dictates the general architectural principles of the developed software (for example if it is centralized, real-time etc.). It is true that tasks considered trivial by humans are extremely hard to be solved in a generic way from a robotic device, as the environmental conditions are altered in a dynamic fashion. So, in order to create genuinely intelligent
robotic software it is essential to use a tool like a robotic framework that allows for rapid robotic development, as it provides a priori the necessary modules of a robotic system, such as safe message passing, motor driving etc.

The Robotic middleware’s definition is similar to the one of the Robotic framework. A descriptive definition of the "robotic middleware" term could be the glue that holds together the different modules of a robotic system. The most basic task of a robotic middleware is to provide the communications infrastructure between the software nodes running in a robotic system. The usual case is providing the essential software - hardware interfaces between the high level (software) and the low level (hardware) components of the system, as these consist of various OS specific drivers that an average robotics researcher is impossible to develop. It is apparent that the concepts of a robotic framework and a robotic middleware are tightly connected and in most of the cases not possible to distinguish. A difference that could be noted is that a robotic middleware (if considered the glue keeping together the distinct modules) should provide only basic functionalities and be invisible to the developer. On the contrast, a robotic framework is created to provide the above functionality, as well as an API to services or modules already tested by the scientific robotic community. In that way it can be assumed that a robotic middleware is encapsulated in each robotic framework.

A Robotic architecture differentiates from the robotic framework and robotic middleware definitions, as it is a more abstract description of how modules in a robotic system should be interconnected and interact with each other. The real challenge for a successful robotic architecture is to be defined in such a way that can be applied to a large number of robotic systems. Obviously this is a very hard task since robotic systems are characterized by extreme diversity. For example it is very difficult to define a single architecture that can operate both with synchronous/asynchronous, single or multiple robot systems. In conclusion, a robotic architecture should organize a robotics software system and in the general case, to provide the communication infrastructure between the different modules (software or hardware).

There are many surveys that present the state-of-the-art in the scientific area of robotic architectures, middleware and frameworks. For example in [10] a comparison of open source RDEs (Robotic Development Environments) is being made, concerning their specifications, platform support, infrastructure, implementation characteristics and predefined components. Additionally a comparison exists for each RDE’s usability. In [2] eight different robotic frameworks are compared using three distinct metrics: ‘Programming and communication’, ‘Robot control patterns’ and ‘Development and deployment’. Then the CoRoBa framework is presented in detail.

On a similar context, in [3], [4] and [5] a comparison of various famous robotic frameworks is being made. On a more theoretical approach, [6] discusses the consolidation of the two main trends in the integration frameworks (i.e. the robotic frameworks / middleware and architectures): the communication layers and the component-based frameworks. The discussion is being made under the consideration of the bigger picture of a robotics system, regardless of the actual integration layer, and is presented through the prism of Rock (the Robot Construction Kit).

From the definitions presented it is obvious that the limits of each term are fuzzy and in many cases overlapping, although the robotic architecture meaning seems to be more distinct than the other two. For that reason the robotic frameworks and middleware will be presented in the same chapter (3.2) whilst the robotic architectures will be described in a separate one (3.3).

3 Robotic frameworks and middleware

The current section contains a state-of-the-art survey of the most famous robotic frameworks and middleware. The two most relevant frameworks to RAPP are initially presented (ROS and HOP), then the most wide-spread and the rest are mentioned in an alphabetic order.

3.1 ROS (Robot Operating System)

The Robot Operating System (ROS) is a framework targeted for writing robot software. It is comprised of tools, libraries and conventions that aim for complexity reduction, concerning the procedure of writing complex and robust robotic behaviours (and generally robotic software). Its creators describe it as meta-operating system [7], as it provides standard system operating services, such as hardware abstraction, low-level device control, implementation of commonly used functionality and message-passing between processes and package management. It is fully distributed, as it supports transparent node execution on heterogeneous robotic devices or computers and is comprised of three main core components:
A. Communications infrastructure: The middleware part of ROS is the communications infrastructure, which is a low-level message passing interface for intra-process message exchange. Apart from the message passing functionality, it supports the recording and playback of messages via the rosbag tool, remote procedure calls, as well as a distributed parameter system.

B. Robot-specific features: In addition to the core components, ROS is equipped with various robot-specific tools that speed up the robotic software development. Some of the most important ones include:

- Standard Message Definitions for Robots
- Robot geometry library
- Robot description language
- Diagnostics
- Pose estimation algorithms
- Localization modules
- Mapping algorithms
- Navigation and path creation modules

C. Tools: One of ROS strengths is the powerful development toolset. Various tools are included that provide introspecting, debugging, plotting and visualizing variables, procedures and even the state of the robotic system. Using these, the data flow can be easily visualized and debugged, as the message transmitting system is underlying. The two most famous tools ROS includes are rviz (for experiment visualization) and rqt (for data visualization and graphical module incorporation), whereas others such rosgraph, rxplot etc. provide additional debugging capabilities.

Finally ROS provides seamless integration with other community accepted robotic libraries such as the Gazebo 3D simulator, OpenCV for image processing, PCL (Point cloud library) and MoveIt! for navigation purposes. It must be stated that ROS is not real time but real-time code can be incorporated with it. Additionally in 2009 the integration of ROS and Orocos RTT (real-time framework - will be described later) was announced. Conclusively ROS is the state-of-the-art of robotic frameworks and it tends to be a standard for robotic application development.

This fact is supported by a grate number of publications concerning ROS. In [6] ROS is investigated as the tool to traverse from robotic components to whole systems. Additionally, the distributed characteristic of ROS, as well as some of its ports to the JavaScript language [8], allows it to be the link between intelligent environments and the "internet of things" [9]. Elkady, Joy and Sobh in [10] use ROS as a plug and play middleware for sensory modules, actuator platforms and task descriptions in robotic manipulation platforms, whereas in [11] it is used as basis for the creation of another framework (CRAM - Cognitive Robot Abstract Machine) for everyday manipulation in human environments.

3.2 Hop

The Hop system is a toolset for programming the Web of Things [12]. Hop is typically used to coordinate home automation and robotic environments for assisted living. Environments consist in the aggregation of communicating objects (sensors and active components such as robots) which are discovered, identified, and linked to client/server Hop software modules distributed among components. Hop orchestrates data and commands transfer among objects, to and from web services and user interface components.

Hop is a multi-tier programming environment, built on top of web protocols and languages (http, web sockets, html, JavaScript). Hop servers run indifferently on PC or smaller devices, whereas Hop clients run within the JavaScript environment of web browsers [13], on PCs and wireless devices. HOP servers may also act as clients of other HOP servers [14].

Hop supports software extensions, enabling the integration of additional objects and system libraries (for example, Hop provides bindings to control and command Phidget sensors and actuators, widely used in robotic prototypes). This approach is very powerful as it allows for arbitrary extensions, at the cost of some specific integration work to support additional third party libraries.

Another integration model is being implemented, promoting the use of JavaScript as the default programming language for Hop (replacing an ad hoc language, based on Scheme) and the generic integration of third party software frameworks (such as ROS). This new approach is expected to dramatically decrease the cost of integrating new components, such as hardware devices or software libraries.

HOP applications are called weblets. Applications are written either in the HOP language or using javascript (Javascript execution is native within web browsers hosting HOP user interface clients, and a compiler is being prototyped to also support JavaScript in a HOP server environment). The HOP environment is extensible; standard libraries provide
access to operating system services (file system, process management, peripherals, network services including multicast discovery services), whereas additional libraries (such as drivers to control specific hardware, or motion control libraries) may be linked to the environment if needed and made available to application developers through additional HOP API.

HOP is designed to allow for the simple specification of distributed applications. The language syntax allows to direct functions to run either on the server or the client side, with automatic serialization of client/server messages using web protocols.

3.3 Player / Stage / Gazebo

The Player / Stage / Gazebo project is one of the most famous and "traditional" robotic frameworks. It was initially distributed in 2001 from the USC Robotics Lab and from then it is being used in various robotic labs and projects respectfully. As the title suggests, it consists of three distinct software packages:

A. Player: Player provides a network interface to a large ensemble of robot and sensor hardware. Its strength lies in the fact that the client/server model it provides, allows for developing programs in any programming language (that supports the TCP/IP protocol) and running them in a distributed fashion on a computer with a network connection to the respective robot. It supports Linux, Solaris and BSD operating systems. As stated in Player’s website "Player supports multiple concurrent client connections to devices, creating new possibilities for distributed and collaborative sensing and control".

B. Stage: Stage is a 2D (two dimensional) multi-robot simulator. It simulates a variety of sensors including sonar range finders (SRFs), laser range finders (LRFs), pan-tilt-zoom cameras and odometry. Stage is created to work seamlessly with Player, aiming to minimize the software robot controllers needed to perform a simulation. For that reason many controllers created with Player and tested in Stage were directly able to work on real robots. A screenshot of Stage is presented in Fig. 1.

C. Gazebo: Gazebo is the third and most recently developed part of the Player/Stage/Gazebo project and is a 3D (three dimensional) physics multi robot simulator for outdoor environments. It provides realistic sensor simulation and supports four different physics engines: ODE (Open Dynamics Engine), Bullet, DART (Dynamic Animation and Robotics Toolkit from Georgia Tech) and Simbody from Standford University. Gazebo, except for its native interface, presents a standard Player interface. In that way the controllers written for the Stage 2D simulator can be used (in most of the cases) with Gazebo with minimum modifications. A screenshot of Gazebo simulator is presented in Fig. 2.

Player is referenced in a vast number of publications. In [15] its architecture is explained and the authors consider it as a "practical" robot programming framework. Its distributed character is also appraised in many works such as in [16], where the massive multi-robot simulating capabilities are described and in [17] and [18] where the distributed control services of Player/Stage are presented. Of course, Gazebo has drawn a lot of attention as well [19] and has been lately supported officially by ROS. Finally Player/Stage/Gazebo naturally participates in various robotic framework surveys [20].
3.4 MSRS (Microsoft Robotics Studio)

Microsoft Robotics Studio is a Windows based environment for robot control and simulation. It is based on a .NET-based concurrent library implementation for managing asynchronous parallel tasks, CCR (Concurrency and Coordination Runtime). MRS implementation involves message-passing and a lightweight services-oriented runtime called DSS (Decentralized Software Services), which coordinates several services to orchestrate more complex behaviours. It also provides a 3D simulation for physics-based virtual environments Fig. 3.

MSRS requires C# as controller programming language and is not open source. Microsoft states that MSRS supports a number of robotic devices that can be controlled either by installing MSRS in them (in an embedded PC running Windows), or remotely via wi-fi or bluetooth. In [21] the full description and documentation of MSRS exists, whereas in [22] a technical introduction in MSRS is attempted. Additionally, in [23] Microsoft Robotics Studio is investigated as a mechanism for service oriented robotics. Finally [24] compares the Player / Stage / Gazebo framework to MSRS in two different ways: by examining the documented features of each and by examining the usability experience gained from implementing two distinct robotic tasks (wandering and foraging) in a simulated environment. The conclusion reached was that both frameworks are very capable RDEs (robot developing environments), though MSRS wins in installation ease whilst Player / Stage / Gazebo is superior on an architectural basis.

Fig. 3 3D simulation in MSRS

3.5 ARIA (Adaptive Robot-Mediated Intervention Architecture)

ARIA is basically a C++ library that provides various tools, so it can be denoted as a "pure" robotics framework. These tools include the software input / output (I/O) integration with custom hardware devices (digital, analog or serial) and, as its creators state, it supports all MobileRobots / ActivMedia robot accessories. Additionally, a core part of ARIA is ArNetworking, the tool that enables the distributed nature of the framework. Specifically ArNetworking implements an extensible infrastructure for easy remote network operations, user interfaces and other networked services. Additionally a variety of useful tools is provided, such as sound effect playback, speech synthesis and recognition, mathematical functions, cross-platform thread and socket implementations etc. ARIA has been used for inclusion purposes [25], where a "children with autism" specific implementation was created.

3.6 ASEBA

ASEBA is a robotic framework that "provides a set of tools which allow novices to program robots easily and efficiently". The difference of ASEBA from the previously described frameworks is that it is an event-based architecture for real-time distributed control of mobile robots. ASEBA is using a lightweight virtual machine as core and targets integrated multi-processor robots or groups of single-processor units, real or simulated. Its strength is that it provides access to microcontrollers from high level languages, as it integrates with D-Bus and ROS.

The real-time and event-based character of ASEBA is referred by various publications, such as [26], where is described as a modular architecture for event-based control of complex robotic systems. In [27] ASEBA is used in a "games and computer science" context, where an open-source multiplayer introduction to mobile robots programming is presented. Finally in [28], the D-Bus integration to ASEBA is described, that converts the low-level event architecture into a robotics middleware.

3.7 Carmen (Robot Navigation Toolkit)

Carmen is an open source collection of software for mobile robot control created from the Carnegie Mellon University. It is constructed in a modular way and provides basic navigation primitives including base
and sensor control, logging, obstacle avoidance, localization, mapping and path planning. Carmen uses the inter-process communication platform IPC (InterProcess Communication facilities) and supports process monitoring. In addition it provides robot hardware support for different platforms, some of which are iRobot’s ATRV and B21R, ActivMedia’s Pioneer I and II, Nomadic Technology’s Scout and XR4000, as well as OrcBoard and Segway. Except for robotic devices, Carmen provides API functions for robotic sensors such as the Sick LMS laser range finder, GPS devices using the NMEA protocol, sonars and Hokuyo’s IR sensors. Carmen supports the Linux operating system and the controllers are programmed in the C++ language. It must be stated that it is not control or real-time oriented.

At a higher level, it provides a two dimensional robot and sensor simulator. Similarly to ROS, a centralized parameter server exists, as well as message logging and playback functionalities. The Carmen framework is written in C but it also provides Java support, runs under Linux and is available under GPL. In [29] Carmen is used to showcase a Monte Carlo method for mobile robot localization, whereas in [30] is presented as a robotics framework in the context of robot mapping.

3.8 CLARAty (Coupled Layer Architecture for Robotic Autonomy)

CLARAty was designed and implemented by the Jet Propulsion Laboratory (JPL) of California Institute of Technology that cooperates with NASA. The developers of CLARAty describe it as a “reusable robotic software framework”. In fact it is a generic object-oriented framework used for the integration of new algorithms in many different scientific areas of robotics: motion control, vision, manipulation, locomotion, navigation, localization, planning and execution. Additionally it can be used in a number of heterogeneous robots with different mechanisms and hardware control architectures. From its description and capabilities, it can be inferred that deviates from the classical "framework" definition and approaches the one of "robotic architecture". Though, since it provides a variety of robotic algorithms it is more suitable to be categorized under the framework / middleware definition. It supports Unix operating systems and the controllers are written in C++. CLARAty claims to be open-source, though its development seems to be discontinued, as it was impossible to find a download webpage or information about development employing it. In [31] CLARAty is investigated under the reusable robotics software prism. There is a variety of publications about the same subject: In [32] and [33] Nesnas et al describe CLARAty as a means to develop interoperable robotic software, whereas in [34] the hardware heterogeneity is specifically mentioned. In a more general manner, in [35] a survey is performed concerning CLARAtys capability of unifying the robotic control software mechanisms. Finally [36] and [37] address its employment under the "autonomous robotics" perspective.

3.9 CoolBOT

CoolBOT introduces an interesting parallelism to the robotics software definition. The main idea is that a software component should be like an electronic component in a chip. The advantages of an electronic component are that it has a very clear functionality and a well-established external interface. If this concept is extended to a robotic system, it could be seen as the integration of multiple software components. If so, the system’s modularity and the software reusability are maximized. CoolBOT aims at constructing a programming tool, allowing to program robotic systems by integrating and composing software components.

The three main software component types that CoolBOT describes are components, views and probes. Components are contained in integrations, which is another name for processes. Integrations can also contain views, which denote essentially a one-to-one association of an integration and a component. Finally probes are software components that wrap non CoolBOT software components with CoolBOT systems.

CoolBOT can operate both in Windows and Linux and the controllers are developed in C++. In [38] CoolBOT is described as "a component-oriented programming framework for robotics", whereas in [39] as a distributed component-based programming framework for robotics.

3.10 ERSP (Evolution Robotics Software Platform)

ERSP is a development platform for creating robotic products, meaning that is mostly oriented in commercial robotic systems and not in hobbyist constructions [40]. It provides critical infrastructure, core capabilities and tools that enable developers to build robotic applications quickly and easily. It provides an ensemble of robotic oriented algorithms:
ERSP Vision is used for recognizing images and objects in real world scenarios and vSLAM help a robotic agent to move autonomously and with safety. ERSN Navigation incorporate obstacle avoidance, collision detection, bump detection and cliff detection. Additionally a set of APIs is included aiming at incorporating the above functionalities in robotic applications written by developers. The ERSP architecture aims at providing the developers with standards for structuring their application with a modular way, as well as tools for combining software and hardware modules seamlessly. Finally ERSP runs both on Linux and Windows and it is a commercial product. Its distribution was discontinued since Evolution (the development company) was acquired from iRobot.

3.11 iRobot Aware

iRobot Aware is the robotics framework developed by the iRobot company and is used in all of its robotic products. Of course Aware is not open source and information about the operating systems or programming languages it supports are not available. The latest version of Aware is 2.0 and as iRobot states, ”it utilizes proven industry languages and open source technologies, providing a flexible and open architecture for third-party development”. It provides advanced robot development tools such as live data viewers, loggers, web-based data management and other debugging tools.

3.12 Marie (Mobile and Autonomous Robotics Integration)

Marie is a robotic framework / design tool for mobile and autonomous robot applications. It was designed in such a way that can integrate multiple heterogeneous software elements. It is based on a distributed model, fact that enables the execution of applications in a group of systems (robots or computers). Its main goals / motivations are:

- To increase the reusability of robotic software components, APIs and even frameworks like Player, CARMEN etc., and to support distributed computing in heterogeneous platforms.
- To boost the development process by adopting a rapid-prototyping approach.
- To allow concurrent use of different communication means (protocols, mechanisms, standards).
- To accelerate user defined development with well-defined layers, interfaces, frameworks and plugins.
- To support multiple sets of concepts and abstractions.

MARIE adopts a layered architecture. The three dominant layers are the core layer which contains tools for low-level OS manipulation, the component layer which specifies and implements basic frameworks that enable component incorporation and application layer that contains tools to create and manage applications using components, aiming at the creation of a complex robotic system. Having a closer look in the main architectural blocks of MARIE, there exist four types of components:

- Application Adapter (AA) that handles the connection between applications
- Communication Adapter (CA), enabling for connection of incompatible communication mechanisms, as well as for routing functions
- Application Manager (AM) and Communication Manager (CM). These two components are used for managing the different application either locally or in a distributed manner

Marie is an open source project, though it seems that is no longer maintained. In [41, 42] and [43] the software design patterns and software integration problems that can be solved with the use of Marie are investigated.

3.13 MCA2 (Modular Control Architecture)

MCA2 is a component-based, real-time capable C/C++ robotic framework for developing robotic controllers. Its main parts are called modules (Fig. 4(a)), which include sensory input and output, controller input and output, as well as internal parameters and variables. The higher level consists of groups (Fig. 4(b)), each of which is a graph of modules. MCA2 treats groups as modules, so the overall architecture is quite flexible [44]. MCA2 is network transparent, meaning that groups can be distributed in a network environment.

The main supporting platform is Linux / RTLinux, but support exists for MCA OS/X and Win32. MCA2 can also be used in conjunction with visualization / simulation tools like SimVis3D 4 and other software systems like TinySEP [45], a tiny platform for ambient assisted living [46].

3.14 Miro (Middleware for Robotics)

Miro is a C++, Linux distributed robotic framework that has an object oriented character, aiming to be
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Fig. 4 MCA2 Architecture

used in robotic control. Its is adherent to the common object request broker architecture (CORBA) standard, fact that enables for inter-process communication and cross-platform interoperability.

Miro was developed in C++ for Linux. Though, since CORBA is programming language independent, components for Miro can be written in any language or platform that provides CORBA implementations. The Miro core components were created with the employment of ACE (Adaptive Communications Environment), which is an object oriented multi-platform framework for OS-independent interprocess, network and real time communication. Additionally they use TAO (The ACE ORB) as their Object Request Broker (ORB), a CORBA implementation designed for high performance and real time applications.

Miro architecture consists of three layers:

- **Miro Device Layer** is the platform-dependent part of the framework and provides abstractions for utilization of robotic sensors and actuators. It takes high-level military-style plans and executes them with a team of real or simulated robotic vehicles. It supports multi-robot execution both in simulation and reality. Each vehicle executes its portion of the mission using reactive control techniques.

- **Miro Service Layer** contains service abstractions for sensors and actuators via CORBA IDL (CORBA Interface Definition Language) and implements them as network-transparent modules, allowing for cross-platform systems.

- **Miro Class Framework** provides high-level robotic functionalities, such as mapping, navigation, path planning, logging and visualization.

Miro has appeared in a number of publications such as [47] and [48].

3.15 MissionLab

MissionLab was developed by the Mobile Robot Laboratory under the direction of prof. Ronald Arkin. It takes high-level military-style plans and executes them with a team of real or simulated robotic vehicles. It supports multi-robot execution both in simulation and reality. Each vehicle executes its portion of the mission using reactive control techniques.

Programming in MissionLab occurs in CDL (Configuration Description Language) and CNL (Configuration Network Language) that after compilation are transformed to C++ code. Also console-like and graphical tools are provided for easy experiment monitoring. MissionLab uses two servers: HServer (Hardware Server) that directly controls all the robot hardware and provides a standard interface for all the robots and sensors, and CBR Server (Case-Based Reasoning Server), which generates a mission plan based on specifications provided by the user by using information stored from previous mission plans. Though MissionLab is not widely used, publications exist that exhibit its capabilities, such as [50] where a design process for planning in micro-autonomous platforms is described and [51] where MissionLab is employed in the TAME (Time Varying Affective Response for Humanoid Robots) model.

3.16 MOOS

MOOS (Mission Oriented Operating Suite) is a C++ cross platform middle ware for robotics research. It is helpful to think about it as a set of layers:

- **Core MOOS** - The Communications Layer: This layer implements a network based communications architecture (two libraries and a lightweight communications hub called MOOSDB) which enables for building inter-communicating applications.
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- Essential MOOS - This consists of applications that deploy CoreMOOS. They offer many functionalities such as process control, logging and others.

Additional tools/applications and libraries are available, with which:
- a Matlab session can be connected to a set of MOOS enabled processes
- visually debugging a set of communicating processes is possible
- replay of logged communications can be performed

MOOS has a maritime heritage (its development initiated while the creator was a postdoc in the Dept. Ocean Engineering at MIT). It is still used for ocean-bound work \[52\] and for that reason the full package contains a few legacy applications which have a maritime bent:
- Applications to control NMEA GPS, Orientation and Depth Sensors
- State - based control of vehicles (pHelm)
- A pose estimation framework for underwater and surface vehicles (pNav)

3.17 OpenRave

OpenRave is oriented in testing, developing and deploying motion planning algorithms for robots. The main focus is on simulation and analysis of kinematic and geometric information related to motion planning. For that reason its use is more oriented to robotic arms and generally in systems that include many degrees of freedom. It provides command line tools and the run-time core is easy to be deployed in larger and more complex robotic systems. The most important technology OpenRAVE provides is a tool called IKFast, the Robot Kinematics Compiler. This can analytically solve the kinematic equations of any complex kinematics chain and generate language specific files, like C++, for later use. An important target application is industrial robotics automation, where OpenRave can in theory be easily integrated due to its stand-alone nature.

OpenRAVE framework was initially created in a thesis and was then expanded through relevant publications \[53\].

3.18 OpenRDK

OpenRDK is a modular software framework that intends to accelerate the creation of complex robotic systems. The main entity is a software process called agent (Fig 5). A module is a single thread inside the agent process. Modules can be loaded and started dynamically once the agent process is running. OpenRDK is distributed, so modules can run in the same or different machines and communicate using a blackboard-type object, called repository, in which they publish some of their internal variables called properties. An extensive description of OpenRDK can be found \[54\] and \[55\].

3.19 OPRoS (Open Platform for Robotic Services)

OPRoS is an open source platform based on components. It provides:
- An integrated development environment (IDE) for the development of robotic software and the monitoring of the robots
- A framework to manage the distinct software components, including a simulator for easier debug and evaluation
- A server that handles the component repository and specifically the proxy services between the different components.

A European community for OPRoS exists (since OPRoS is a Corean product), where a comparison to other robotic frameworks can be found. OPRoS has been drawing attention since 2008 and there are a number of publications that include it. In \[56\], \[57\] and \[58\] its component-based architecture is being discussed, in \[59\] attention is paid in its fault detection capabilities, whereas in \[60\] an UPnP single event mechanism for OPRoS is presented.

3.20 Orca

Orca is an open-source C++ framework for developing component-based robotic systems. It provides the means for defining and developing the building blocks
which can be placed together to form arbitrary complex robotic systems, from single vehicles to distributed sensor networks. It supports the Linux, Windows and QNX Neutrino operating systems and its goals are to

- Promote and enable software reuse by standardization of interfaces
- Provide a high-level and easy to use API, aiming at module reuse
- Creation of a repository of components

In [61] and [62] the component based characteristic of Orca is presented, whereas in [63] Orca is used as a showcase for the component-based robotics in general. Finally in [64] the lightweight characteristics of Orca are described and the advantage of a 'thin' robotic software frameworks is discussed.

3.21 Orocos (Open Robot Control Software)

Orocos is free software project (basically a collection of portable C++ libraries) oriented in robot control. One of its main characteristics is that is component based: complex software systems are not constructed at "compile time" but at "deployment time" or "run time". Additionally it has multi-vendor support, meaning that components that are built from different vendors can participate in a more complex system. Finally, its main strength is that it is free and is focused on real time control of robots and machine tools. Orocos is comprised of three basic tools (Fig. 6):

- A Kinematics and Dynamics library which include kinematic chains, real-time inverse and forward kinematics
- A Bayesian Filtering Library which has Dynamic Bayesian Networks, (Extended) Kalman filters, particles filters and Sequential Monte Carlo methods
- The Orocos Toolchain that enables for real time software components, interactive scripting, state machines, distributed processes and code generation.

A detailed description of Orocos can be found in [65], whereas in [66] Orocos is used as an architecture for indoor navigation. Finally, as stated in the ROS description, ROS and Orocos RTT were integrated in 2009, thus allowing for real-time control in the ROS environment.

3.22 RoboFrame

RoboFrame is a C++ message-oriented middleware. It is designed as a framework from bottom-up following the concept of inversion-of-control. The platform specific implementation is wrapped in a thin abstraction layer and currently the operating systems Linux, BSD Linux, Windows are supported. RoboFrame provides message exchanging and shared memory communication mechanisms having in mind two important parameters:

- Enabling of message exchange between components running in the same thread using references without any overhead commonly present
- Enabling remote monitoring of the robotic device, taking under consideration the specific parameters of the robot-to-base station communication difficulties.

RoboFrame is described as a modular software framework for lightweight autonomous robots in [67]. Finally it provides a graphical user interface that enables for easier robotic software development, though no information was discovered about if it is open-source or about downloading and employing the package.

3.23 RT middleware (Robotics Technology Middleware) OpenRTM-aist

RT middleware is a collection of standards for robots, supporting distributed execution. The basic unit of this framework is the RT-component which is a generic class of robotic "objects", such as actuators.
RT-middleware uptakes the task of creating a network graph consisting of RT-components in order to create a more complex system, aiming at code and consecutively component reusability. Each RT-component is attached to another RT-component via a "port". There are many types of ports and only common types of ports can be connected. Each RT-component is stateful, in the meaning that it can be perceived as a state machine.

OpenRTM-aist is a software platform based on the RT middleware standard. It implements some real-time features and includes a manager that allows easier manipulation of RT-Components.

A general description of RT-middleware, including its overall architecture, as well as the functionalities of RT-Components can be found in the work of Ando, Noriaki et al [68], [69], [70].

3.24 Pyro (Python Robotics)

Pyro stands for Python Robotics and its main goal is to promote the high-level concept of programming robotic systems. This means that the developer will pay minimum attention to low-level implementation details, allowing him to easily concentrate to more interesting advanced robotic topics such as artificial intelligence, multi-robot planning etc. Its main features are:

– It is open source, so it is available for expansion
– Designed for research and education use
– Works on many heterogeneous robotics platforms and simulators
– Encapsulates a rich module repository, comprising control methods, vision (motion tracking, blobs, etc.), learning (neural networks, reinforcement learning, self-organizing maps, etc.), evolutionary algorithms, and more.

As its name suggests, Pyro is written in Python, which means that the researcher can interactively experiment with the robot programs. Of course, as a middleware, it abstracts all of the underlying hardware details, enabling for easy diverse robot integration. Pyro is often presented as a convenient tool for teaching robotics [71], [72], as well as for more sophisticated use, e.g. artificial intelligence in robotics [73], [74]. Finally it must be stated that Pyro is used both in research and in education as a courseware.

3.25 ROCI (Remote Objects Control Interface)

Remote Objects Control Interface (ROCI) is a middleware that provides software developers the tools to construct a sensing and processing network, in a manner that can be easily managed. As most of the robotic frameworks, it uptakes the task of providing the underlying infrastructure for message passing and generally the whole system inter-communication. Some more specific features include thread management, peer to peer file search and download, process sandboxing, remote system management and logging.

As far as architecture is concerned, ROCI is a collection of ROCI modules, each of which is a process: it takes input, performs computations and exports an output. An ensemble of ROCI modules is called a ROCI task which is in fact the conception of a complete functionality. In other words a ROCI task contains the needed ROCI modules to complete a goal. Finally a ROCI node is a collection of ROCI tasks and plays a more organizational than functional role.

Its distributed manner and its ability to work on a multi-robot team at the same time are discussed in publications like [75], [76] and [77].

3.26 RSCA (The Robot Software Communications Architecture)

RSCA tries to standardize the whole development procedure of robotic applications. One of its main strengths is that supports real-time functionalities in conjunction with a communication middleware and a deployment middleware. The latter manages the components which comprise the while robotic system, allowing the robotics researcher to install, uninstall, create, start, stop and tear-down them.

In designing RSCA, a middleware called SCA from the software defined radio domain was adopted and extended, since the original SCA lacks the real-time guarantees and appropriate event services [78].

3.27 ROCK (The Robot Construction Kit)

ROCK is a software framework that is used for the development of robotic systems. The whole system is based on the Orocos RTT framework and increases its functionality by providing ready-to-use drivers and modules. Of course it makes it possible for the provided ensemble of components to be enriched by other external algorithms. ROCK was specifically constructed in order to give solution to the following issues:

– Robustness and time-sustainability of robotic systems. It provides error detection, reporting and
handling mechanisms that allow a system to be maintained in an easy way.

- Scalability and easy extension. Tools are provided for complex systems management, though they are not essential for a robotics researcher to start developing. Instead, components can be manipulated with oroGen, the ROCK’s component manager, in a high-level fashion.
- Repository of modules and reusability. As any other robotic framework, ROCK allows for easy, off-the-shelf employment of diverse algorithms in a modular way. Specifically, ROCK’s architectural functionality is designed to be independent of the framework itself, allowing for module integration with other frameworks.

3.28 SmartSoft

SmartSoft is a framework that focuses on a component approach of a complex robotics system and specifically, it treats the proposed communication patterns as the core of its component model. One important aspect it provides - and differentiates it from other approaches - is the dynamic, on-line wiring of the components, meaning that it allows for loose coupling systems that can be dynamically reconfigured during execution, under specific conditions. Generally SmartSoft’s ambition is to help A) the component developer, B) the application builder and C) the end user, to create in an easy manner applications by merging different software components, whose inter-communication is predefined. SmartSoft is a UNIX framework and the controllers are developed in C++.

The real-time strengths of SmartSoft are described in \[79\]. Finally in \[80\] SmartSoft is used for developing an application for sensorimotor systems.

3.29 TeamBots

TeamBots is a collection of Java packages and algorithms for multi-agent robotics research. It supports prototyping, simulation and execution of multi-robot control systems \[51\]. Robot control systems developed in TeamBots can run in simulation using the TBSim simulation application. One important aspect is that it provides seamless execution of the robotics software in real robots using the TBHard robot execution environment, meaning that the same control systems can run both in simulation and real world. The fact that TeamBots is based on the Java programming language has its pros and cons. The obvious advantage is that it extremely portable, as it can operate under the Windows, Linux, MacOS or any other operating system that supports Java. On the other hand Java is infamous about its performance compared to C or C++, due to the fact that the programs developed in Java are executed in a virtual machine, instead of the real operating system.

3.30 Urbi and Urbiscript

Urbi is not a robotics framework in its strict sense, as it allows to model any complex system in general. Its component library is developed in C++ and is called UObject, providing a standardized way to specify and use motors, sensors and algorithms. The interaction between the different modules of the system is performed by the urbiscript utilization, a script language by which high level behaviours can be described. It has similarities to Python or LUA, but additionally supports embedded parallel and event-driven semantics. Conclusively urbiscript is a robotics programming language that supports concurrency and event-based programming, thus can be used in asynchronous systems.

The goal of Urbi is common to the majority of the robotic frameworks and is to help making robots compatible, by seamless integration of diverse software modules. In \[82\] and \[83\] the universality of Urbi regarding its capabilities as a robotic platform is presented, whereas \[51\] describes a design of software architecture for an exploration robot based on Urbi. Urbi now supports ROS, so a developer has a more extended toolset to produce a robotic application by combining the strengths of both frameworks.

3.31 Webots

Webots is a commercial development environment, developed by Cyberbotics, used for modelling, programming and simulating mobile robots. It provides multiple-robot (heterogeneous) simulation in a shared environment that allows for physical collaboration of robotic agents. Each robot, sensor and generally any object can be altered, regarding its basic properties such as shape, mass, friction, color, texture etc. The robot behaviours implemented can be tested in physically realistic worlds, as a 3D physics engine is employed (ODE - Open Dynamics Engine). Additionally it has interfaces with Matlab, ROS and Urbi and can collaborate with CAD software packages such as SolidWorks, AutoCAD, Blender and others.
Webots is available for Windows, Linux and OS/X. In [85] and [86] the WebotsTM is presented.

### 3.32 YARP (Yet Another Robot Platform)

The YARP framework incorporates a collection of libraries, protocols and tools, aiming to clearly decoupled modules. Its architecture promotes a transparent way of inter-connecting the different modules, in a manner that possible future alterations (change sensors, actuators) or expansions (add modules) can be performed with minimum effort. YARP is open-source, supports Windows, Linux, OS/X and Solaris and the modules are developed in the C++ language. Its main parts (components) are:

- libYARP\_OS - Uptakes the task of cross-OS functionality, as it interfaces the applications with the operating system. This library is written to be as generic as possible, by using the ACE (Adaptive Communication Environment) library, which is portable, fact that enables YARP to be portable too.
- libYARP\_sig - performing common signal processing tasks (visual, auditory) in an way that can be easily interfaced with other robotic (and not only libraries) such as OpenCV.
- libYARP\_dev - Uptakes the task of interfacing with hardware robotic devices, such as cameras, motor control boards etc.

A presentation of YARP can be found in [87], whereas in [88] YARP is used in the context of robotic vision applications. Finally in [89] the modular capabilities of YARP are described. There the software pieces are described as 'robot genes' and YARP helps in their 'preservation', meaning the code reuse.

### 4 Robotic architectures

The current chapter will briefly introduce some examples of robotic architectures.

#### 4.1 AuRA

The official description of AuRA [90] is followed by the "Principles and Practice in Review" phrase. AuRA is a hybrid deliberative / reactive robotic architecture. The high level part is the deliberative component, whilst the low level part is a reactive behavioural control scheme. An example of a system that uses AuRA is TAME [91], a framework for affective robotic behavior. It must be stated that the MissionLab system itself is a version of AuRA.

#### 4.2 BERRA

Another example of robotics architecture is BERRA [92]. This robot architecture is again of the hybrid deliberative/reactive behavioural type. The architectural scheme is divided in three layers:

- Deliberative layer that holds the higher-level plans
- Task execution layer that includes the tasks needed to complete the higher level plans
- Reactive layer that serves whatever reactive low-level events could occur while executing the tasks

Additionally, the specific architecture is designed to be scalable and flexible, aiming at minimum effort system reconfiguration.

#### 4.3 DCA

DCA (Distributed Control Architecture) is described in [93]. There, the need for distributed software is addressed, not only in different executables, but in a network of computers as well. Thus, a distributed architecture is proposed, that primarily aims at robot control, but of course can be applied in a broad spectrum of applications. The main design decisions were based on the following concepts.

- Modularity: The programming language used by DCA is modular in nature and special attention was paid in constructing the architecture in a way that the implementation and incorporation of new modules is facile.
- Scalability: The DCA programming language supports hierarchical implementation of systems. That way a complex system can be scalable if designed with a distributed fashion.
- Efficiency: A separation of real-time event and non-real-time event is being made, in order to increase the efficiency of the overall system.
- Flexibility and generality: The type of communication scheme used, allows for duplex communication among single or teams of nodes.
- Theoretical foundation: As the publication authors state "This was addressed by using a process algebra adopted from a formal model of computation".

4.4 Saphira

The Saphira architecture is an integrated sensing and control system for robotics applications. Initially was developed for use on the research robot Flakey at SRI International and then was formulated in an actual architecture for development of robotic systems.

The initial Saphira system was divided into two parts. The low-level part was separated and formulated in another framework, Aria (see subsection 3.5), maintained by ActivMedia Robotics. As stated, it is a C++ framework oriented in robot control.

Aria provides a set of communication routines that allow for easy linking with client programs. This enables researchers to create control systems, without the need of dealing with low level details.

On top of the Aria subsystem is a robot control architecture, that addresses problems like navigation, path planning, object recognition, relying on Aria for interfacing with the hardware part.

4.5 GenoM

The Generator of Modules (GenoM) [94] is a tool to design real-time software architectures and is oriented to complex embedded systems. The requirements that GenoM satisfies are:

– The integration of a wide algorithmic variety that can have different real-time constraints and complexities.
– A standardized system to incorporate the above functions, in the context of time control and data flow.
– The management of the parallelization, the physical distribution and the portability of the functions

Finally many review publications exist that investigate the differences between various robotic architectures. In [95] three architectures are studied more closely, Saphira, TeamBots and BERRA. Qualities such as portability, ease of use, software characteristics, programming and run-time efficiency are evaluated. In order to get a true hands-on evaluation, all the architectures are implemented on a common hardware robot platform. A simple reference application is made with each of these systems. All the steps necessary to achieve this are discussed and compared. Run-time data are also gathered. Conclusions regarding the results are made, and a sketch for a new architecture is made based on these results.

5 Conclusions

In this paper a presentation of the most "famous" robotic frameworks, middleware and architectures is performed. The presented frameworks were of wide diversity in the operation systems they support, the programming languages and their orientation (simulation, control, real-time etc.). Additionally, the survey contained both commercial and open-source software. Here, it must be stated that the software packages described could incorporate simulators, but pure simulators were not reviewed.

In Table 1 a comparison of the robotics frameworks described in section 3 is attempted. The metrics used are:

– a. The operating systems supported by the framework
– b. Programming languages that can be used to develop applications with
– c. If it is open source
– d. If its architecture supports distributed execution
– e. If it has HW interfaces and drivers
– f. If it contains already developed robotic algorithms
– g. If it contains a simulator
– h. If it is control, or real-time oriented

For the metrics c to h the following symbols are used:

– ✓: Yes
– X: No
– ~: Not entirely accurate
– ?: Sources not found

Some conclusions extracted from the review follow.

The first conclusion is that there has been a great effort in creating a large number of robotic frameworks, fact that indicates that modern robotic development is extremely hard to perform from scratch. This is supported by the extreme specialization that currently exists in the robotic scientific area, forcing the researchers to make use of already developed tools in order to construct a complex robotic system, or perform a complete test. These circumstances led the scientific community to create a number of robotic frameworks that best suited their needs. Of course there are cases of frameworks that officially support usage in conjunction with others, increasing their capabilities and potential target group.

Currently, the robotic framework with the larger momentum and appeal to the community is ROS (Robot Operating System). It is open source and extremely modular with great tools, such as rviz for
| RFWs          | OS                  | Programming Language | Open source | Distributed architecture | HW interfaces and drivers | Robotic algorithms | Simulation | Control / Realtime oriented |
|--------------|---------------------|----------------------|-------------|--------------------------|----------------------------|----------------------|------------|----------------------------|
| ROS          | Unix                | C++, Python, Lisp    | ✓           | ✓                        | ✓                          | ✓                    | ∼          | x                          |
| HOP          | Unix, Windows       | Scheme, Javascript   | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Player/Stage/Gazebo | Linux, Solaris, BSD | C++, Tcl, Java, Python | ✓           | ~                        | ✓                          | ✓                    | ✓          | x                          |
| MSRS (MRDS)  | Windows             | C#                   | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| ARIA         | Linux, Win          | C++, Python, Java     | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Aseba        | Linux               | Aseba                | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Carmen       | Linux               | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| CLARAty      | Unix                | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| CoolBOT      | Linux, Win          | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| ERSP         | Linux, Win          | ?                    | x           | ✓                        | ✓                          | ✓                    | ✓          | ✓                          |
| iRobot Aware | ?                   | ?                    | x           | ?                        | ?                          | ?                    | ?          | ?                          |
| Marie        | Linux               | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| MCA2         | Linux, Win32, OS/X  | C, C++               | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Miro         | Linux               | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| MissionLab   | Linux, Fedora       | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| MOOS         | Windows, Linux, OS/X| C++                  | ✓           | ~                        | ✓                          | ✓                    | ✓          | x                          |
| OpenRAVE     | Linux, Win          | C++, Python           | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| OpenRDK      | Linux, OS/X         | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| OPRoS        | Linux, Win          | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Orca         | Linux, Win, QNX Neutrino | C++              | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Orocos       | Linux, OS/X         | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| RoboFrame    | Linux, BSD, Win     | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| RT middleware | Linux, Win, CORBA platform | C++, Java, Python, Erlang | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Pyro         | Linux, Win, OS/X    | Python               | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| ROCl         | Win                 | C#                   | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| RSCA         | ?                   | ?                    | x           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| ROCK         | Linux               | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| SmartSoft    | Linux               | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| TeamBots     | Linux, Win          | Java                 | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Urbi (language) | Linux, OS/X, Win   | C++ like             | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| Webots       | Win, Linux, OS/X    | C, C++, Java, Python, Matlab, Urbi | x           | ✓                        | ✓                          | ✓                    | ✓          | x                          |
| YARP         | Win, Linux, OS/X    | C++                  | ✓           | ✓                        | ✓                          | ✓                    | ✓          | x                          |

Visualization and tf for investigation of geometric transforms both in space and time. The scientific community embraced it, fact supported from the large amount of submitted algorithms in the ROS wiki that cover a wide range of applications, from mapping and navigation to motor control. ROS was initially developed in 2007 by the Stanford Artificial Intelligence Laboratory, then in 2008 the development.
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