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A LIGHTWEIGHT OPEN-SOURCE COMMUNICATION FRAMEWORK FOR NATIVE INTEGRATION OF RESOURCE-CONSTRAINED ROBOTICS DEVICES WITH ROS

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A chi mi supporta e mi sopporta

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Abstract

The ongoing evolution of computing devices, especially of embedded systems, introduces new opportunities to enhance robotics software.
The goal of this thesis is to develop a rapid prototyping robotics communication framework which can run on cheap embedded systems, while still having native compatibility with an existing widespread high-level framework, typically run on powerful computers.
We created *µROSnode*, an open source communication framework with small code and memory footprints, able to run on recent advanced microcontrollers, and having native compatibility with the popular *ROS* robotics framework, which follows the *publish/subscribe* approach. The developer, often accustomed to ROS nowadays, can still write high-level software for it, with the non-trivial capability to interface directly to hardware modules running µROSnode.
The framework is written in *ANSI C89*, supported by almost all of the compilers targeting embedded systems, and which can be easily integrated with other common programming languages. The codebase is partitioned into purpose-specific modules and extensively documented, to improve ease of use and maintenance. In order to assist the user in the development of µROSnode-based software, we developed a code generator and a static stack analysis tool.
We performed some simple benchmarks to determine the maximum transmission and reception throughput of a topic with variable-sized messages, running on a *Raspberry Pi* and a *STM32F407* microcontroller (*ARM-CM4* core). On both platforms it was possible to reach several thousands of messages per second without too much effort if messages are rather small or processed on-the-fly.
We also measured the usage of both program and working memories by a ROS *turtlesim* clone, which easily fitted tight resource constraints of the STM32F407.
An existing robot, whose hardware/software architecture was built around a *CAN bus*, was interfaced to ROS through an inexpensive CAN-to-Ethernet gateway running µROSnode on a STM32F407.

Sommario

La continua evoluzione dei dispositivi di calcolo, specialmente dei sistemi embedded, introduce nuove opportunità per migliorare il software per la robotica.
Lo scopo della tesi è di sviluppare un framework di comunicazione robotica per la prototipazione rapida, che possa funzionare su sistemi embedded economici, mantenendo compatibilità nativa con uno dei diffusi framework esistenti di alto livello, che tipicamente funzionano su computer avanzati.
Abbiamo creato *μROSnode*, un framework di comunicazione open source con piccola occupazione in memoria, che possa funzionare sugli avanzati microcontrollori recenti e con compatibilità nativa con il popolare framework *ROS*, che segue l'approccio *publish/subscribe*. Lo sviluppatore, oggigiorno spesso abituato al sistema ROS, può continuare a sviluppare software per esso, con la non banale possibilità di interfacciarsi direttamente a moduli hardware funzionanti tramite μROSnode.
Il framework è scritto in *ANSI C89*, supportato pressoché dalla totalità dei compilatori per sistemi embedded, il quale può essere facilmente integrato da altri linguaggi di programmazione. Il codice è suddiviso in moduli per compiti specifici e largamente documentato, per migliorare facilità d'uso e manutenzione. Al fine di assistere l'utente nello sviluppo di software basato su μROSnode, abbiamo sviluppato un generatore di codice e uno strumento per l'analisi statica degli stack.
Abbiamo compiuto dei semplici benchmark per determinare la massima capacità di trasmissione e ricezione di un singolo topic con messaggi a dimensione variabile, su un *Raspberry Pi* e un microcontrollore *STM32F407* (core *ARM-CM4*). Per entrambe le piattaforme è stato possibile raggiungere capacità di diverse migliaia di messaggi al secondo senza particolari sforzi in caso di messaggi piccoli o processati al volo.
Abbiamo anche misurato l'occupazione nelle memorie programma e centrale di un clone del *turtlesim* di ROS, che ha rispettato agevolmente i severi limiti dell'STM32F407.
Un robot esistente, la cui architettura hardware/software fu costruita intorno a un *bus CAN*, è stato interfacciato a ROS tramite un gateway CAN-a-Ethernet in cui opera μROSnode su un STM32F407.

Ringraziamenti

«Dimmi con chi vai e ti dirò chi sei,
e se so di che cosa ti occupi
saprò che cosa puoi diventare»
Johann Wolfgang von Goethe

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La compagnia di studio è stata determinante per confrontarsi, comprendere ciò che sfugge, trovare nuove soluzioni, superare le comuni frustrazioni e compiacersi dei risultati ottenuti.
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Chapter 1

Introduction

Robotics research brings to a high degree of innovation. Many new ideas for future robotics products are conceived every year, targeting a broad range of fields, and requiring multidisciplinary skills. Therefore, researchers need to build and evaluate new ideas quickly, without spending too much time in the development of every subsystem composing the whole robot.
Robots are composed by parts which often belong to a standard set of mechanical, electrical, and software components. While mechatronics parts have been available for a long time, thus providing well established interfaces, the ongoing evolution of computing devices, especially of embedded systems, introduces new opportunities to enhance robotics software.
Several software *frameworks* were proposed to build robotics communications systems, artificial intelligence, motion control, and so on, assisting the researcher in the rapid development of robotics software.

The goal of this thesis is to develop a rapid prototyping robotics communication framework which can run on cheap embedded systems, while still having native compatibility with an existing widespread high-level framework, typically run on powerful computers. This would allow the development of low-cost hardware modules able to communicate with one of the state-of-the-art, high-level frameworks, to enhance the rapid-prototyping development cycle on the low-level side.
We created *μROSnode*, an open source communication framework with small code and memory footprints, able to run on the latest microcontrollers, and having native compatibility with the popular ROS robotics framework. The framework is written in *ANSI C89*, supported by almost all of the compilers targeting embedded systems, and which can be easily integrated with other common programming languages. The code is partitioned into purpose-specific modules and extensively documented, to improve ease of use and maintenance.

The choice of a *BSD* license makes it *free software*, modifiable by anyone and employable for commercial products. A code generator and a static stack analysis tool assist in the development of the user application, so that repetitive coding is lightened, and the memory usage on resource-constrained platforms is kept under control. A set of benchmarks prove its good performance on low-cost embedded systems, and a demonstration project on a real-life robot was easy to develop.

We first analyzed the requirements for rapid prototyping in the robotics field. The most intuitive way is to assemble some ready-to-use parts together, and apply a high-level behavior to them. While mechatronics parts often share a roughly common interface, robotics software is still under heavy evolution. However, there are some widely accepted software frameworks which help in the rapid development of the robotics software.
ROS [22] is the most popular framework nowadays, providing a huge repository of pre-made software packages, support for both high-performance (C++) and high-level/scripting (Python, Lisp) languages; communication over XML-RPC, TCP (*TCPROS*), and UDP (*UDPROS*); an automated compilation toolchain by a strict filesystem structure; compatibility wrappers for many other robotics frameworks.
Orocos [4] follows strict software engineering rules and development cycle, and targets realtime robots; its runtime architecture is CORBA-based.
LCM [12] is a lightweight high-performance system for low-latency communications among processes over UDP.
R2P [2] is a hybrid hardware/software framework to build the robot electronics out of small and cheap hardware modules, which communicate through a robust CAN bus, and has support for hard-realtime applications.

The state-of-the-art offers frameworks which are either very good at the software, communication, or hardware level, but there is no framework which helps in blending of all of them together. Moreover, high-level robotics software is usually run on fairly powerful computers, while the hardware is driven by industrial processors or microcontrollers, which cannot manage a huge computation load.
That being so, we outlined our research strategy to develop a framework which can be used to interface high-level robotics software with the hardware. The framework should have small footprint and simple architecture, so that it can fit into a microcontroller of nowadays. Since most embedded systems do not have a compiler toolchain support as advanced as general-purpose computers or workstations do, the choice for the programming language is limited. There is mature support only for *C* and *C++* targeting embedded system architectures, while other languages are experimental or compatible with only a few platforms.

For maximum compatibility and performance we chose *ANSI C* (a.k.a *ISO C89*). Compared to C++ it has some restrictions, but compiler support is still more mature; all of the C89 features are available, while some C++ features (e.g., *RTTI* and exceptions) must be disabled on resource-constrained platforms. However, it is still possible to write wrappers for C++, and even for other higher level languages (*Python*, *Java*, *C#*, and so on).

Since ROS is the most widely accepted framework for the development of high-level robotics applications, we chose to develop a lightweight communications framework, *µROSnode*, which has native support for ROS protocols, and can be run even on cheap embedded systems based on recent microcontrollers. The user, often a robotics researcher accustomed to ROS nowadays, can still write software for it, with the non-trivial capability to interface directly to hardware modules connected via the IP network protocol (e.g., via Ethernet).
In order to assist the user in the development of µROSnode-based software, we also developed a code generator and a static stack analysis tool. The code generator creates the desired topic and service handler function stubs, as well as (un)marshaling functions for the involved data types. The stack analyzer is useful to keep the stack usage under control when developing applications for memory-constrained platforms, for instance to size the stacks assigned to topic and service handler thread pools.

We then performed quantitative and qualitative analyses of our work, to prove its effectiveness. The target platforms were an Ethernet board driven by a *STM32F407* microcontroller (*ARM-CM4* core), which is tightly resource constrained, and a *Raspberry Pi model B* (*ARM-11* core), which is a popular extremely-low-cost embedded computer.
For the quantitative analysis we performed some simple benchmarks to determine the maximum transmission and reception throughput of a variable-sized topic. Both the platforms can reach several thousands of messages per second without too much effort if messages are rather small (less than 500 B, common for simple sensors) or can be processed on-the-fly. When buffering large messages (more than 1 kB) the overall performance decreased dramatically, not because of our framework itself, but because of expected limitations of both the target processors and the 100 Mb/s Ethernet links.
On the first board we also measured the usage of both program and working memory by a ROS *turtlesim* clone. The results proved that a fully-featured µROSnode implementation has a rather low impact on the program memory, in the order of less than 40 kB when compiled with optimizations; XML-RPC and TCPROS thread pools require less than 1300 B for their stacks in the worst case, which is reasonable considering the complexity of such protocols and their management.

The qualitative analysis consisted in the development of a µROSnode-based firmware for a real-life robot, the omnidirectional three-wheeler *Triskar2*, which is controlled through a CAN-to-Ethernet gateway communicating with some R2P boards. Thanks to the code generator, the well-documented API, and the simple software architecture, the development did not require much effort, indeed the whole firmware was written and tested in less than a week by a single person.

As proven by experimental results, µROSnode fits the missing link between high- and low-level robotics software frameworks. It is lightweight enough to run elementary tasks on modern microcontrollers with good performance and low memory requirements. Its development cycle is eased by the simple software architecture, assistance by development tools, and extensive API documentation. Native compatibility with ROS ensures its effectiveness when building robot prototypes out of fairly inexpensive robotics components running µROSnode.

Future work may include C++ support, by writing wrappers around the C implementation, or as a stand-alone C++ version. UDPROS may be added for low-latency applications and wireless connection efficiency. Existing products may be made ROS-ready by building proprietary-to-ROS hardware adapter running µROSnode, or by writing a custom µROSnode-based firmware if a product already features Ethernet or Wi-Fi. Being employable by inexpensive embedded systems, µROSnode can be used for low-cost educational or recreational products connected to ROS.

The structure of this thesis is explained in the following.
Chapter 2 presents the state-of-the-art robotics frameworks, in terms of software, communication, and hardware features. Through their comparison, we identified a missing link between high- and low-level frameworks.
Chapter 3 describes the objectives and the strategy of the research, in order to develop a communication framework capable of running on cheap embedded systems, with native compatibility to an existing high-level framework, *ROS*. This will fill the gap between the high-level, number crunching software frameworks, and the cheap hardware platforms.
Chapter 4 illustrates the ROS communication features, adopted by our work to maintain native compatibility with ROS itself.
Chapter 5 shows the detailed architecture of our communication framework, *µROSnode*, the code generator tool, and the static stack analysis tool.
Chapter 6 contains experimental results, which prove the effectiveness of our framework both in performance (quantitative analysis) through some network benchmarks, and in ease of development (qualitative analysis) by controlling a

real-life robot through a ROS-based application.
Chapter 7 draws conclusions about our work, and outlines some possible future research directions to undertake.
Appendix A lists the API to manage topics, services, and ROS parameters.
Appendix B contains some useful listings, like grammar definitions and demonstration scripts.

Chapter 2

State of the art

In the following, the state-of-the-art works related to robotics, communication, and rapid prototyping frameworks are described, highlighting their objectives, architecture, and typical usage scenarios. By analyzing their advantages and disadvantages, we will show that there is still a gap to fill between high-level frameworks which run on powerful computers, and those which are mainly focused on the hardware or the communication sides. These observations will lead to our proposal, illustrated in the next chapters.

2.1 The need for rapid-prototyping frameworks

Robot development is a truly multidisciplinary task, involving mainly mechanical structures, electronics design, software engineering, and artificial intelligence. Each of these disciplines needs its own environment to build a complete robot, requiring time, planning, hardware, and operation.
On the contrary, a robotics researcher should build new ideas in a fast, cheap, and easy way. So, it is needed to provide friendly environments, which reduce the resource requirements to build a new idea, not necessarily in its optimized final form, but at least as a meaningful approximation.
Also, most parts of a robot, either physical or virtual, share a common design, so a robot prototype could be built without redesigning everything from scratch, but rather by assembling pre-made parts. Indeed, by partitioning the development into purpose-specific tasks, the design, operation, and maintenance of the whole system are much easier than by reinventing the wheel every time; this is a well-known strategy in any fields.
Pre-made parts share a well defined interface, and they were already tested by the manufacturer, who can keep the price lower thanks to mass-production.

Figure 2.1: ROS logo

Throughout our work we will focus mainly on software environments for rapid robot development. Such environments come in the form of *frameworks*, which are sets of tools and libraries with which the user build complex software out of some small and purpose-specific pieces. For example, to control a robot it is needed to gather data from sensors, reason about their values, and generate commands for the actuators.
An intuitive way is to have a piece of software for each of the sensors, connected to a virtual brain (or even multiple ones), which is then connected to the software components of every actuator. Such a framework typically provides the underlying communication subsystem, to which user modules can communicate through a well-defined API.
The most widespread frameworks also supply some modules commonly used, like those for image elaboration, robotic arm operation, odometry, and so on, as well as some tools to ease development and debugging.

2.2 Robot Operating System

The *Robot Operating System* (*ROS* [22], logo in **Figure 2.1**) is a *meta* operating system targeted at the rapid development of robotic software, developed by *Willow Garage*. It has become a very widespread framework, probably the most active and adopted one in the research field, supplying a large number of pre-made packages. Its source code is released under a *revised BSD* license, so that it can be freely modified and employed by hobbyists and institutions, but also by commercial companies; by the way, some packages are released under more restrictive licenses, like the common *GPL*. It natively runs on *Ubuntu Linux*, but has some degree of support for other Unix-like operating systems. ROS *client (core) libraries* are written primarily in C++, Python, and Lisp, with experimental support for Java, Lua, and Mono/.NET.

2.2.1 Architecture

The ROS framework is highly modular. Software developed with ROS is composed by a set of *Nodes*, which are virtual processing elements providing very specific interface and operation. For example, there exist Nodes for

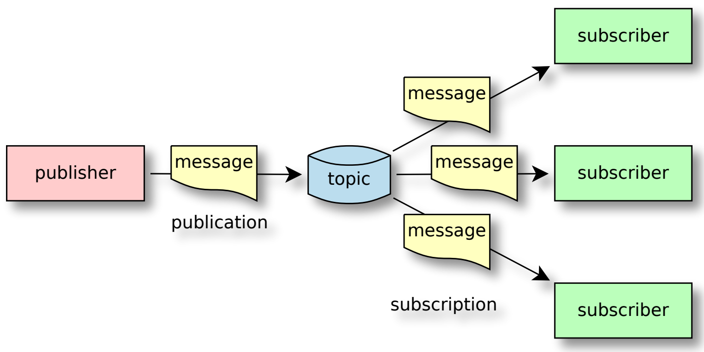


Figure 2.2: Conceptual message flow of a published and subscribed topic

the elaboration of *point clouds*, those to extract geometrical primitives out of stereo images, others for the path planning, artificial intelligence, motion control, interfaces to common peripherals (e.g., joysticks, *Microsoft Kinect*, laser scanners, servomotors), and so on.

Nodes by themselves have little purpose, but by *connecting* them together it is possible to build a very complex robotics application. Nodes communicate through a *publish/subscribe* technique. Nodes producing some kind of data publish it by a *topic* of specific *type*, and those Nodes which need such data receive it by subscribing to that topic; this concept is depited in **Figure 2.2**.

ROS supports continuous data streaming through topics, but also supports *request/response* calls to global *services*, and shared environment *parameters*. The setup and control of the Node network (called *computation graph*) are made through a *XML-RPC*-based protocol, which ensures maximum portability among any platforms with TCP/IP capabilities; there is a centralized Node, the *Master*, which supervises the whole network. Instead, topic and service data streams employ a custom low-level protocol, which is typically TCP-based, but also UDP-based for latency-sensitive applications. In-depth information about the ROS communication system can be found in Chapter 4.

Software developed with ROS can be grouped into *stacks* and *packages*. A ROS package is a container of software which provides a specific functionality to be reused with ease. For instance, there exist packages for a particular sensor, or for a specific recognition algorithm. A package may contain ROS Nodes, ROS-independent libraries, data sets, configuration files, or anything else that logically constitutes an useful module. A stack is a container of packages which share a common goal; for example, computer vision or motion planning. Stacks can have dependencies on other stacks, in order to be maintained independently. Some rules define the filesystem structure of packages and stacks, so that they can be built through an automated toolchain, based on the *CMake* build system [5], keeping the code well organized and maintainable by different people.

2.2.2 Development process

Developing robotics software with ROS is straightforward. The user has to know how to navigate inside the ROS meta-filesystem and *workspaces* (folders which include package source code), how to create a Node, and how to make it communicate with the rest of the computation graph. This knowledge base is well documented inside the *ROS Wiki* [25], and the set of automated commands of the meta-OS shortens the creation of a bare-bone application.

Then, the user has to outline the software capabilities of the robot. Most of the times, there already exist some ROS packages which provide them, so it is often a matter to just pick the right ones from the official repositories. If some features are missing, specific user Nodes can be written with ease, thanks to the good support for common high level languages; typically, C++ is used for high performance, Python for its simplicity, and Lisp for artificial intelligence.

After writing the user application out of Nodes, the workspace has to be compiled into its binary form, by using the automated package compilation flow defined by ROS. Nodes will then need to be instantiated and connected together through *launch files*.

If needed, the developer can capture the data being exchanged inside the computation graph thanks to a set of debugging tools. They can inspect the current state of the network, or record streams for further analysis, elaboration, and replay.

2.3 Open Robot Control Software

Open Robot Control Software (*Orocos*, [4]) is a software framework for the control of realtime robots, mainly the industrial ones. It is written in C++ under the *GNU Lesser GPL*. Its aim is to provide a highly modular, high-performance, easy-to-use framework for complex robot control and machine learning. There exist some offspring projects for non-realtime control based on Orocos.

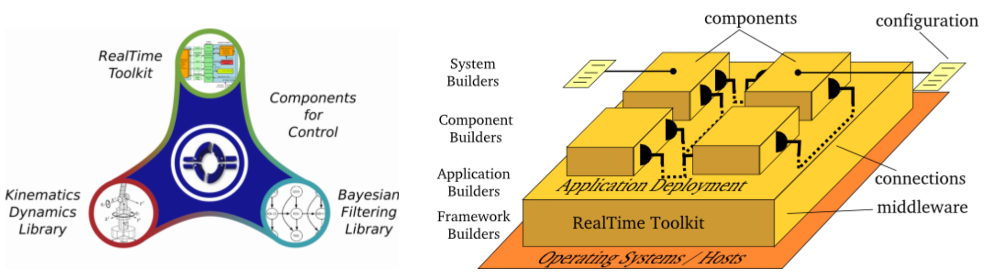


Figure 2.3: Orocos framework

2.3.1 Architecture

The framework is split into the following libraries, grouped by **Figure 2.3**: the *Orocos Real-Time Toolkit* (*RTT*), the *Orocos Components Library* (*OCL*), the *Orocos Kinematics and Dynamics Library* (*KDL*), and the *Orocos Bayesian Filtering Library* (*BFL*). The RTT provides the infrastructure and the functionalities to build robotics applications in C++. The emphasis is on *realtime*, *on-line interactive* and *component-based* applications. OCL provides some ready to use *control Components*. Both Component management and Components for control and hardware access are available. The KDL is a C++ library which allows to calculate *kinematic chains* in realtime. BFL provides an application independent framework for inference in *dynamic bayesian networks*, i.e. recursive information processing and estimation algorithms based on Bayes' rule, such as (extended) Kalman Filters, particle filters (sequential Monte methods), and so on.

Being a modular framework, an Orocos application is made of networked purpose-specific components. A *CORBA*-based communications system is used for the setup and control of the network, so that applications follow an effective software engineering approach. There are five distinct (and optional) ways in which an Orocos component can be interfaced, as seen in **Figure 2.4**: through its *properties* (parameters modifiable at run-time), *events* (functions executed when a change occurs), *methods* (immediate-result functions), *commands* (procedures to reach a goal) and *data flow ports* (thread-safe un-/buffered data transport channels). Besides defining the above component communication mechanisms, Orocos allows the Component or Application Builder to write *hierarchical state machines* which use these primitives; this is the Orocos way of defining application specific logic. State machines can be (un)loaded at run-time in any component.

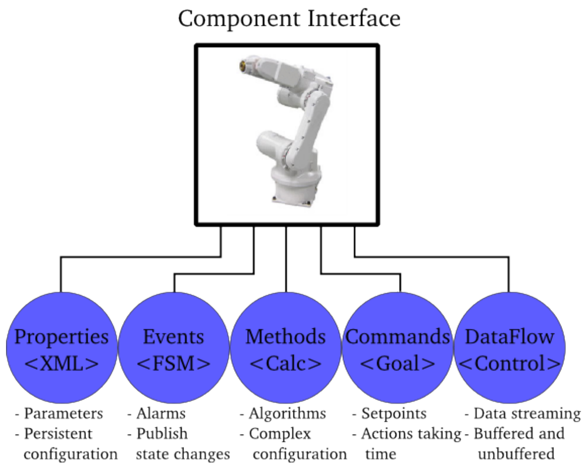


Figure 2.4: Orocos component interface

2.3.2 Development process

The Orocos community already provides pre-made components to be used to create the user application; otherwise, one has to write his own components. The application can be setup through XML properties or command/method interfaces.

2.4 Lightweight Communications and Marshaling

The *Lightweight Communications and Marshaling* framework (*LCM*, [12]), developed by the *Massachusetts Institute of Technology*, offers a very high performance communications system over UDP/IP, so that multiple processes can exchange data with high throughput and low latency. It is designed for very complex robotics software, which need optimized communications to satisfy soft-realtime constraints, in a modular fashion, and with the minimum requirements. The most prominent application was for the 2007 *DARPA Urban Challenge* [12], in which the MIT team governed an autonomous car by running 70 concurrent processes spread across 10 networked workstations, with a very heterogeneous network traffic (almost 100 data types involved). It is used also for aerial, underwater, and land robots.

A set of tools helps in the development of user applications, and thanks to the protocol design they have almost no impact on the network performance. LCM has support for C, C++, Java, Python, MATLAB, and C#, so that it can be natively used with many operating systems and for different purposes (high performance, prototyping, and simulation). It is released under the *GNU*

```
struct waypoint_t {
  string    id;
  float     position[2];
}

struct path_t {
  int64_t       timestamp;
  int32_t       num_waypoints;
  waypoint_t    waypoints[num_waypoints];
}
```

Listing 2.1: LCM message types for path planning

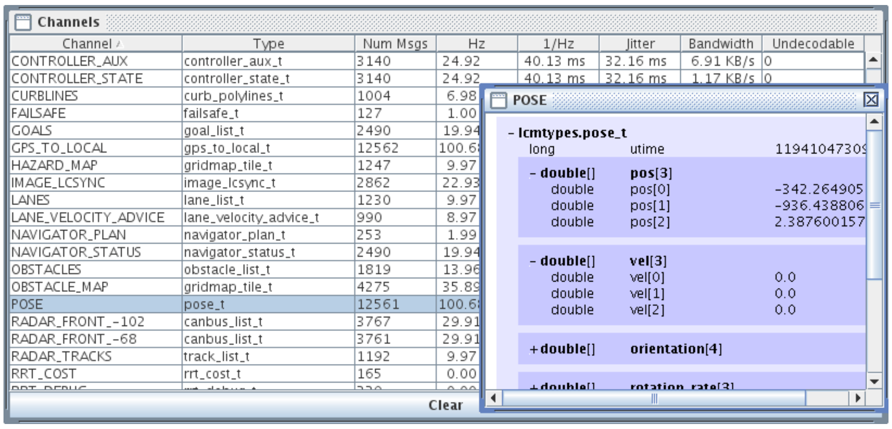
Lesser GPL.

2.4.1 Architecture

LCM is a networked communications framework, in which a network *Node* is typically a single process of the operating system. This guarantees the isolation of memory address spaces for each Node, which helps in keeping the application safe and easy to maintain. Nodes communicate through a *publish/subscribe* approach, in that Nodes can publish or subscribe to *topics*. By not requiring centralized control, topics are *stateless*, reducing protocol and software complexities. LCM employs only UDP *multicast* messaging, so that a message is sent once for the whole network, scaling very well with the number of Nodes. UDP is a *best-effort* protocol directly based on IP, so that there is no flow control at all. A dropped packet is not resent, reducing the latency of successive packets, thus making soft-realtime applications possible. If flow control is required, it can be implemented on a higher network layer.

Messages of a topic must be of the same data type. The type descriptor is written in a simple C-like formal language, so that a tool can generate native source code for all of the languages supported by LCM. Each message is headed by the 64-bit *hash code* of its type descriptor, providing type checking for each message being received. **Listing 2.1** displays an example of path planning message types, described with the custom C-like language defined by LCM.

A network debugger, *lcm-spy* of **Figure 2.5**, simply subscribes to all of the topics being exchanged across the network, and visualizes message contents (syntax is inferred by type descriptors). Thanks to the multicast protocol, the debugger is almost completely transparent to the network. It can also record the network traffic, which can be analyzed or elaborated for later replay.



Channels

Channel	Type	Num Msgs	Hz	1/Hz	Jitter	Bandwidth	Undecodable
CONTROLLER_AUX	controller_aux_t	3140	24.92	40.13 ms	32.16 ms	6.91 KB/s	0
CONTROLLER_STATE	controller_state_t	3140	24.92	40.13 ms	32.16 ms	1.17 KB/s	0
CURBLINES	curb_polylines_t	1004	6.98				
FAILSAFE	failsafe_t	127	1.00				
GOALS	goal_list_t	2490	19.94				
GPS_TO_LOCAL	gps_to_local_t	12562	100.6				
HAZARD_MAP	gridmap_tile_t	1247	9.97				
IMAGE_LCSYNC	image_lcsync_t	2862	22.93				
LANES	lane_list_t	1230	9.97				
LANE_VELOCITY_ADVICE	lane_velocity_advice_t	990	8.97				
NAVIGATOR_PLAN	navigator_plan_t	253	1.99				
NAVIGATOR_STATUS	navigator_status_t	2490	19.94				
OBSTACLES	obstacle_list_t	1819	13.96				
OBSTACLE_MAP	gridmap_tile_t	4275	35.89				
POSE	pose_t	12561	100.6				
RADAR_FRONT_-102	canbus_list_t	3767	29.91				
RADAR_FRONT_-68	canbus_list_t	3761	29.91				
RADAR_TRACKS	track_list_t	1192	9.97				
RRT_COST	rrt_cost_t	165	0.00				

Clear

POSE

```
- lcmtypes.pose_t
    long              utime                   11941047309
  - double[]          pos[3]
      double          pos[0]                  -342.264905
      double          pos[1]                  -936.438806
      double          pos[2]                  2.387600157
  - double[]          vel[3]
      double          vel[0]                  0.0
      double          vel[1]                  0.0
      double          vel[2]                  0.0
  + double[]          orientation[4]
```

Figure 2.5: Screenshot of lcm-spy *capturing messages*

2.4.2 Development process

To build an application for LCM, a developer must outline the needed topics and message types. Actual (un)marshaling source code is generated for the chosen programming language through the generator supplied with LCM. The application should then be partitioned into sub-processes, each providing a specific logical functionality. Then, processes are developed and run.

Since there is no centralized build toolchain, nor any particular rules for the source code organization, everything is up to the user's appeal. LCM is just a communication framework, with no interest in providing pre-packaged modules, nor in defining software engineering rules.

2.5 Rapid Robot Prototyping

Rapid Robot Prototyping (*R2P*, [2]) is a hardware/software framework for the robotics research. It has been designed to be low-cost, lightweight, easy to use, and with realtime capabilities. The idea is to shorten development times when researching for a new robot design, by employing small and cheap hardware modules. Sure enough, most of the time is often spent in the development of the mechanics, electronics and their firmware from scratch rather in the development of the actual robot application, even for simple designs [2]. By giving the researcher a set of hardware modules commonly found in robots, realtime communication and operating systems, and a set of development tools, one can make a working physical prototype in a shorter time. R2P is the most promising hybrid hardware/software framework for rapid robot prototyping.

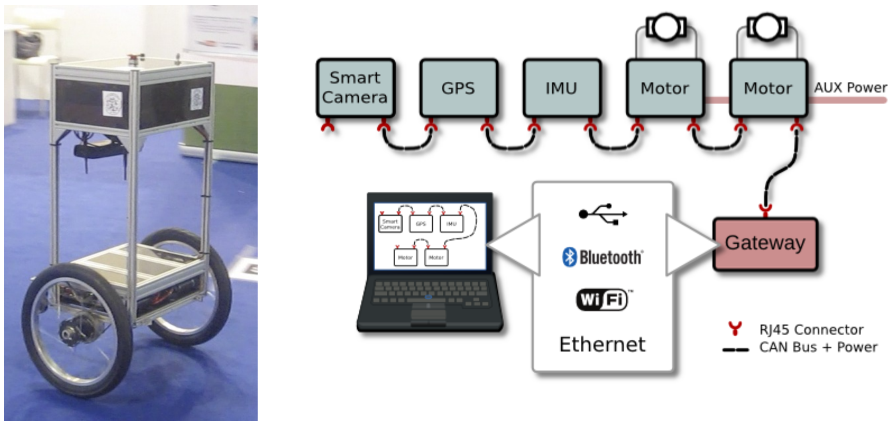


Figure 2.6: TiltOne*, a self-balancing robot controlled through R2P*

2.5.1 Architecture

R2P has a hybrid hardware/software nature. It employs a *publish/subscribe* technology just like the other state-of-the-art frameworks, both for communications among physical nodes (boards) and virtual nodes (intra-process communications). The framework is written in C++, and currently supports the *ChibiOS/RT* RTOS [6].

A R2P hardware module is a tiny board which provides a basic functionality, for example DC motor control, *13-dof* IMU (3 acc + 3 gyro + 3 mag + barometer + GPS), ultrasonic or generic *Sharp* distance sensors, an Ethernet gateway, and so on. Such boards are connected across a CAN bus through Ethernet patch cables, thanks to the high availability and low cost of both CAN controllers and Ethernet cables. The CAN bus allows the implementation of hard-realtime message loops, and is also widely used in harsh environments, such as in the automotive and industrial fields, being a well-established technology. Interconnection cables carry both the differential CAN signals and 5 V power rails for low-power (up to very few amperes) circuits; if high voltage or current are needed (e.g., for DC motors), then auxiliary power sources must be added to the design. **Figure 2.6** shows the architecture of a self-balancing robot, *TiltOne* [20], which uses a R2P network to gather data from sensors and to actuate motors, connected to an external workstation for debugging and user control.

There are three kinds of topic scheduling: hard-realtime, soft-realtime, and non-realtime. Hard-realtime topics exploit the hardware priority packet arbitration defined by the CAN specifications. Their messages are arranged by a *time-triggered* scheduler, hosted by a centralized node (fairly elected among all of the nodes). A fixed *time quantum* of the scheduler is declared, and is split into *time* *slices*, each assigned to at most one control loop publisher; this constitutes the (fixed) scheduling policy of hard-realtime control loop messages. Soft-realtime is satisfied by an *Earliest Deafline First* scheduler, applied to the free time slices of the hard-realtime scheduler; this is useful for sporadic or low-latency events with soft-realtime requirements. Any remaining free time slices can be used to exchange non-realtime topic messages.

It is possible to employ a packet capture tool which is completely transparent to the network, thanks to the inherent broadcast nature of the CAN bus. Again, a standard set of tools allows live recording and analysis of the exchanged messages, as well as record and replay features.

2.5.2 Development process

A robotic researcher may choose R2P when willing to build a new physical prototype idea. The researcher should first outline the hardware requirements of the structure being developed; for instance, the need for motors, distance sensors, a bridge to *Wi-Fi*, and so on, suggesting the appropriate pre-made R2P hardware module to be used. Otherwise, designing a custom board is rather simple, requiring only a CAN bus interface, commonly found in almost all of the latest microcontrollers.

After choosing or designing the right hardware modules, the user has to write their firmware application; the simple R2P API makes the writing of custom firmware rather easy. The R2P roadmap proposes some code generators, which will automatically generate a working application template out-of-the-box, and a high-level scripting language for those users who are less knowledgeable about firmware programming; this in turn would help in porting R2P applications to different embedded platforms.

2.6 Framework comparison and observations

All of the state-of-the-art frameworks described previously excel in some fields, but they also show lacks elsewhere.

ROS is the best choice when developing robotics research software, thanks to its immense library of ready-to-use algorithms and the automated development process. Being an highly active and successful project, bugs can be fixed quickly, and the huge user base can make the library grow even more. By contrast, the use of high-level languages and protocols make it unsuitable for simple and cheap robots, like those affordable by students or hobbyists, requiring a

Feature	**ROS**	**Orocos**	**LCM**	**R2P**
Publish/Subscribe	✓	✓	✓	✓
Scripting languages	✓		✓	planned
Embedded systems support	*rosserial*		✓	✓
Lightweight			✓	✓
Realtime support		✓		✓
Package repository	✓	✓		planned
Connectivity (transport)	TCP, UDP	TCP, generic	UDP	CAN, generic

Table 2.1: Comparison of the state-of-the-art robotics software frameworks

moderately powerful computer to be run (no microcontrollers).

Orocos perfectly follows software engineering principles, which helps in making long-term, high-quality realtime robot control. As such, it is more suitable for industrial-grade robots rather than rapid prototyping of new ideas, also because of the relatively complex software architecture (if compared to ROS).

LCM is a very high efficiency communications framework, which can fit in any UDP-capable computer, from workstations to embedded systems. Although simplicity and performance are the key features of this project, it is merely a communications system, lacking any higher level features, such as ready-to-use robotic algorithms, automated toolchains, or even *Quality of Service* over UDP itself.

R2P is a promising hybrid hardware/software system for the rapid development of new robotic ideas, which is lightweight, realtime, and targeted at cheap embedded systems. Despite of the almost *plug-and-play* nature, it does not provide any higher level libraries yet, reducing the appeal for a novice.

Overall, there are frameworks which are good either at the software/communications level, or at the lower/hardware levels. We could not find a state-of-the-art framework which can be used for rapid-prototyping among all of these levels. Indeed, the researcher can be fast and assisted only at some stages of the development, while other stages still need to be done alone currently. **Table 2.1** summarizes the features of the state-of-the-art frameworks.
These observations have driven us to outline and develop a framework which interfaces to computation graphs of ROS, to exploit its high-level rapid prototyping features, but can still be run on cheap embedded systems, like the R2P Ethernet gateway module. The proposal illustrated in Chapter 5 can fit the missing link between high- and low-level rapid prototyping.

Chapter 3

Research strategy

In the previous chapter, state-of-the-art robotics software frameworks were described, each with its benefits and drawbacks. In this chapter, we illustrate our research objectives and strategy, which will lead to the proposed framework described in the next chapters.

3.1 Objectives

It is very important to provide a good framework both in the hardware and software domains, so that it is possible to develop robots without spending too many resources, primarily time and money. Previous works are either very good in the software or in the hardware domains on their own, but there seems to be a missing link between them.
Sometimes, prepackaged algorithms are available only for frameworks which are excessively complex for the actual application. Instead of losing time for the reimplementation of those algorithms for a simpler system, it is common to equip the robot with a more powerful computer. This would be a price and performance overkill, which cannot turn into a future product without re-engineering at some point of the design process. Again, such a powerful computer may not be suitable for the specific robot domain, because of the required size and weight; think about a quadrotor, which cannot equip a desktop-grade computer. For these reasons, we will focus on embedded systems in our research.

Framework design Instead of proposing a brand new software framework, we are going to enhance an existing one towards embedded systems development. As seen in the previous chapter, some works like LCM and R2P are already

available on embedded platforms, but both miss the availability of user level device libraries. By contrast, ROS has plenty of *packages* ready to be used, but ROS itself is not well suitable for embedded systems.
By extending existing frameworks, it is still possible to take advantage of their benefits, while trying to solve its drawbacks, or at least part of. Frameworks are designed to be modular, and the purpose of our research is to let simple, cheap peripheral modules communicate with the central framework modules (often workstations) in a native way.

Small footprint However, the development of an embedded system always copes with some resource constraints. An embedded system, with respect to a desktop computer or a workstation, has often tight constraints about memory size, CPU speed, and timings. A well endowed microcontroller of nowadays is equipped with roughly 1 MB of code memory (ROM, EEPROM, Flash), 256 kB RAM, and 200 DMIPS.
While not being able to host a full framework in its entirety, a microcontroller can still manage the the native communication protocols of the framework itself. A piece of embedded hardware would still communicate with the framework out-of-the-box, with the possibility to run prepackaged algorithms, and without the need of *proxies* or *bridges* to handle different protocols.

Portability The proposed framework should also be portable. This is a tricky feature in the field of embedded systems, because the hardware abstraction layer is almost incompatible even among devices of the same family. Also, embedded system compilers often fall behind those for generic-purpose computers; the most recent programming languages (or their updates) are not available, or the compiler implementation is not fully standard-compliant.

Handiness Last but not least, the code should be easy to use. A simple design with simple code, good documentation, and utility tools can make the development process more efficient and less error-prone. Since the target of our work is rapid robot prototyping, it must be understood and modified in the shortest possible time, so that users can focus on their goals rather than on the software framework library itself.

To summarize, the enhanced system should have the following features:

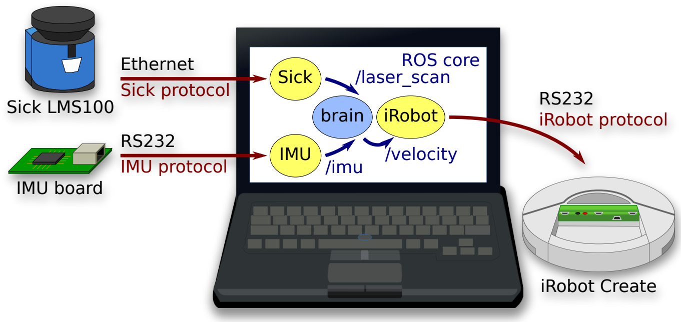
- support for an existing framework;
- small code/memory footprint;
- portable among different hardware/software architectures;

- simple and clean design.

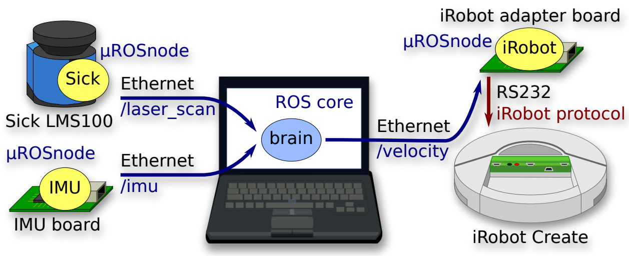
3.2 Strategy

Our work is an extension of an existing framework. Among the ones described in the state-of-the-art presented in Chapter 2, we have found that the most suitable for rapid prototyping purposes is ROS. Its development is the most active, and the availability of hundreds of fully modular packages shortens development times. Conversely, its lack of an embedded systems point of view discourages its use for simple systems, although there are some workarounds (e.g., *rosserial*).
The framework we are proposing, called *µROSnode*, is designed to run on embedded systems. Indeed, an user accustomed to ROS can still use its packages on the central computer, and deploy on peripheral modules which can natively communicate with ROS.
A consequence of native ROS support on microcontrollers is that it would be possible to directly connect µROSnode-based devices to a ROS-based network. Take the example of a simple robot, as in **Figure 3.1a**, made of an *iRobot Create* [13] moving base controlled via RS232, a *Sick LMS100* [27] Ethernet laser scanner, and a custom IMU board yet to be designed. These devices are connected to a host computer running a ROS application which uses them. As they do not communicate with ROS directly, the host must run custom ROS nodes which interface with their low-level drivers to ROS itself.
Instead, take the example in **Figure 3.1b**. The laser scanner runs a modified µROSnode-based firmware by exploiting the available Ethernet port; the custom IMU board, designed from scratch, is programmed around µROSnode; an inexpensive adapter board interfaces the RS232 mobile robot platform to Ethernet by an inexpensive adapter board. With this design, the user only has to connect them to ROS (e.g., by linking to the host through Ethernet cables) and start developing the application, without worrying about the low-level protocols or device drivers. This design eases prototyping of new ideas, and provides the user a homogeneous API.

Communication The communication stack of ROS (see Chapter 4) was not designed to be used by resource-constrained platforms (unlike LCM and R2P), but rather for easy integration by different programming language libraries. Anyway, it is still possible to keep its implementation small enough to be deployed on a microcontroller, as proven in Chapter 6.
A major flaw of ROS for memory-constrained systems is that it communicates



(a) devices with legacy centralized ROS adapter Nodes



(b) ROS-ready devices by using μROSnode

Figure 3.1: A simple robot running ROS, the legacy way and the μROSnode way

through point-to-point TCP channels most of the times. This choice has an impact on the bandwidth, RAM allocation, and threads, because each channel needs its own management, while with a broadcast approach (UDP is capable of) they are unified per topic, not per channel. The UDP version of the ROS protocol is still experimental at the moment of writing, so we have to deal with the allocation of one channel per each TCP connection.
Despite of being a design flaw, we will prove that the TCP approach is not a major issue with simple systems based on microcontrollers. For example, they can hardly saturate a 100 Mbps Ethernet link, and the user is aware of the fairly small number of simultaneous connections manageable by a microcontroller.

Language One of our objectives is software portability. In the embedded systems domain, portability is essentially assured by only one programming language, *ANSI C*. This language is broadly available for embedded systems of nowadays. Almost all of the embedded-grade C compilers can manage code written in pure ANSI C, thanks to its maturity. This ensures that object code generated by ANSI C compliant compilers will work as it should, while this is not always true for other languages.
Also, software written in ANSI C is still compatible with most of *C++* and

Objective C compilers, so there is still the possibility to integrate it with these higher level languages the native way, or by writing idiomatic wrappers. Incidentally, some features of a full C++ implementation (e.g., *RTTI*, exceptions) will make the object code explode in size only because they are enabled, thus exceeding the MCU code memory size. C++ without them is simply C with some *syntax sugar*, a redundancy with the additional risk of non-compliance as stated before.

System abstraction Software portability for embedded systems is fulfilled also through an appropriate hardware abstraction layer. Our design includes *bindings* to the low-level features of the hardware, so that the user can write or choose the low-level drivers which best match the target architecture.
Our framework needs low-level binding for communication, multithreading, and memory management. Communication libraries talk to a TCP/IP stack in a common fashion.
A multithreaded environment is needed because it drastically simplifies the development of a complex firmware, and the overhead introduced by an multithreaded environment is marginal on modern MCUs.
Memory management drivers should handle dynamic allocations (e.g., *memory heaps*). All of these features are often provided by an adequate operating system, and writing of bindings is rather straightforward.
The API chosen for the deployment on general-purpose computers is *POSIX*, which is available in most of the operating systems. In the case of microcontrollers, we have chosen *ChibiOS/RT*, which supports some of the most advanced microcontrollers available nowadays, and *LWIP* as its TCP/IP stack.

Coding style and tools The design of the proposed framework, extensively described in Chapter 5, consists of a few abstract entities, which are managed through a simple and clean software interface. The modular approach is also reflected on the filesystem structure of the package.
The code follows mostly the style rules of ChibiOS/RT, which are derived from the canonical *K&R* (Kernighan and Ritchie) style. There are other coding rules which are aimed at portability (e.g., *MISRA* rules), but we think that K&R-derived styles are still the most clean and intelligible. The code also features extensive self-documentation for *Doxygen*, a widespread self-documentation tool.
The user is provided with a code generator, which can generate templates suitable for the target application by specifying the needed topics, services, and their respective message types.
A static analyzer can help in the development targeted at memory-constrained

platforms, by estimating the total stack usage of a set of functions (*entry points* of threads).

In conclusion, the enhanced framework of our research has the following main features:

- native compatibility with the ROS communication stack;
- code written in ANSI C;
- preconfigured for POSIX, and ChibiOS/RT + LWIP;
- simple modular design;
- extensively self-documented for Doxygen;
- a code generator for user application message management;
- static stack usage analyzer.

Chapter 4

The ROS communications model

Before going ahead to the detailed description of the research work, a detailed knowledge of the communication protocol is essential. This chapter illustrates the protocol defined by the current implementation of ROS, *Groovy*. It is the one adopted by our framework, to have native compatibility with ROS itself.

4.1 Definitions

The following are the definitions of terms occurring frequently within the ROS environment, as stated by the ROS documentation. The reader is aware that some terms can have a different meaning outside ROS, and the present document may make an ambiguous use because of the lack of valid synonyms.

Name Graph resource names are an important mechanism in ROS for providing encapsulation. Each resource is defined within a namespace, which it may share with many other resources. In general, resources can create resources within their namespace and they can access resources within or above their own namespace. Connections can be made between resources in distinct namespaces, but this is generally done by integration code above both namespaces. This encapsulation isolates different portions of the system from accidentally grabbing the wrong named resource or globally hijacking names.

Names are resolved relatively, so resources do not need to be aware of which namespace they are in. This simplifies programming as nodes that work together can be written as if they were all in the top-level namespace. When these nodes are integrated into a larger system, they can be pushed down into a namespace that defines their collection of code.

Computation Graph The Computation Graph is a peer-to-peer network, which consists of nodes connected together in any *mesh* topologies, exchanging topics or providing services.

Node A node is a process that performs computation. Nodes are combined together into a graph and communicate with one another using streaming topics, RPC services, and the Parameter Server. These nodes are meant to operate at a fine-grained scale; a robot control system will usually comprise many nodes. For example, one node controls a laser range-finder, one Node controls the robot's wheel motors, one node performs localization, one node performs path planning, one node provide a graphical view of the system, and so on.

The use of nodes in ROS provides several benefits to the overall system. There is additional fault tolerance as crashes are isolated to individual nodes. Code complexity is reduced in comparison to monolithic systems. Implementation details are also well hidden as the nodes expose a minimal API to the rest of the graph and alternate implementations, even in other programming languages, can easily be substituted.

All running nodes have a graph resource name that uniquely identifies them to the rest of the system.

Master node The Master node provides naming and registration services to the rest of the nodes in the ROS system. It tracks publishers and subscribers to topics as well as services. The role of the Master is to enable individual ROS nodes to locate one another. Once these nodes have located each other they communicate by peer-to-peer connections.

The Master node also provides the Parameter Server.

Message Nodes communicate with each other by publishing messages to topics. A message is a simple data structure, comprising typed fields. Standard primitive types (integer, floating point, boolean, and so on) are supported, as are arrays of primitive types. Messages can include arbitrarily nested structures and arrays.

Nodes can also exchange a request and response message as part of a ROS service call.

Topic Topics are named buses over which nodes exchange messages. Topics have anonymous publish/subscribe semantics, which decouples the production of information from its consumption. In general, nodes are not aware of who they are communicating with. Instead, nodes that are interested in data subscribe to the corresponding topic, while nodes that generate data publish to the corresponding topic. There can be multiple publishers and subscribers to a topic.

Topics are intended for unidirectional, streaming communication. Nodes that need to perform remote procedure calls, i.e. receive a response to a request, should use services instead. There is also the Parameter Server for maintaining global parameters.

Each topic is strongly typed by the ROS message type used to publish to it and nodes can only receive messages with a matching type. The Master does not enforce type consistency among the publishers, but subscribers will not establish message transport unless the types match. Furthermore, all ROS clients check to make sure that the MD5 matches. This check ensures that the ROS nodes were compiled from consistent code bases.

Service Services are used to execute *request/response* calls of raw data. A service consists of two messages (the request and the response) exchanged in a way similar to topic messages. If more than one Node advertise the same service, only the last one will be considered when trying to establish a service stream.

Parameter A parameter is a globally defined variable, stored by the Parameter Server. Parameters are named using the normal ROS naming convention. This means that ROS parameters have a hierarchy that matches the namespaces used for topics and nodes. This hierarchy is meant to protect parameter names from colliding. The hierarchical scheme also allows parameters to be accessed individually or as a tree.

Publisher A publisher node of a specific topic generates and sends TCPROS messages to all of the topic subscribers.

Subscriber A subscriber node of a specific topic receives TCPROS messages from all of the topic publishers.

Parameter server A parameter server is a shared, multi-variate dictionary that is accessible via network APIs. Nodes use this server to store and retrieve parameters at runtime. As it is not designed for high-performance, it is best used for static, non-binary data such as configuration parameters. It is meant to be globally viewable so that tools can easily inspect the configuration state of the system, and modify if necessary.

The Parameter Server is implemented using XML-RPC and runs inside of the ROS Master, which means that its API is accessible via normal XML-RPC calls.

API Set of software methods exposed by a process, so that other processes can call it.

URI Textual representation of a node API address, in the format:
`protocol://host:port`
where *protocol* is either `http` or `rosrpc`, and *host* is either a host name or an IP address. The *port* is the API port number.

Remote procedure call A technique to call a method on a remote machine, and receive its result.

XML-RPC Portable XML-based protocol to execute remote procedure calls. For detailed information, see below.

TCPROS TCP-based protocol used by topic/service binary data streams. For detailed information, see below.

4.2 Overview

The communication layer of ROS, part of the `ros_comm` *stack*, follows the *publish/subscribe* paradigm, as depicted in **Figure 2.2**. The network, also called *computation graph*, involves several *nodes*, either physical or virtual, which are assigned an unique name. A node is a process which gathers data from its inputs, executes computations, and generates data for its outputs. Each node is specialized to a particular function, and does not rely on the existence of other nodes (purely modular design). A node can *publish* some *topics*, which other nodes can *subscribe* to; *services* work a similar way. Topics and services are assigned a known *type*, delivered with their respective ROS package (e.g., `std_msgs/Float`).

For example, think about a simple autonomous rover, equipped with two motors, a set of distance sensors, and the brain computer hosting the ROS framework. A possible ROS network can consist of a node per each sensor or wheel, and a node for the robot brain. Let us suppose that each `sensor_X` node publishes a topic called `sensor_X/distance`, where X is the identifier of the sensor itself. The implementation samples a value measured by the actual sensor at a fixed rate, converts it to the representation advertised for the topic, and sends a marshaled message to the topic subscribers. In a similar manner, each `wheel_Y` node subscribes to a topic called `wheel_Y/speed`, with reference to the speed of the Y-th wheel. The implementation continuously receives a subscribed topic message, converts its unmarshaled speed value to a voltage, and applies the latter to the wheel DC motor to obtain the communicated speed. Instead, the `brain` node subscribes to all of the `sensor_X/distance` topics, and publishes all of the `wheel_Y/speed` topics. Its implementation can follow a suitable logic which determines the wheel speeds by the distances measured by the sensors, for example to move the robot while avoiding obstacles. Its communication flow should be deducible by the reader now.

There can also exist some globally declared *services* (a sort of special *request/response* topics) and *parameters*. For example, the `brain` node publishes the service `sleeping` which replies *true* if the robot is in an idle state, or *false* if the robot is fully operational. This way, `sensor_X` and `wheel_Y` nodes can call the `sleeping` service, and switch off their hardware modules if the response is *true*. Again, a global parameter called `max_speed` holds the maximum speed value, useful to calibrate the behavior of wheel modules.

A special node, the *Master* node, acts as a centralized dispatcher when connecting together publishers and subscribers. It keeps track of published/subscribed topics/services, and in the current implementation it is also the centralized directory for globally defined parameters (the *parameter server*).

Communication with the Master node is accomplished by the exchange of *XML-RPC* messages, through *remote procedure calls*. The topic and service data streams between peers are encoded in a custom protocol, *TCPROS*. Both these protocols will be extensively explained below. ROS connection addresses are sent in URI format.

4.3 Remote procedure calls

ROS nodes are capable of calling *remote procedures*, available through the API exposed by the nodes themselves. Remote procedure calls are executed by using the *XML-RPC* protocol, which is a subset of the XML specification (see Appendix B.1 for its XML Schema and DTD). These calls are used to manage the status of the computation graph and some global settings, and are not supposed for the actual data streams (which use TCPROS or UDPROS instead). XML-RPC was chosen by the designers of ROS because of its large availability of supported languages. The use of XML as its basis makes it simple to debug by a human, and its text-only nature makes it independent by the transport layer encoding format; indeed, it is encapsulated inside HTTP transfers, which prefer text-only contents. Also, XML-RPC calls are *stateless*, a property which simplifies the control logic, since there is no state to keep track of. On the language side, its XML tags follow strict syntax rules, and they lack any attributes. These characteristics make its parsing much easier than XML, while keeping most of its advantages.

4.3.1 Roles

Every ROS node hosts a XML-RPC server. Depending on the role, the set of callable methods is different, and they are defined by the appropriate API. The *Master API* exposes the methods managed by the unique Master node, for example those for (un)registrations of topics and services. The *Slave API* declares the methods managed by a generic node (Slave), for instance the request to establish a topic stream, or the shutdown command. The *Parameter Server* API is used by the unique Parameter Server, which manages the centralized directory of shared global parameters. Detailed information about the APIs is given in Appendix B.1.

4.3.2 Value types

In XML-RPC, method parameters and return values are enclosed by the `value` entity, and can belong only to a small set of types (`value` children):

- **`string`** is an ASCII string. This is the default `value` type, where not stated otherwise. The only illegal characters are `&` and `<`, encoded respectively as `&amp;` and `&lt;`.
- **`int`** or **`i4`** is a 32-bit signed integer, in decimal representation, prefixed by `-` if negative.
- **`boolean`** can be either `0` or `1`.
- **`double`** is a real number, in decimal representation, prefixed by `-` if negative.
- **`dateTime.iso8601`** is a date/time value, in *ISO-8601* format.
- **`base64`** is a binary string encoded with the *Base64* algorithm.
- **`array`** is a list of `value`s, globally enclosed by a `data` entity.
- **`struct`**, also called *map*, is an associative collection. Each entry is a `member`, with a `name` string and a generic `value`.

4.3.3 Request and response

Remote procedure calls consist of two phases: the *request*, and the *response*. A caller (client) sends the method request to the callee (server), which processes

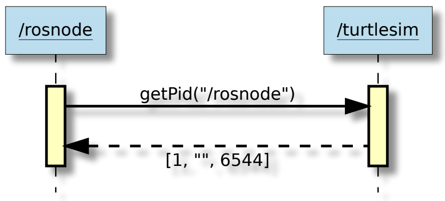


Figure 4.1: Sequence diagram of a `getPid()` XML-RPC call example

it. After processing, the callee returns a *response*, which can be either the call result if successful, or a *fault* if unsuccessful.

A request is introduced by the `methodCall` entity, whose method name is specified by the `methodName` string. Following the method name, a `params` entity encloses a list of `param` children, where each one contains a `value`. The listed `params` are the method parameters, and depend on the API specification. Usually, the first parameter is the name of the caller node within the computation graph.

A response contains the value returned by the remote method. In ROS, the value is an array with three fields. The first field, the *status code*, is an integer with one of the following values:

- `-1` if there was an *error* by the caller, for example due to wrong API method name, parameters or types. The method is not executed at all.
- `0` if there was a *failure* while executing the method call by the remote node.
- `1` if the call was successful.

The second field is for *status string*, a human readable text which explains the reason of the status code value. Its value is optional (it can be empty).
The third field, the *return value*, contains the actual XML-RPC `value` returned by the method call. Its meaning is defined by the specific API.

If the response is a XML-RPC *fault*, it means that there was a hard error, typically a request non XML-RPC compliant.

An example of XML-RPC call to `getPid()` is shown by **Figure 4.1**, with request and response dumps respectively in **Listing 4.1** and **Listing 4.2**.

```
POST /RPC2 HTTP/1.1
Content-Type: text/xml
Content-Length: 178

<?xml version="1.0"?>
<methodCall>
  <methodName>getPid</methodName>
  <params>
    <param>
      <value><string>/rosnode</string></value>
    </param>
  </params>
</methodCall>
```

Listing 4.1: Example of `getPid()` XML-RPC call contents over HTTP

```
HTTP/1.1 200 OK
Content-Type: text/xml
Content-Length: 309

<?xml version="1.0"?>
<methodResponse>
  <params>
    <param>
      <value>
        <array>
          <data>
            <value><i4>1</i4></value>
            <value></value>
            <value><i4>6544</i4></value>
          </data>
        </array>
      </value>
    </param>
  </params>
</methodResponse>
```

Listing 4.2: Example of `getPid()` XML-RPC response contents over HTTP

4.4 Connection patterns

A node on its own has no purpose, and needs to be connected to other nodes some way. In the following, a generic communication pattern is shown, to let a node connect to its peers, and eventually instantiate the required topic data streams. A special case involves service calls.

Upon the introduction of a node to the computation graph, the node has to *register* its published and/or subscribed topics to the Master node. Each topic publisher is registered through a `registerPublisher()` remote procedure call, while each topic subscriber is registered through a `registerSubscriber()` call. The Master is thus omniscient, and can connect together publishers and subscribers of the same topic.

Whenever a node registers its subscribed topics to the Master, a successful response includes the list of publisher URIs already registered. The caller node can then connect to these publishers to receive topic messages. Whenever a new publisher registers to the Master, the latter issues a `publisherUpdate()`

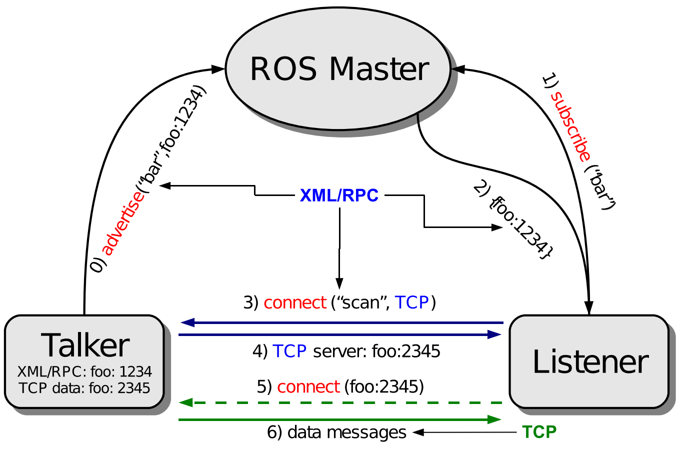


Figure 4.2: Summarized steps to establish a topic data stream [23]

call to the subscribers, with the updated list of available publisher URIs. Topic message streams are exchanged by the TCPROS protocol.

A symmetric case is the *unregistration*. Publishers are unregistered through a `unregisterPublisher()` remote procedure call to the Master node, while subscribers are unregistered through a `unregisterSubscriber()` call. By the way, it is up to publishers and subscribers to close any established data streams for the unregistered topics.

Services work in a slightly different way. The same service can be published by multiple nodes, but only the last advertisement is taken into consideration. A node willing to call the service first looks up the service URI by the Master, through a `lookupService()` remote call. Then, it actually calls the service provider via an appropriate request message. The service provider processes the request and generates a response message, if successful; otherwise, a response with an error message is replied. All of these messages are exchanged by the TCPROS protocol, where the response is headed by an additional *ok byte* (to distinguish success or fault).

4.5 Data streams

While XML-RPC provides an easy and clean protocol for remote method calls, its verbosity and text-centric encoding make it unsuitable for high bandwidth and low latency tasks. This is the case of data streams, like the ones sent by sensors or to actuators. ROS defines a custom binary protocol for such streams; this permits the transfer of raw data among nodes, with the minimum required message length (maximizing bandwidth) and almost no processing

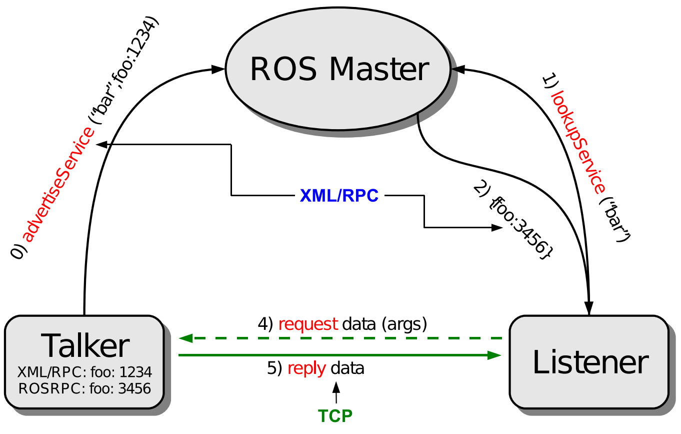


Figure 4.3: Summarized steps to execute a service call [23]

time (minimizing latencies). For detailed information about the topic and service message grammars, please refer to Section 5.3.1.

4.5.1 Type descriptors

Data streams are based on the exchange of messages of a particular type, specified by the topic/service at registration time (see previous section). A message is a sequence of values, arranged in the order defined by the type descriptor. In ROS, there exist two kinds, the *topic descriptor*, and the *service descriptor*. We will consider the topic descriptor first, because service types are just a simple extension.

Topic types A ROS topic message descriptor is written as a plain text file, where the file name coincides with the type name, plus the `.msg` extension. Every line can define a strong-typed variable, where the type is either a primitive type, or the name of another message type descriptor, or even an array (fixed or variable) of any of such types. Thus, messages can be nested, and, being strongly typed, their streaming is simplified (no dynamic types to handle). Descriptors can also declare constant names of primitive types.

Listing 4.3 shows the `rosgraph_msgs/msg/Log.msg` contents, while **Listing 4.4** is its clean expanded version, generated by `rosmsg show`.

Service types While topics are uni-directional, thus needing only the definition of one message type, services work on a request/response approach.

```
##
## Severity level constants
##
byte DEBUG=1 #debug level
byte INFO=2  #general level
byte WARN=4  #warning level
byte ERROR=8 #error level
byte FATAL=16 #fatal/critical level
##
## Fields
##
Header header
byte level
string name # name of the node
string msg # message
string file # file the message came from
string function # function the message came from
uint32 line # line the message came from
string[] topics # topic names that the node publishes
```

Listing 4.3: Contents of `rosgraph_msgs/msg/Log.msg`

```
byte DEBUG=1
byte INFO=2
byte WARN=4
byte ERROR=8
byte FATAL=16
std_msgs/Header header
  uint32 seq
  time stamp
  string frame_id
byte level
string name
string msg
string file
string function
uint32 line
string[] topics
```

Listing 4.4: Clean, expanded contents of `rosgraph_msgs/msg/Log.msg`

So, a service involves two types, the one for the request, and the one for the response. Service type descriptors are stored similarly to topic types, where the extension is `.srv` instead. The descriptor is split into two parts by a `--` separator line, where the first part is the request message descriptor, and the second part is the response message descriptor.

Listing 4.5 is an example of the `dynamic_reconfigure/srv/Reconfigure.srv` contents, while **Listing 4.6** is its clean expanded version, generated by `rossrv show`.

Hashing Because descriptor texts may be different among nodes, while their names can be the same, there must be a way to determine if two nodes actually share the same type. For such task, the MD5 sum was chosen for comparing two different type descriptions. The comparison function executes the following

```
Config config
---
Config config
```

Listing 4.5: Contents of `dynamic_reconfigure/srv/Reconfigure.srv`

```
dynamic_reconfigure/Config config
  dynamic_reconfigure/BoolParameter[] bools
    string name
    bool value
  dynamic_reconfigure/IntParameter[] ints
    string name
    int32 value
  dynamic_reconfigure/StrParameter[] strs
    string name
    string value
  dynamic_reconfigure/DoubleParameter[] doubles
    string name
    float64 value
  dynamic_reconfigure/GroupState[] groups
    string name
    bool state
    int32 id
    int32 parent
---
dynamic_reconfigure/Config config
  dynamic_reconfigure/BoolParameter[] bools
    string name
    bool value
  dynamic_reconfigure/IntParameter[] ints
    string name
    int32 value
  dynamic_reconfigure/StrParameter[] strs
    string name
    string value
  dynamic_reconfigure/DoubleParameter[] doubles
    string name
    float64 value
  dynamic_reconfigure/GroupState[] groups
    string name
    bool state
    int32 id
    int32 parent
```

Listing 4.6: Clean, expanded contents of `dynamic_reconfigure/srv/Reconfigure.srv`

operations on each type descriptor:

1. comments are removed;
2. whitespace is removed;
3. package names of dependencies are removed;
4. constants are moved ahead of variable declarations, keeping their arrangement;
5. for nested types, their hashing text is computed and appended to the current hashing text, in the order they appear;
6. the MD5 sum of the whole hashing text is computed.

If the MD5 sums are the same, then the two descriptors are equal.

ROS type	**C99 type**
uint8	uint8_t
uint16	uint16_t
uint32	uint32_t
uint64	uint64_t
int8	int8_t
int16	int16_t
int32	int32_t
int64	int64_t
time	uros_time_t
duration	uros_time_t
string	struct UrosString { size_t length; char *datap; };
type[]	struct UrosTcpRosArray { uint32_t length; void *entriesp; };
byte	uint8_t
char	char
uint	uint32_t
int	int32_t

Table 4.1: ROS to C type mapping

4.5.2 Message structure

Messages are serialized in *little-endian* binary form. This makes its processing straightforward by most of the little-endian CPU architectures available on the market, such as those based on *x86* or *ARM* designs. Therefore, a data stream message is much like the serialization of a *C struct* variable; for example, on x86 architectures a message is a one-to-one dump of the variable itself, because of 8 bit field alignments in memory (by contrast, 32 bit on ARM cores).

Primitive types can be directly mapped to C types as seen in **Table 4.1**. Variable-length arrays and `string`s (arrays of `char`s) are a special case, because they provide the number of entries by a `uint32` length, followed by the serialized entries themselves. By contrast, fixed-length arrays are treated as a sequence of entries of the specified type. Any nested types are expanded into their respective primitive types or arrays.

Ahead of the message content just described, a `uint32` value anticipates the total length of the content itself.

Topic messages Topic messages simply follow the length+content scheme described above, since a topic involves uni-directional messages of the same type.

An example of `"Hello, World!"` message of type `std_msgs/String` is in **Figure 4.4**. Stream offsets are written as hexadecimal indexes in bold font; values are written as ASCII characters if printable, as hexadecimal numbers otherwise. Comments on the right indicate the specific field being streamed, and its

```
00 01 02 03   uint32 message_length
11 00 00 00   17

04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 10 11 12 13 14   string data
0D 00 00 00  H  e  l  l  o  ,     W  o  r  l  d  !    13 "Hello, World!"
```

Figure 4.4: Dump of a "Hello, World!" *message of type* std_msgs/String

```
00 01 02 03   uint32 message_length
10 00 00 00   16

04 05 06 07 08 09 0A 0B   int64 a
D2 04 00 00 00 00 00 00   1234

0C 0D 0E 0F 10 11 12 13   int64 b
2E 16 00 00 00 00 00 00   5678
```

Figure 4.5: Dump of a call to service of type rospy_tutorials/AddTwoInts

human-readable value.

Service messages Service requests are serialized the same way as topic messages. Instead, the serialization of the response needs to take into account the status of the response, which can be an actual response value, or an error message.
A so-called *ok byte* is sent ahead of the response. If `1`, it means that the following streamed data is of the expected service response type. If `0` it means that there was an error while processing the request, and the following streamed value is of `string` type, representing a human-readable error text.

Examples of `rospy_tutorials/AddTwoInts` service request and response are shown by **Figure 4.5** and **Figure 4.6**. Instead, a service response reporting an unknown error can be seen in **Figure 4.7**.

4.5.3 Connection header

As soon as the topic/service client and the related server connect, they must agree upon the streaming parameters. They include the topic/service name and type, the possibility of multiple service requests, the use of bandwidth optimizations, and so on. All of these parameters are set up by the *connection header*, which is a special message sent at the very beginning of the whole stream, by both endpoints. At first, a header is sent by the client, which acts as a request. The server will then reply with another header, which acts as a response.

The connection header is made of fields. They are encoded like `strings`, thus a `uint32` telling the string length is sent ahead of the string characters. The value follows the *field=value* format, where the available fields and their semantics

```
00   uint8 ok
01   acknowledge

01 02 03 04   uint32 message_length
08 00 00 00   8

05 06 07 08 09 0A 0B 0C   int64 sum
00 1B 00 00 00 00 00 00   6912
```

Figure 4.6: Dump of the response to the service call of Figure 4.5

```
00   uint8 ok
00   error

01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 10 11   string error_text
0D 00 00 00  U  n  k  n  o  w  n     e  r  r  o  r   13 "Unknown error"
```

Figure 4.7: Dump of a service error response

depend on the topic/service request/response headers. The connection header is introduced by a `uint32` holding the whole header length, just like common messages.

Table 4.2 summarizes the fields of a connection header, and their presence within topic, service, or error headers (✓), some of which are optional ((✓)) or can be *probed* by the requesting header (the field value equals to $*$).

Figure 4.8 and **Figure 4.9** show respectively the request and response connection headers for the `/turtle1/command_velocity` of the `/turtlesim` Node, by a `turtlesim_teleop` Node.

Field	Description	Request		Response		
		Tpc	Srv	Tpc	Srv	Err
`callerid`	Sender Node name	✓	✓	(✓)	✓	(✓)
`topic`	Topic name	✓				
`service`	Service name		✓			
`md5sum`	MD5 sum of the type	✓*	✓*	✓	✓	(✓)
`type`	Message type	✓*	✓*	✓	✓	(✓)
`request_type`	Service request type		✓*		✓	
`response_type`	Service response type		✓*		✓	
`message_definition`	`.msg`/`.srv` contents	(✓)	(✓)	(✓)	(✓)	(✓)
`persistent`	Persistent service		(✓)			
`latching`	Latched values			(✓)		
`tcp_nodelay`	*Nagle* alg. disabled	(✓)				
`error`	Error text					✓

Table 4.2: Connection header fields

```
00 01 02 03   uint32 header_length
91 00 00 00   145

04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 10 11 12 13 14 15 16 17 18 19 1A   (string field)
13 00 00 00  c  a  l  l  e  r  i  d  =  /  t  u  r  t  l  e  s  i  m

1B 1C 1D 1E 1F 20 21 22 23 24 25   (string field)
27 00 00 00  m  d  5  s  u  m  =
26 27 28 29 2A 2B 2C 2D 2E 2F 30 31 32 33 34 35
 9  d  5  c  2  d  c  d  3  4  8  a  c  8  f  7
36 37 38 39 3A 3B 3C 3D 3E 3F 40 41 42 43 44 45
 6  c  e  2  a  4  3  0  7  b  d  6  3  a  1  3

46 47 48 49 4A 4B 4C 4D 4E 4F 50 51 52 53 54 55 56   (string field)
0D 00 00 00  t  c  p  _  n  o  d  e  l  a  y  =  0

57 58 59 5A 5B 5C 5D 5E 5F 60   (string field)
1F 00 00 00  t  o  p  i  c  =
61 62 63 64 65 66 67 68 69 6A 6B 6C 6D 6E 6F 70 71 72 73 74 75 76 77 78 79
 /  t  u  r  t  l  e  1  /  c  o  m  m  a  n  d  _  v  e  l  o  c  i  t  y

7A 7B 7C 7D 7E 7F 80 81 82   (string field)
17 00 00 00  t  y  p  e  =
83 84 85 86 87 88 89 8A 8B 8C 8D 8E 8F 90 91 92 93 94
 t  u  r  t  l  e  s  i  m  /  V  e  l  o  c  i  t  y
```

Figure 4.8: Dump of a connection header request

```
00 01 02 03   uint32 header_length
A5 00 00 00   165

04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 10 11 12 13 14 15 16 17 18 19 1A 1B 1C 1D 1E
13 00 00 00  c  a  l  l  e  r  i  d  =  /  t  e  l  e  o  p  _  t  u  r  t  l  e

1F 20 21 22 23 24 25 26 27 28 29 2A 2B 2C
0A 00 00 00  l  a  t  c  h  i  n  g  =  0

2D 2E 2F 30 31 32 33 34 35 36 37
27 00 00 00  m  d  5  s  u  m  =
38 39 3A 3B 3C 3D 3E 3F 40 41 42 43 44 45 46 47
 9  d  5  c  2  d  c  d  3  4  8  a  c  8  f  7
48 49 4A 4B 4C 4D 4E 4F 50 51 52 53 54 55 56 57
 6  c  e  2  a  4  3  0  7  b  d  6  3  a  1  3

58 59 5A 5B 5C 5D 5E 5F 60 61 62 63 64 65 66 67 68 69 6A 6B 6C 6D 6E
32 00 00 00  m  e  s  s  a  g  e  _  d  e  f  i  n  i  t  i  o  n  =
6F 70 71 72 73 74 75 76 77 78 79 7A 7B 7C 7D
 f  l  o  a  t  3  2     l  i  n  e  a  r \n
7E 7F 80 81 82 83 84 85 86 87 88 89 8A 8B 8C 8D
 f  l  o  a  t  3  2     a  n  g  u  l  a  r \n

8E 8F 90 91 92 93 94 95 96 97 98 99 9A 9B 9C 9D 9E 9F A0 A1 A2 A3 A4 A5 A6 A7 A8
17 00 00 00  t  y  p  e  =  t  u  r  t  l  e  s  i  m  /  V  e  l  o  c  i  t  y
```

Figure 4.9: Dump of a response to the connection header in Figure 4.8

Chapter 5

The proposed framework – µROSnode

According to the objectives of the research, explained in Chapter 3, we designed and implemented a communication framework, **µROSnode** (`uros` inside the code, logo in **Figure 5.1**), which has native compatibility with ROS, and is targeted towards embedded systems software. Its software architecture and implementation details highlight its modular approach, along with the design optimized for simplicity and portability. Furthermore, we developed some tools which help the user integrate the application software with the framework, by generating (un)marshaling procedures, and estimating the stack usage for memory-constrained target platforms. A development process is finally proposed, showing an ideal way to develop an application with our framework from scratch, or by integration.

5.1 Implementation choices

In the following, the major features and implementation choices are illustrated, for a better understanding of the work done in the field of embedded systems. Developing for tightly resource-constrained devices, we had to find the right compromise between language portability and features, and between footprint size and code elegance.

Figure 5.1: μROSnode logo

5.1.1 Language observations

The framework is written in almost pure *ANSI C89* [1], also known as *ISO C90* [26], in the corrected version supported by *GCC* [10]. This ensures the maximum portability across multiple platforms, as extensively illustrated by the research strategy of Section 3.2. The framework widely uses *C99* standard integer types (e.g., `uint32_t`), which can mostly be defined in C89 by hand; actually, any recent compilers support them, by including `stdint.h`. Conformity to the C89 standard holds if compiling with `gcc -ansi -pedantic`.

The choice of this language, despite of its portability, made us accept some strong limitations not found in other similar languages, notably its widespread evolution *C++*. The lack of generic programming features, namespaces and classes, which could have made the code strictly typed and more readable, pushed us down to some common compromises.
For example, objects in lists are weakly addressed by pointers to `void`, where C++ templates would assign them the right type; the use of typing macros in this case worsens the readability. The absence of namespaces is solved by prefixing function names with `uros`, often followed by the module name (`_lld_`+module for low-level drivers); major type names are prefixed by `Uros`, minor by `uros_`. We tried to write a clean codebase, with an user-friendly coding style, in order to cope with the limitations of ANSI C.

As stated in Chapter 3, not all of the C++ features are available on all of the embedded systems, or are an overkill. For example, by just enabling *RTTI* the compiler generates a much bigger object code, which could not fit into the small code memory of a microcontroller.
Additionally, the useful exception handling is not supported at all by some compilers, target architectures, or operating systems. Moreover, the C++ language has not the same mature support of the plain old ANSI C.

5.1.2 Footprint optimizations

Wherever possible, the code was written to minimize memory usage. This may make the code a little obfuscated, but we tried to minimize the usage of aliased structures (through `unions`) only where the stack analysis tool showed a great opportunity to minimize the stack usage. Anyway, such optimizations are typically for internal use, while the user API is clean.

Thanks to the stack analysis tool, we reduced the number of function calls, and minimized the function parameters or local variables. Although declaring more variables with meaningful names and single assignments makes the code more readable, the compiler was not always capable of optimizing the stack usage. So, some functions reuse local variables or parameters to reduce the stack usage, without aggressive reuse to not obfuscate the code.

Objects with a predictable life span are usually placed onto the stack, even the fairly big ones. This way, the stack analysis tool can keep track of such objects, and the programmer is aware of the consequences. Furthermore, stack allocations are faster and managed automatically.
By contrast, heap allocations are slower (even not constant-time) and error-prone; also, negligent allocation into the heap could saturate it (thus failing) unpredictably. This is why we encouraged stack allocations throughout the codebase.

In order to reduce stack usage, we avoided aggressive function nesting wherever possible, while keeping a reasonable degree of factorization.

Object code size is a minor concern in our perspective, since the latest micro-controllers have more than enough space, as proven in Section 3.2. Nevertheless, as common sense suggests, factorization of features, along with a set of preprocessor switches to ignore unused code, can reduce the object code size.
For instance, TCPROS connection header transmission and reception functions, which are rather lengthy, are shared between the client and the server; similarly, XML-RPC client calls rely on a common syntax. Some optimizations made by the compiler can help in reducing the object code footprint too, even those which target speed.

5.2 Framework description

The framework is composed by software modules which reflect their domain of expertise. Most of the modules are platform-independent, while some have a platform-dependent counterpart, prefixed by `lld` (*low-level driver*) which *binds* to the low-level libraries provided for the specific platform. There are also some application-dependent modules, which should be provided by the user, defining callback functions. Optionally, some user modules contain serialization functions and handlers for ROS topics and services. Major optimizations for resource-constrained platforms (embedded systems) are highlighted.

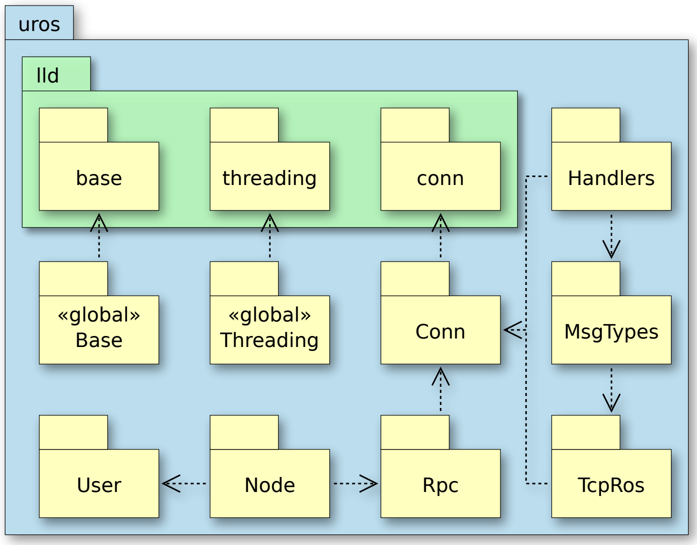


Figure 5.2: Logical view of μROSnode modules

Figure 5.2 shows a logical view of software modules of the framework.

5.2.1 Base module

The **urosBase** module provides the software features used throughout the framework, such as basic types and memory management functions. The low-level counterpart, **uros_lld_base**, provides bindings for memory management functions.

Basic types The basic types provided by the framework are those defined by the *C99* standard, plus some commonly used types. In addition, some useful function types (signatures) are defined, like the predicate, comparison, and thread entry point signatures.

Strings The string type, `UrosString`, is used for string management, instead of the *null-terminated* strings used by the C language. They consist of a `size_t` field which holds the string length, followed by the pointer to the string content. This representation optimizes string management, for example by parsing and serialization functions, thanks to the embedded length counter; this allows to share the same text chunk among different string descriptors, which may employ only parts of it.

The module provides functions for conversion from C strings (both assigned or cloned), checking functions, and the string comparison function.

Lists The list type, `UrosList`, is a uni-directional concatenated list of elements of any types (the user is aware of). The list object itself holds the count of entries, and the pointer to the first one. List nodes, `UrosListNode`, consist of a pointer to the node data, and a pointer to the next node.

The library provides functions for common list operations (addition, removal, existence of nodes), as well as some predicate function types, used for finding entries.

Message types A message type record, `UrosMsgType`, holds the name, the optional text description, and the MD5 sum of a topic/service message type, usually well known inside the application domain. Thus, a global list, built at start-up, keeps all of the message types used within the application; a set of functions operates on this list.

Service message types are handled the same way, but on a separate global list.

Topic/service descriptors Topics and services share the same descriptor type `UrosTopic`. It holds the topic/service name, the pointer to its message type, the pointer to the handler function, a set of flags, and a reference counter. The message type is typically contained into the global static register (see above). The flags specify some connection settings, plus the switch between topic and service. The reference counter is used so that the descriptor can be shared by multiple handler instances which refer to it (*shared pointer* mechanism).

Heap allocators Most of the operations managed by the framework need dynamic allocations; think about the parsing of an incoming XML-RPC request holding a list of URIs. The *heap allocator* technique is used by the framework. A set of functions permits the dynamic allocation and deletion of memory chunks of any possible size. The library supports multiple heaps, for those platforms with disjointed memory spaces, commonly found in embedded system architectures.

Memory pools A common approach when managing memory blocks of the same size, for example thread pool stacks, is the *memory pool*. Blocks work as an uni-directional list, where each node is a memory chunk with an additional reserved pointer at the very beginning, which addresses the next node in the list.

A memory pool is defined by the `UrosMemPool` type. It holds the block size (comprehensive of the reserved pointer), the pointer to the first block in the list, and the number of free blocks left, the allocator function and the lock word (for multithreaded access).
If the allocator function is provided, when the pool is full and a new block is requested, then the allocator function will create a new block. Otherwise, the memory pool has fixed size, and the applicant thread is suspended.

The library provides functions for the creation of a memory pool, both dynamically by an allocator function, or from a fixed-size memory chunk (array), and functions for requesting or releasing blocks.

The memory pool mechanism illustrated above is platform independent, but can be overridden for native memory pools, if available.

5.2.2 Connectivity module

The **urosConn** module provides the TCP and UDP connectivity features of the framework. The low-level counterpart, **uros_lld_conn**, interfaces to the network stack chosen by the user.

Addresses The library provides data types for holding an IP number (`UrosIp`), and a TCP or UDP address (`UrosAddr`). Some helper functions can resolve hostnames or ROS URIs to addresses.

Connection record The connection record, `UrosConn`, holds the local and remote addresses, the protocol identifier, and the total number of received and transmitted bytes. Some fields may be added by the chosen low-level driver.

Comparison with BSD sockets

The connection life cycle and usage are equivalent to the widespread *POSIX sockets* [11], with only a few meaningful exceptions, so the reader is aware of consulting the POSIX sockets manual. The differences, explained below, are only in the transmission and reception call behaviors. They were introduced for a higher degree of portability among different network stacks; for example, there was no other clever way to provide bindings for the *LWIP* stack, while keeping a reasonable implementation for POSIX sockets. Connections can also support timeouts, if available on the target architecture.

Transmission A call to `urosConnSend()` (or related) sends the specified chunk of data in its entirety, while POSIX sockets can send it partially (even not at all).

Reception A call to `urosConnRecv()` (or related) fills a buffer provided by the low-level driver, instead of a buffer provided by the user as with POSIX sockets.

5.2.3 XML-RPC module

The **urosRpc** module provides all of the XML-RPC features needed by a ROS-compliant Node, like parsing and streaming functions, along with client calls and the Slave API server.

Parameters A XML-RPC parameter is described by `UrosRpcParam`. It specifies the value class (parameter type switch), and the polymorphic value itself. See Section 4.3 for more information about XML-RPC parameter types.

Parameter lists A parameter list, `UrosRpcParamList`, is a double-ended, uni-directional list of `UrosRpcParamNode` entries. The list descriptor holds the number of entries and pointers to the head and tail nodes. A node embeds a `UrosRpcParam` value, and the pointer to the next node.

Such a structure makes parameter management easier while parsing or processing XML-RPC streams. Indeed, nodes are appended at the end (tail), and the list can still be traversed from the oldest node (head) to the newest node (tail); by contrast, a `UrosList` can be managed in constant time and traversed only in reverse order. The embedding of the value inside the node avoids the unneeded indirections and heap fragmentation of a `UrosListNode`.

Parser Being an XML-based language, one of the many XML parsers supplied by external libraries could be used for XML-RPC parsing. Anyway, most (if not all) were not designed specifically for resource-constrained platforms, as embedded systems are. Thus, this module provides an optimized parser, which can perform a one-pass parsing of the incoming XML-RPC request over HTTP, with small code and stack footprints.

The `UrosRpcParser` record holds the last error code (convenient for avoiding local variables on the stack), the pointer to the connection, and fields for parsing; among these, the pointer to the received HTTP buffer and its length, and the current cursor status. Moreover, a buffer holds a possible incoming `string` entity; indeed, the only case where the $LL(k)$ hypotheses [24] do not hold is when a `value` is of `string` type without `string` tags, so a workaround is to prefetch a string of the maximum length possible.

Streamer The library is also capable of streaming XML-RPC messages over HTTP. The streamer object type is `UrosRpcStreamer`, which is structured similarly to the parser; this makes aliasing possible wherever needed, by reusing a memory chunk for both the parser and the streamer (mutually exclusive), thus optimizing the memory usage.

Calls A set of all of the possible ROS client calls to the Master, Slave, and Parameter server APIs is available. Their footprint in both code and memory usage is kept to a minimum, by exploiting the common syntax and XML-RPC parameters.

Slave The framework is used to create a Slave ROS Node, so it exposes its Slave API server, performed by the Slave server thread. It listens to any incoming XML-RPC request messages, and dispatches them to the appropriate Slave API method handler, which processes them and generates the expected response message.

5.2.4 TCPROS module

The **urosTcpRos** module provides functions to communicate through the TCPROS protocol.

Connection status The TCPROS connection status is held by the descriptor, `UrosTpcRosStatus`, which specifies the caller name, the referenced topic or service descriptor and flags, the exit request flag, and other options.

Functions Since the TCPROS protocol is very close to the binary representation in memory, its functions are merely shorthands for raw data transmission and reception. Instead, (un)marshaling routines should be implemented by application-specific code, inside the `urosMsgTypes` module (see Section 5.2.8). A pair of functions can send and receive TCPROS connection headers, for both publishers and subscribers.

Macros Furthermore, to simplify the body of topic/service handler functions, a set of useful macros provided. They are expanded to (un)marshaling statements, along with meaningful error checking, (un)initialization, and (de)allocation statements. Those macros are extensively used by those handlers created by the code generator (see Section 5.3.1).

Arrays In order to manage TCPROS variable-length arrays, records of type `UrosTcpRosArray` can be used by (un)marshaling procedures. The array type holds the number of entries, and a pointer to the entries memory chunk (of any type, the user is aware of type checking).

5.2.5 Node module

The **urosNode** module manages the configuration, the status, and the life of the Node *singleton*.

Configuration The configuration record, `UrosNodeConfig`, holds the Node configuration, loaded at boot time. It consists of the node name, the URI and the TCP/IP addresses of the remote Master XML-RPC server, the local XML-RPC Slave server, and the local TCPROS server.

Status The status record, `UrosNodeStatus`, holds the runtime status of the Node. It contains the publishers and subscribers lists, the active TCPROS connections list, the thread (and memory) pools for XML-RPC and TCPROS handlers, and functions for multithreaded access to all of them.

Registration functions A set of routines is used to manage topic publications/subscriptions, service publications/calls, and parameter subscriptions. These routines perform checks and operations on the Node status lists, as well as automatic management of TCPROS channels to be established or closed.

Node thread The Node thread takes care of the life of the Node. It populates the thread pools, registers topics/services/parameters to the Master node, keeps checking if the latter is always reachable, and performs a graceful shutdown in the reverse order.

5.2.6 Threading module

The **urosThreading** module provides a multithreading environment as needed by the framework, like threads, synchronization primitives, and thread pools. The low-level driver, **uros_lld_threading**, binds to the multithreading API of the target operating system.

Primitives The synchronization primitives supplied by the framework are the canonical ones, such as semaphores, mutexes, and condition variables. Their usage should be straightforward.

Threads As for synchronization primitives, threads follow a canonical approach. A thread can be created with a stack either from the heap or from a memory pool; the thread can be eventually joined.

Thread pools The threading library includes a thread pool mechanism, where thread pools have `UrosThreadPool` type, and they make use of memory pools (`UrosMemPool`) as their stack supplier. The thread pool can be started (threads created) and stopped (threads joined) gracefully.

5.2.7 User module

Some features of the framework cannot work without some kind of management by the user application. Callback functions of the **urosUser** module provide the link between the framework internals and the user application.

Node configuration persistence If deciding not to load the default, hard-coded Node configuration at boot time, a pair of load/save functions access a non-volatile memory device.

Registrations and unregistrations There is a set of functions to manage message type, topic, and service (un)registration callbacks, triggered by the Node thread.

Shutdown callback A callback function must be defined to gracefully close communication channels, and release resources whenever a `shutdown()` remote call is issued to the Node.

Parameter update callback A further callback function is triggered whenever the Master issues a `paramUpdate()` to this Node, holding the global ROS parameter name, and its value.

5.2.8 Message types module

An optional module, **urosMsgTypes**, should provide the (un)marshaling functions of topic and service message types, along with their registration. This approach is highly suggested, as it keeps the codebase clean and easily maintainable. This module is application-dependent, and it can be automatically generated by the code generator tool. See Section 5.3.1 for in-depth description.

5.2.9 Handlers module

Another optional module, **urosHandlers**, should provide the topic and service handler functions. Like for `urosMsgTypes`, it is highly suggested, and automatically generated (at least its skeleton) by the code generator tool of Section 5.3.1.

5.3 Development tools

In order to facilitate the development of user applications, a code generator, a stack usage analyzer, and demonstration projects are included by the framework package.

5.3.1 Code generator

Writing marshaling procedures and topic/service handler routines by hand can take much time, and it is an error-prone task. The generation of marshaling procedures can be automated by processing the message descriptors delivered with ROS packages. Additionally, handler routines share a common skeleton, which can be exploited and reused. That being so, a generation tool, **urogen** (implemented as a *Python 2.7* script, `urosgen.py`), was developed.

Compilation flow

The compilation flow, depicted in **Figure 5.3**, is pretty straightforward. The tool is configured through a file (full example in **Listing B.11**), which lists the

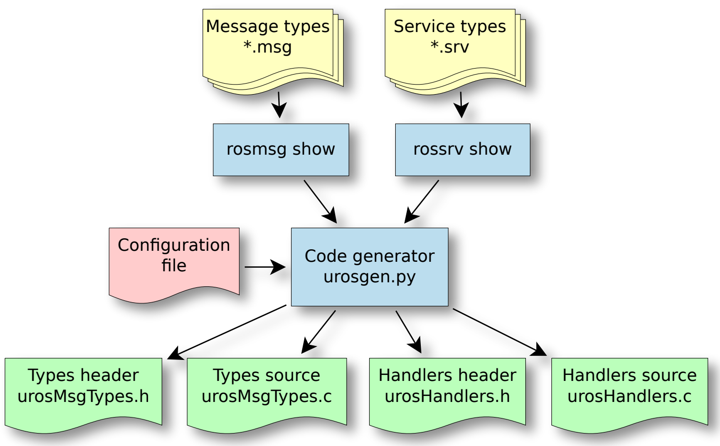


Figure 5.3: Code generator flowchart

topic/service names and types, along with some options. Once the involved message type names are known, the tool loads their description from the related `.msg` and `.srv` files of the installed ROS packages. Finally, the message types are processed, thus producing marshaling and unmarshaling functions. Topic and service handler stubs are generated for those names listed inside the configuration file. The tool also generates detailed self-documentation for *Doxygen* (not reported in listing examples, as well as most of the comments).

Name mangling

All ROS names have a path-like structure, with `/` (slash) as separator. C identifiers cannot contain it, so ROS names are mangled by replacing `/` with `__` (double underscore).

Topic and service mangled names always start with `__`, since they have an implicit `/` at the beginning.

Messages

A message type is loaded from its `.msg` file through a call to `rosmsg show`, which removes comments and has a clean syntax. Its inherent structure mapped to a C `struct`, where the mangled name is prefixed by `msg__` (*msg_name*). Primitive types are directly mapped, while nested message types are declared separately. In order to conform with the C language, `struct`s are defined in topological order; this can be done because ROS types cannot have circular dependencies.

```
struct msg__rosgraph_msgs__Log {
  struct msg__std_msgs__Header  header;
  uint8_t                       level;
  UrosString                    name;
  UrosString                    msg;
  UrosString                    file;
  UrosString                    function;
  uint32_t                      line;
  UROS_VARARR(UrosString)       topics;
};

#define msg__rosgraph_msgs__Log__DEBUG      ((uint8_t)1)
#define msg__rosgraph_msgs__Log__INFO       ((uint8_t)2)
#define msg__rosgraph_msgs__Log__WARN       ((uint8_t)4)
#define msg__rosgraph_msgs__Log__ERROR      ((uint8_t)8)
#define msg__rosgraph_msgs__Log__FATAL      ((uint8_t)16)
```

Listing 5.1: Definition of the rosgraph_msgs/Log descriptor and its constant values

```
size_t length_msg__rosgraph_msgs__Log(
  struct msg__rosgraph_msgs__Log *objp
) {
  size_t length = 0;
  uint32_t i;

  urosAssert(objp != NULL);

  length += length_msg__std_msgs__Header(&objp->header);
  length += sizeof(uint8_t);
  length += sizeof(uint32_t) + objp->name.length;
  length += sizeof(uint32_t) + objp->msg.length;
  length += sizeof(uint32_t) + objp->file.length;
  length += sizeof(uint32_t) + objp->function.length;
  length += sizeof(uint32_t);
  length += sizeof(uint32_t);
  length += (size_t)objp->topics.length * sizeof(uint32_t);
  for (i = 0; i < objp->topics.length; ++i) {
    length += objp->topics.entriesp[i].length;
  }

  return length;
}
```

Listing 5.2: Stream length computation of a rosgraph_msgs/Log message

A message type example, `rosgraph_msgs/Log`, is in **Listing 5.1**.

The code generator creates functions for the following operations: initialization, cleaning, length computation, marshaling, and unmarshaling.

The initialization function (`init_`+*msg_name*, **Listing 5.3**) sets the preliminary, safe values. The cleaning function (`clean_`+*msg_name*, **Listing 5.4**) deallocates any allocated fields, reaching the safe initialization state.

The length computation function (`length_`+*msg_name*, **Listing 5.2**) computes the length of the serialized message.

The marshaling function (`send_`+*msg_name*, **Listing 5.6**) serializes the message contents and sends them over the outgoing TCPROS stream. Instead, the unmarshaling function (`recv_`+*msg_name*, **Listing 5.5**) unserializes the received message from the incoming TCPROS stream.

```c
void init_msg__rosgraph_msgs__Log(
  struct msg__rosgraph_msgs__Log *objp
) {
  uint32_t i;

  urosAssert(objp != NULL);

  init_msg__std_msgs__Header(&objp->header);
  urosStringObjectInit(&objp->name);
  urosStringObjectInit(&objp->msg);
  urosStringObjectInit(&objp->file);
  urosStringObjectInit(&objp->function);
  urosTcpRosArrayObjectInit((UrosTcpRosArray *)&objp->topics);
  for (i = 0; i < objp->topics.length; ++i) {
    urosStringObjectInit(&objp->topics.entriesp[i]);
  }
}
```

Listing 5.3: Initialization of a rosgraph_msgs/Log descriptor

```c
void clean_msg__rosgraph_msgs__Log(
  struct msg__rosgraph_msgs__Log *objp
) {
  uint32_t i;

  if (objp == NULL) { return; }

  clean_msg__std_msgs__Header(&objp->header);
  urosStringClean(&objp->name);
  urosStringClean(&objp->msg);
  urosStringClean(&objp->file);
  urosStringClean(&objp->function);
  for (i = 0; i < objp->topics.length; ++i) {
    urosStringClean(&objp->topics.entriesp[i]);
  }
  urosTcpRosArrayClean((UrosTcpRosArray *)&objp->topics);
}
```

Listing 5.4: Cleaning function of a rosgraph_msgs/Log descriptor

```c
uros_err_t recv_msg__rosgraph_msgs__Log(
  UrosTcpRosStatus *tcpstp,
  struct msg__rosgraph_msgs__Log *objp
) {
  uint32_t i;

  urosAssert(tcpstp != NULL);
  urosAssert(urosConnIsValid(tcpstp->csp));
  urosAssert(objp != NULL);
#define _CHKOK { if (tcpstp->err != UROS_OK) { goto _error; } }

  recv_msg__std_msgs__Header(tcpstp, &objp->header); _CHKOK
  urosTcpRosRecvRaw(tcpstp, objp->level); _CHKOK
  urosTcpRosRecvString(tcpstp, &objp->name); _CHKOK
  urosTcpRosRecvString(tcpstp, &objp->msg); _CHKOK
  urosTcpRosRecvString(tcpstp, &objp->file); _CHKOK
  urosTcpRosRecvString(tcpstp, &objp->function); _CHKOK
  urosTcpRosRecvRaw(tcpstp, objp->line); _CHKOK
  urosTcpRosArrayObjectInit((UrosTcpRosArray *)&objp->topics);
  urosTcpRosRecvRaw(tcpstp, objp->topics.length); _CHKOK
  objp->topics.entriesp = urosArrayNew(objp->topics.length,
                                       UrosString);
  if (objp->topics.entriesp == NULL) { tcpstp->err = UROS_ERR_NOMEM; goto _error; }
  for (i = 0; i < objp->topics.length; ++i) {
    urosTcpRosRecvString(tcpstp, &objp->topics.entriesp[i]); _CHKOK
  }

  return tcpstp->err = UROS_OK;
_error:
  clean_msg__rosgraph_msgs__Log(objp);
  return tcpstp->err;
#undef _CHKOK
}
```

Listing 5.5: Reception and unmarshaling of a rosgraph_msgs/Log message

```c
uros_err_t send_msg__rosgraph_msgs__Log(
  UrosTcpRosStatus *tcpstp,
  struct msg__rosgraph_msgs__Log *objp
) {
  uint32_t i;

  urosAssert(tcpstp != NULL);
  urosAssert(urosConnIsValid(tcpstp->csp));
  urosAssert(objp != NULL);
#define _CHKOK { if (tcpstp->err != UROS_OK) { return tcpstp->err; } }

  send_msg__std_msgs__Header(tcpstp, &objp->header); _CHKOK
  urosTcpRosSendRaw(tcpstp, objp->level); _CHKOK
  urosTcpRosSendString(tcpstp, &objp->name); _CHKOK
  urosTcpRosSendString(tcpstp, &objp->msg); _CHKOK
  urosTcpRosSendString(tcpstp, &objp->file); _CHKOK
  urosTcpRosSendString(tcpstp, &objp->function); _CHKOK
  urosTcpRosSendRaw(tcpstp, objp->line); _CHKOK
  urosTcpRosSendRaw(tcpstp, objp->topics.length); _CHKOK
  for (i = 0; i < objp->topics.length; ++i) {
    urosTcpRosSendString(tcpstp, &objp->topics.entriesp[i]); _CHKOK
  }

  return tcpstp->err = UROS_OK;
#undef _CHKOK
}
```

Listing 5.6: Marshaling and transmission of a rosgraph_msgs/Log message

Service messages

Service messages are a pair of plain in/out messages, thus being split into an input `struct` (`in_srv__` + mangled name, *in_name*) and an output `struct` (`out_srv__` + mangled name, *out_name*), shown in **Listing 5.7**. They are loaded from the relative `.srv` file through a call to `rossrv show`, similarly to plain messages.

Each of the sub-messages have dedicated initialization (**Listing 5.9**), cleaning (**Listing 5.10**), and length computation (**Listing 5.8**) functions, with the assignments and prefixes seen above.

Only the input message has an unmarshaling function (`recv_`+*in_name*, **Listing 5.11**), while only the output message has a marshaling function (`send_`+*out_name*, **Listing 5.12**).

Type registrations

The `urosMsgTypesRegStaticTypes()` procedure registers all message types to their respective static registers (see Section 5.2.1), as reported by **Listing 5.13**.

Handler routines

Handler routines, except those for service calls, are supposed to work inside their own thread. The user can decide whether to place local message variables on the stack or in the heap, to optimize and harmonize memory management; as a rule of thumb, small message descriptors are put on the stack, big message descriptors on the heap.

Topic publishers The topic publisher routine, `pub_tpc` + mangled name, generates and sends plain messages to the subscriber, until disconnection.

A generated template can be seen in **Listing 5.14**, where the message descriptor is allocated into the heap. The user is only required to remove the dummy loop statements, and fill in the `msgp` descriptor fields.

Topic subscribers On the other hand, the topic subscriber routine, `sub_tpc` + mangled name, continuously receives and processes messages until disconnection.

```
struct in_srv__turtlesim__Spawn {
  float         x;
  float         y;
  float         theta;
  UrosString    name;
};

struct out_srv__turtlesim__Spawn {
  UrosString    name;
};
```

Listing 5.7: Definition of the `turtlesim/Spawn` descriptors

```
size_t length_in_srv__turtlesim__Spawn(
  struct in_srv__turtlesim__Spawn *objp
) {
  size_t length = 0;

  urosAssert(objp != NULL);

  length += sizeof(float);
  length += sizeof(float);
  length += sizeof(float);
  length += sizeof(uint32_t) + objp->name.length;

  return length;
}

size_t length_out_srv__turtlesim__Spawn(
  struct out_srv__turtlesim__Spawn *objp
) {
  size_t length = 0;

  urosAssert(objp != NULL);

  length += sizeof(uint32_t) + objp->name.length;

  return length;
}
```

Listing 5.8: Stream length computation of `turtlesim/Spawn` messages

As seen in **Listing 5.15**, the user is only required to process the contents of the received message, `msgp`.

Service publishers The service publisher, `pub_srv` + mangled name, receives the request message (*in_name*), processes it, then sends the response message (*out_name*) if successful, or the error string if unsuccessful. If persistent, these operations are repeated until disconnection.

Listing 5.16 is the generated template of a service publisher. It is an union of message reception and transmission, so the user must provide code for both the request processing and the response generation.

Service calls The service call routine, `call_srv` + mangled name, is executed by clients. It sends a request to the publisher, then receives the response or the error string. As opposed to the other handler routines, which generate or process messages within their body, the service call routine is used only for

```c
void init_in_srv__turtlesim__Spawn(
  struct in_srv__turtlesim__Spawn *objp
) {
  urosAssert(objp != NULL);

  urosStringObjectInit(&objp->name);
}

void init_out_srv__turtlesim__Spawn(
  struct out_srv__turtlesim__Spawn *objp
) {
  urosAssert(objp != NULL);

  urosStringObjectInit(&objp->name);
}
```

Listing 5.9: Initialization of `turtlesim/Spawn` descriptors

```c
void clean_in_srv__turtlesim__Spawn(
  struct in_srv__turtlesim__Spawn *objp
) {
  urosAssert(objp != NULL);

  urosStringClean(&objp->name);
}

void clean_out_srv__turtlesim__Spawn(
  struct out_srv__turtlesim__Spawn *objp
) {
  urosAssert(objp != NULL);

  urosStringClean(&objp->name);
}
```

Listing 5.10: Cleaning function of `turtlesim/Spawn` descriptors

communication; message descriptors are also allocated outside.

An example of generated handler is shown in **Listing 5.17**. The user is not required to do anything, but it is suggested to deallocate the request descriptor before receiving the response, in order to reduce the memory usage.

```
uros_err_t recv_in_srv__turtlesim__Spawn(
  UrosTcpRosStatus *tcpstp,
  struct in_srv__turtlesim__Spawn *objp
) {
  urosAssert(tcpstp != NULL);
  urosAssert(urosConnIsValid(tcpstp->csp));
  urosAssert(objp != NULL);
#define _CHKOK { if (tcpstp->err) { goto _error; } }

  urosTcpRosRecvRaw(tcpstp, objp->x); _CHKOK
  urosTcpRosRecvRaw(tcpstp, objp->y); _CHKOK
  urosTcpRosRecvRaw(tcpstp, objp->theta); _CHKOK
  urosTcpRosRecvString(tcpstp, &objp->name); _CHKOK

  return tcpstp->err = UROS_OK;
_error:
  clean_in_srv__turtlesim__Spawn(objp);
  return tcpstp->err;
#undef _CHKOK
}
```

Listing 5.11: Reception and unmarshaling of a `turtlesim/Spawn` request message

```
uros_err_t send_out_srv__turtlesim__Spawn(
  UrosTcpRosStatus *tcpstp,
  struct out_srv__turtlesim__Spawn *objp
) {
  urosAssert(tcpstp != NULL);
  urosAssert(urosConnIsValid(tcpstp->csp));
  urosAssert(objp != NULL);
#define _CHKOK { if (tcpstp->err) { return tcpstp->err; } }

  urosTcpRosSendString(tcpstp, &objp->name); _CHKOK

  return tcpstp->err = UROS_OK;
#undef _CHKOK
}
```

Listing 5.12: Marshaling and transmission of a `turtlesim/Spawn` response message

```
void urosMsgTypesRegStaticTypes(void) {

  urosRegisterStaticMsgTypeSZ("rosgraph_msgs/Log",
                              NULL, "acffd30cd6b6de30f120938c17c593fb");

  urosRegisterStaticMsgTypeSZ("std_msgs/Header",
                              NULL, "2176decaecbce78abc3b96ef049fabed");

  urosRegisterStaticSrvTypeSZ("turtlesim/Spawn",
                              NULL, "0b2d2e872a8e2887d5ed626f2bf2c561");
}
```

Listing 5.13: Registration of the static types used in the examples above

```c
uros_err_t pub_tpc__rosout(UrosTcpRosStatus *tcpstp) {

  UROS_TPC_INIT_H(msg__rosgraph_msgs__Log);

  while (!urosTcpRosStatusCheckExit(tcpstp)) {
    /* TODO: Generate the contents of the message.*/
    urosThreadSleepSec(1); continue; /* TODO: Remove this dummy line.*/

    UROS_MSG_SEND_LENGTH(msgp, msg__rosgraph_msgs__Log);
    UROS_MSG_SEND_BODY(msgp, msg__rosgraph_msgs__Log);

    clean_msg__rosgraph_msgs__Log(msgp);
  }
  tcpstp->err = UROS_OK;

_finally:
  UROS_TPC_UNINIT_H(msg__rosgraph_msgs__Log);
  return tcpstp->err;
}
```

Listing 5.14: Generated handler template for a common /rosout publisher

```c
uros_err_t sub_tpc__rosout(UrosTcpRosStatus *tcpstp) {

  UROS_TPC_INIT_H(msg__rosgraph_msgs__Log);

  while (!urosTcpRosStatusCheckExit(tcpstp)) {
    UROS_MSG_RECV_LENGTH();
    UROS_MSG_RECV_BODY(msgp, msg__rosgraph_msgs__Log);

    /* TODO: Process the received message.*/

    clean_msg__rosgraph_msgs__Log(msgp);
  }
  tcpstp->err = UROS_OK;

_finally:
  UROS_TPC_UNINIT_H(msg__rosgraph_msgs__Log);
  return tcpstp->err;
}
```

Listing 5.15: Generated handler template for a /rosout subscriber

```c
uros_err_t pub_srv__reconfigure(UrosTcpRosStatus *tcpstp) {

  UROS_SRV_INIT_HISO(in_srv__dynamic_reconfigure__Reconfigure,
                     out_srv__dynamic_reconfigure__Reconfigure);

  do {
    UROS_MSG_RECV_LENGTH();
    UROS_MSG_RECV_BODY(inmsgp, in_srv__dynamic_reconfigure__Reconfigure);

    /* TODO: Process the request message.*/
    tcpstp->err = UROS_OK;
    urosStringClean(&tcpstp->errstr);
    okByte = 1;

    clean_in_srv__dynamic_reconfigure__Reconfigure(inmsgp);

    /* TODO: Generate the contents of the response message.*/

    UROS_SRV_SEND_OKBYTE_ERRSTR();
    UROS_MSG_SEND_LENGTH(&outmsg, out_srv__dynamic_reconfigure__Reconfigure);
    UROS_MSG_SEND_BODY(&outmsg, out_srv__dynamic_reconfigure__Reconfigure);

    clean_out_srv__dynamic_reconfigure__Reconfigure(&outmsg);
  } while (tcpstp->topicp->flags.persistent &&
           !urosTcpRosStatusCheckExit(tcpstp));
  tcpstp->err = UROS_OK;

_finally:
  UROS_SRV_UNINIT_HISO(in_srv__dynamic_reconfigure__Reconfigure,
                       out_srv__dynamic_reconfigure__Reconfigure);
  return tcpstp->err;
}
```

Listing 5.16: Generated handler template for a service publisher

```c
uros_err_t call_srv__reconfigure(
  UrosTcpRosStatus *tcpstp,
  struct in_srv__dynamic_reconfigure__Reconfigure *inmsgp,
  struct out_srv__dynamic_reconfigure__Reconfigure *outmsgp
) {

  UROS_SRVCALL_INIT(in_srv__dynamic_reconfigure__Reconfigure,
                    out_srv__dynamic_reconfigure__Reconfigure);

  UROS_MSG_SEND_LENGTH(inmsgp, in_srv__dynamic_reconfigure__Reconfigure);
  UROS_MSG_SEND_BODY(inmsgp, in_srv__dynamic_reconfigure__Reconfigure);

  /* TODO: Dispose the contents of the request message.*/

  UROS_SRV_RECV_OKBYTE();
  UROS_MSG_RECV_LENGTH();
  UROS_MSG_RECV_BODY(outmsgp, out_srv__dynamic_reconfigure__Reconfigure);

  tcpstp->err = UROS_OK;
_finally:
  return tcpstp->err;
}
```

Listing 5.17: Generated handler template for a client service call

5.3.2 Static stack analysis

When dealing with tightly resource-constrained platforms running multiple threads, it is important to keep the stack usage at a minimum. This is even more important when exploiting thread pools with homogeneous stack size, because this size depends on the maximum stack depth reached by any of its worker threads. A static stack analysis tool come handy to estimate, better if precisely, the stack usage of a set of functions of interest. The stack analysis tool provided with µROSnode is **urosstan**, implemented by the `urosstan.py` Python script.

Analysis flow

A diagram of the compilation flow is shown in **Figure 5.4**. The user supplies the configuration file (actual example in **Listing B.12**) and the static analysis outputs to the tool. For each entry point, it builds the call graph, and it traces the paths with maximum stack usage. The tool then outputs the list of unresolved symbols, a report for every entry point, and a summary.

Configuration

The user must provide a configuration file, which specifies the analysis options, and the sets of entry points, custom terminator symbols, and source file mappings.

Entry points An analysis is performed for each entry point (global function name) listed in the entry point set. Each entry point is assigned a value which indicates the stack depth before entering it.

Terminators The user may want to cut away some call graph branches, or to manually define the stack usage of unresolved symbols. For instance, external library functions or assembly calls cannot be analyzed, but the user can still provide the maximum number of bytes allocated by those call triggers. This way, the call graph analysis is stopped when reaching any of the terminator symbols provided by the user.

File mappings The stack analyzer relies upon the static analysis generated by the *GCC* toolchain. The mapping set maps each source file to the `.gkd`,

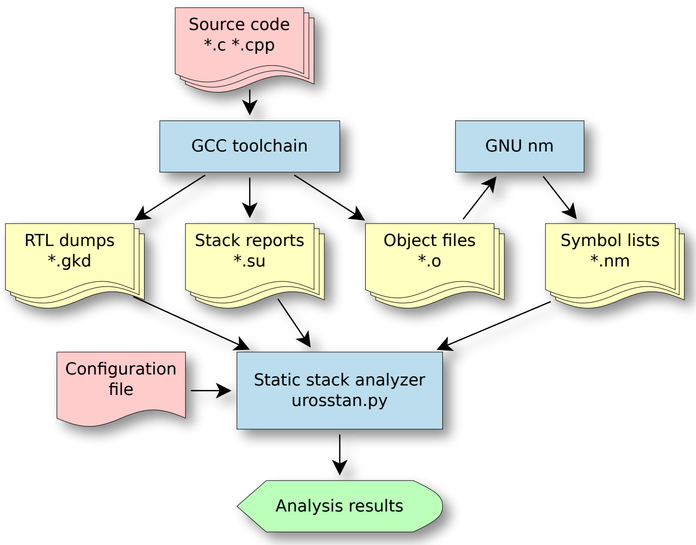


Figure 5.4: Static stack analysis flowchart

`.su`, and `.nm` outputs; respectively, the *GCC* RTL dump, the *GCC* stack usage report, and the *GNU nm* object symbols.

Observations about the effectiveness

Despite of its usefulness, there are often serious obstacles which reduce the effectiveness of the static analysis. Primarily, it analyzes the output files of the *GCC* toolchain only for C/C++ source files. External libraries and assembly code cannot be tracked by the *GCC* static analysis, thus being impossible to build the complete call graph, or to exploit some stack usage reports.

Moreover, indirect functions assigned at runtime cannot be tracked by static analysis tools. This is why the user should be aware of providing a meaningful list of entry points.

Nevertheless, recursion is an unremovable obstacle for static analysis. The tool can spot cycles within the call graphs, so the user is encouraged to profile their impact on the stack usage at runtime.

Anyway, the tool is still very useful to discover paths with unexpectedly deep allocation on stacks, or to have a better idea of the overall stack usage of the analyzed code. This way, the user can optimize the allocation of local variables, or harmonize stack allocation wherever possible.

The tool shows its best usefulness when there is full access to the source code, written entirely in C/C++. By the way, the maximum precision can still be achieved if the usage of all of the assembler and library functions are specified inside the configuration file. If some of the information is missing but known to be bounded, for example through their full-coverage runtime profiling data, then the analysis can report at least conservative results.

It is important to point out that urosstan currently supports only the *GCC* toolchain for a C/C++ codebase, because this is the toolchain we used throughout the development of our projects. If the user is interested only of the overall stack allocation, then a pure C/C++ codebase can be compiled with *GCC* and no optimizations, still providing a rough conservative analysis. If the target toolchain is different, the equivalence of the object code is coarse, but still effective for preliminary analysis.

5.3.3 Demonstration projects

The package provides a *turtlesim* demo, which is almost equivalent to the *turtlesim_node* [7] official ROS node. It supports all of its topics, services and parameters, exploiting almost all of the features needed by a real-life Node. The maximum number of turtles is bounded by the `MAX_TURTLES` constant. The turtle pose is updated at 1 kHz, and streamed at 100 Hz.

Message types and handlers were first generated with the configuration file shown by **Listing 5.18**. Since the names of `turtleX/*` topics and services change with the turtle, their creation and deletion were moved to the application (*app*) module. This module handles the turtle *spawn* and *kill* operations, as well as the generation of `/rosout` messages.

The static stack analysis configuration file is shown in **Listing B.12**.

The demo comes into two ports: one developed with only *POSIX* API, and a second one which runs under *ChibiOS/RT* with the *LWIP* network stack. *Eclipse* project files are included.

Project: turtlesim-posix demo

This demo follows the *POSIX* standard for all of its low-level features. It was tested with *Linux Mint 14 Nadia* on a standard laptop, and *Raspbian Wheezy* on a *Raspberry Pi model B* with 256 MB of RAM (see Section 6.1.3).

When the `/turtlesim` node is shut down, the application will exit.

```
# urosgen.py configuration file for turtlesim

[Options]
author                      = Andrea Zoppi <texzk@email.it>
licenseFile                 = ../../../COPYING
includeDir                  = ../include
sourceDir                   = ../src
nodeName                    = turtlesim
fieldComments               = false

[PubTopics]
rosout                      = rosgraph_msgs/Log
turtleX/pose                = turtlesim/Pose
turtleX/color_sensor        = turtlesim/Color

[SubTopics]
turtleX/command_velocity    = turtlesim/Velocity

[PubServices]
clear                       = std_srvs/Empty
kill                        = turtlesim/Kill
spawn                       = turtlesim/Spawn
turtleX/set_pen             = turtlesim/SetPen
turtleX/teleport_absolute   = turtlesim/TeleportAbsolute
turtleX/teleport_relative   = turtlesim/TeleportRelative

[CallServices]
# none
```

Listing 5.18: Turtlesim *configuration file for* `urosgen.py`

Project: turtlesim-chibios+lwip

This demo uses a combination of the *ChibiOS/RT* RTOS and the *LWIP* network stack, and can run on an *ARM Cortex M4* core. Specifically, it was tested with *ChibiOS/RT* 2.5.2 and *LWIP* 1.4.1. The processor is a *STM32F407* on a custom board with Ethernet capabilities (see Section 6.1), by using a *DP83848* PHY in RMII mode. The USB port is used as a serial port terminal/shell emulator.

When the `/turtlesim` node is shut down, only the Node stops running, while the other features of the board keep running.

5.4 Integration with user applications

µROSnode was developed to be integrated into the user application with low effort. In the following, generic integration requirements are illustrated.

Makefile scripts The µROSnode package supplies a set of *Makefile scripts* to be included into the root `Makefile`; they can be found in the `mk` folder. The main script, `uros.mk`, defines the lists of *core* source and header files, which are required.
In addition, the user has to include scripts for the target platform, which define

the lists of *low-level-driver* source and header files. If a subsystem of the target platform is not yet supported, it can be developed by the template files found in the `template/src/lld` folder; comments labeled with `TODO` give instructions for a correct implementation.

Configuration µROSnode needs to be configured for the user application. A shared header file, `urosconf.h`, must be included by the application, and provides settings for the µROSnode subsystems. A template can be found in the `template/include` folder of the µROSnode package. Comments assist the user in tuning the required settings.

Callbacks The *User* module (see Section 5.2.7) requires some callback functions to be defined inside the `urosUser.c` application source file. A template file in `template/src` assists in the development of such callback functions.

Handler functions The user should create the *Message types* and the *Handlers* modules (see Section 5.2.8 and Section 5.2.9), so that µROSnode can properly process message streams of topics and services. This task is assisted by the code generator tool extensively illustrated in Section 5.3.1.

Initialization The µROSnode framework must be initialized by calling `urosInit()`, which initializes the global state. This should be done when the platform is completely initialized.
The Node is brought to life as soon as the actual user application is run. This is accomplished by a call to `urosNodeCreateThread()` to create the Node thread, which keeps track of the Node life cycle; topics, services, and parameters are registered and unregistered by the Node thread. This thread exits when the Node is shut down.

Chapter 6

Experimental results and evaluation

In order to prove the effectiveness of µROSnode, both quantitative and qualitative analyses were accomplished. The quantitative analysis consists of a set of benchmarks which show the performance of some basic yet meaningful applications, suggesting any possible bottlenecks. Instead, the qualitative analysis focuses more on the ease of software development on a real-life robot, to spot implementation difficulties of a µROSnode-based application.

6.1 Benchmarks

The performance of µROSnode was evaluated through a suite of benchmarks. Designing benchmarks is not a trivial task, because it is almost impossible to approximate real-life applications, especially in the robotics research field.
Some basic benchmarks measured the memory occupation and speed performance of a µROSnode-based firmware, giving an idea of the overhead introduced by µROSnode on simple embedded systems based on recent microcontrollers.

Although these benchmarks are rather simple, even slightly more complex ones would rely more on the multithreading and networking subsystems than on µROSnode itself.
For instance, the CPU impact with many concurrent topics is mainly caused by the RTOS thread synchronization performance, while other effects are caused by the networking subsystem configuration choices (buffering, TCP segmentation, timeouts, and so on).
Nevertheless, every real-life application needs the integration of multiple subsys-

tems running concurrently, on different operating systems, different hardware, and implementing complex communication patterns.

6.1.1 Communication setup

The communication performance was measured by connecting the R2P_GW board (see Section 6.1.2) to a standard notebook host, mounting an *Intel T6500* processor (dual core, 2.1 GHz), through a 100 Mb/s Ethernet connection. The firmware was compiled with *GCC* at the maximum default optimization level (`-O3`), disabling both assertions and error messages.

The communication performed by our tests consist of a single TCPROS topic being continuously streamed. The topic is of `std_msgs/String` type, so that it is possible to easily assign contents with fixed length to each test. The global parameter `/benchmark_size` controls the string length, while the global parameter `/benchmark_rate` controls the message rate. The `/benchmark_rate` parameter was set to `0` (no delays between messages) for both benchmarks, to reach the maximum possible throughput.

The transmission benchmark involves a target platform which publishes the `/benchmark/output` topic, subscribed by a `rostopic` node on the host. The `rostopic` subscriber on the host machine can receive up to ≈20000 msg/s.
This benchmark evaluates the marshaling performance of µROSnode on the target platform, by measuring the CPU usage and the rate of packets being actually streamed.

Instead, the reception benchmark involves a `/benchmark/input` topic published by a `rostopic` process on the host, generating messages at the maximum possible rate, and the target platform subscribed to that topic. The throughput limit of a `rostopic` publisher on the host machine is of ≈10000 msg/s.
This benchmark evaluates the unmarshaling performance, again by CPU usage and packet rate. The topic subscriber handler consumes the incoming message stream on-the-fly.

Result plots show the impact of the message size on both the CPU usage and the throughput. *Log-lin* plots can be useful to estimate the maximum number of concurrent threads, because usage and throughput are shown in linear scale. *Log-log* plots can suggest linear relationships between some series, as well as deriving exponential relationships. Indeed, a *log-log* line in the form $y = mx + b$ represents a *lin-lin* power function in the form $y = 10^b x^m$. So, two parallel lines in a *log-log* plot represent a linear relationship of two power functions of the same degree; more generally, two functions with the same distance over the same domain are tied by a linear relationship.

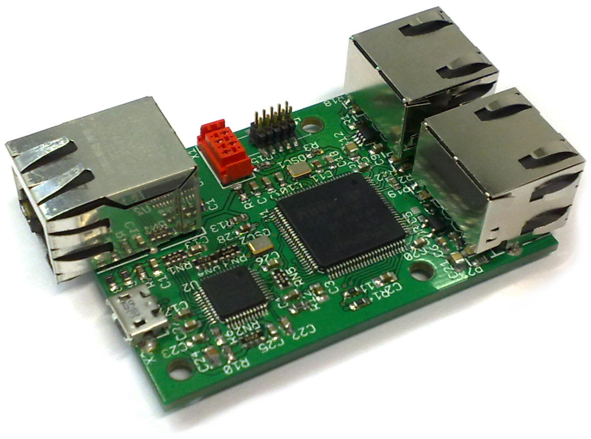


Figure 6.1: R2P_GW prototype board

6.1.2 R2P_GW module

The *Rapid Robot Prototyping* [2] *Gateway* module [29] (*R2P_GW*, prototype board in **Figure 6.1**) interfaces the R2P CAN network to an Ethernet network; a prototype can be seen in **Figure 6.1**. It mounts a *STM32F407* MCU by *STMicroelectronics*, with 192 KiB RAM (112 KiB shared globally), clocked at 168 MHz, and featuring an *ARM Cortex-M4* core. The platform exposes a UART, a CAN, an USB-FS micro-B, and a 100 Mb/s Ethernet ports; the latter controlled by a *DP83848* PHY by *Texas Instruments*. The default operating system is the *ChibiOS/RT* RTOS, combined with the *LWIP* network stack.

Although this board was not designed with ROS in mind, especially memory-wise, it is possible to turn it into a native ROS node, by integrating µROSnode into the firmware. Its RAM size limits the maximum number of communication threads instantiated (for both XML-RPC and TCPROS). Anyway, even by using only the 112 KiB of shared memory provided by the microcontroller, it is still possible to handle a few tens of communication threads, each allocating a 2 KiB stack; this is more than enough for a simple robotics device.

Program memory and stack footprints

A benchmark computed the size of the *turtlesim* firmware, supplied with the `turtlesim-chibios+lwip` demo of the µROSnode package, which emulates the *turtlesim* demo of ROS [7]. The code was compiled with GCC by applying the `-O0`, `-O2`, and `-O3` optimizations levels. A batch had all of the µROSnode and ChibiOS/RT assertions and checks enabled, while another batch had all of them disabled. LWIP checks and error messages were always disabled, while

Component	**With checks [B]**			**Without checks [B]**		
	O0	**O2**	**O3**	**O0**	**O2**	**O3**
turtlesim	52332	42020	45191	32895	23629	26582
µROSnode	123270	97691	103488	61285	36660	43285
LWIP	49898	33133	40820	49195	32414	40086
ChibiOS/RT	67219	45551	49613	63250	41473	44910
unused	731281	805605	784887	817375	889824	869137

Table 6.1: Footprint of the turtlesim *demo in the R2P_GW program memory*

both µROSnode and ChibiOS/RT had all of the remaining features enabled in their configuration files.

This benchmark was made by compiling a plain firmware with ChibiOS/RT and some related features (USB, shell emulator, self-tests, and initializations), then incrementally including LWIP, µROSnode, and the *turtlesim* user application. Experimental results are summarized by **Table 6.1** and **Figure 6.2**. µROSnode is only slightly bigger than the operating system; this is reasonable, since some features like XML-RPC and multithreading stuff are not that lightweight, but they are needed. Anyway, it is small enough to leave more than 70% (≈730 kB) of the program memory unused in the worst case, and more than 85% (≈890 kB) in the best case.

Since µROSnode heavily relies on multithreading, maximum stack usage for each thread was estimated. **Table 6.2** summarizes the maximum stack depth reached by the principal threads of the *turtlesim* demo, identified by either thread entry point or thread pool worker functions, all of which already take into account the space needed to be instantiated. All of the threads involved by XML-RPC and TCPROS thread pools do not show much diversity in memory occupation, and they never exceed 1280 B (5 × 256 B). Indeed, if threads in a thread pool have a rather homogeneous stack usage, then the associated memory pool is exploited properly.

Transmission performance

The transmission benchmark was run so that the board could achieve the maximum possible speed, by setting the `/benchmark_rate` parameter to `0` (no delays between messages). Result plots are depicted in **Figure 6.3**. Message contents are streamed directly from a single static message (i.e. no multiple messages are allocated).
`TcpRosServer` is the µROSnode topic handler function, `lwipthread` the LWIP event dispatcher thread, and `lwip_process` the LWIP packet processing thread.

When sending messages smaller than 100 B, the topic can reach a throughput

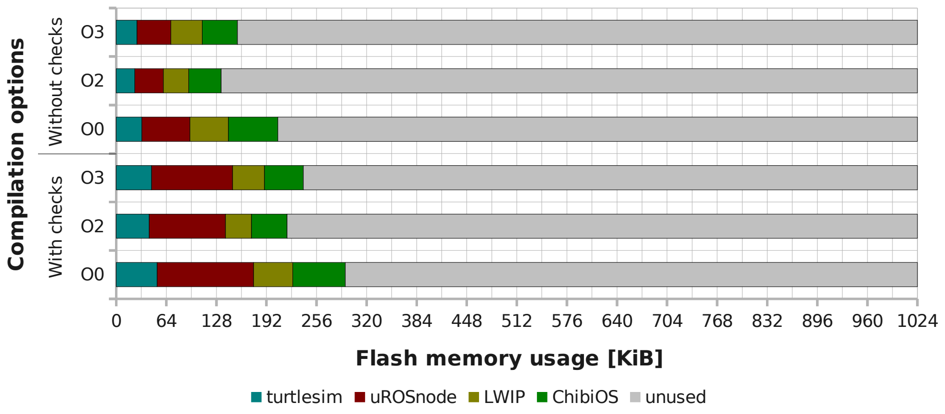


Figure 6.2: Footprint of the turtlesim *demo in the R2P_GW program memory*

of ≈20000 msg/s. This limit is actually imposed by the performance of a `rostopic` process on the host. The CPU is still idle for a small amount of time, while most of the usage is due to the LWIP packet processor. The μROSnode topic handler has an overhead of 30%, caused by the frequent execution of its message transmission loop.
It must be noticed that the step in the handler impact between 8 B and 16 B is caused by the allocation of the string contents; at 8 B the `data` string of the message is empty, thus not calling the allocator.

Around 100 B per message, the CPU usage becomes saturated. By increasing the message size, the LWIP processing thread increases its contribution to the CPU saturation almost linearly with the logarithm of the message size, reaching a peak of ≈90% at 2000 B. At this point, the topic handler impact is as low as 6%. The board can never reach the 100 Mb/s limit of the Ethernet connection, but it gets closer as the message size is increased.

Beyond 2000 B per message, the 100 Mb/s limit is reached. This is confirmed by the small growth of CPU idle time.

The *log-log* plot suggests a linear relationship between the throughput and the overhead caused by the message transmission loop of the topic handler.

Reception performance

The reception benchmarks were run by sending messages to the board at the maximum rate the host can achieve. The limit of `rostopic` on such machine was set to ≈10000 msg/s. Thanks to this limit it is possible to trace graceful CPU utilization plots of the major threads involved.

Thread/pool entry point functions	**Maximum stack depth [B]**	
	O0 +checks	**O3 -checks**
`lwip_thread`	952	740
`main`	264	776
`pub_srv__clear`	716	456
`pub_srv__kill`	1100	784
`pub_srv__spawn`	1244	904
`pub_srv__turtleX__set_pen`	740	472
`pub_srv__turtleX__teleport_absolute`	764	512
`pub_srv__turtleX__teleport_relative`	764	504
`pub_tpc__rosout`	708	432
`pub_tpc__turtleX__color_sensor`	660	400
`pub_tpc__turtleX__pose`	660	408
`sub_tpc__turtleX__command_velocity`	724	464
`urosNodeThread`	1188	888
`urosRpcSlaveListenerThread`	660	476
`urosRpcSlaveServerThread`	1004	616
`urosTcpRosListenerThread`	652	476
`urosThreadPoolWorkerThread`	240	148

Table 6.2: Stack usages of the turtlesim *demo entry points on the R2P_GW working memory*

`TcpRosClient` is the μROSnode topic handler function, `lwipthread` the LWIP event dispatcher thread, and `lwip_process` the LWIP packet processing thread.

A first benchmark buffers the entire received message upon reception, which is the default behavior of the generated topic handlers, and also the most intuitive way to process messages. This benchmark is affected by the tight memory limits of the target platform, which cannot handle a high number of buffered messages.

As shown by **Figure 6.4**, the board cannot handle more than 1000 B per message at 10000 msg/s. At 1000 B/s, the allocator was not able to buffer messages anymore after ≈120 seconds, because of heap fragmentation. At 2000 B/s, the allocator was able to store only 5 messages before failing. This suggests not to buffer large messages on a tightly constrained platform, but rather to process them on-the-fly whenever possible.

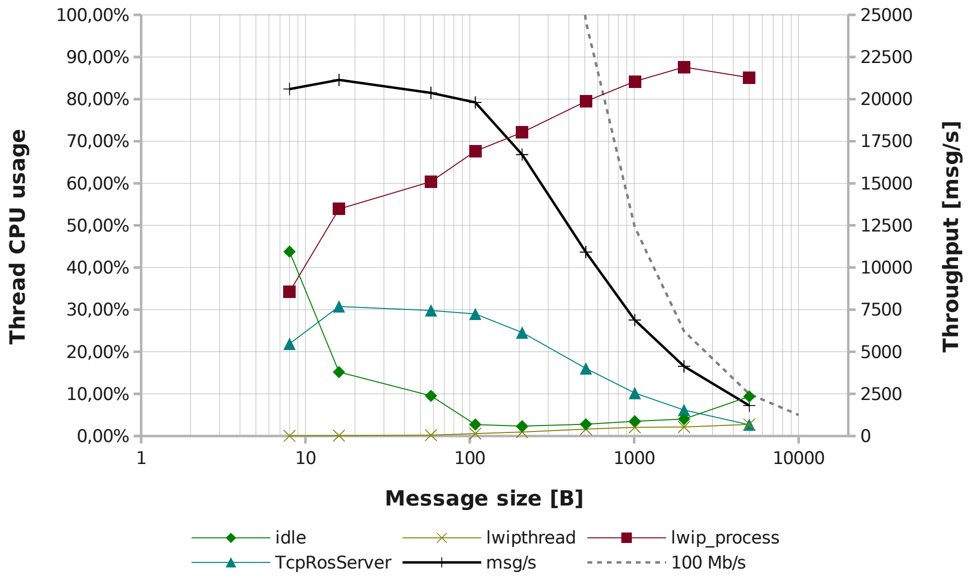
The board can receive a 10000 msg/s stream up to 500 B per message, still having some idle CPU time left. Because of buffered message allocations, the topic handler requires an increasing amount of CPU time, from less than 10% for small messages, to over 50% at 500 B per message.

A second benchmark was then developed so that it excludes any buffering or user processing code, by skipping the entire message contents being streamed by the host. This benchmark simulates the on-the-fly processing mentioned above. Result plots are shown in **Figure 6.5**.

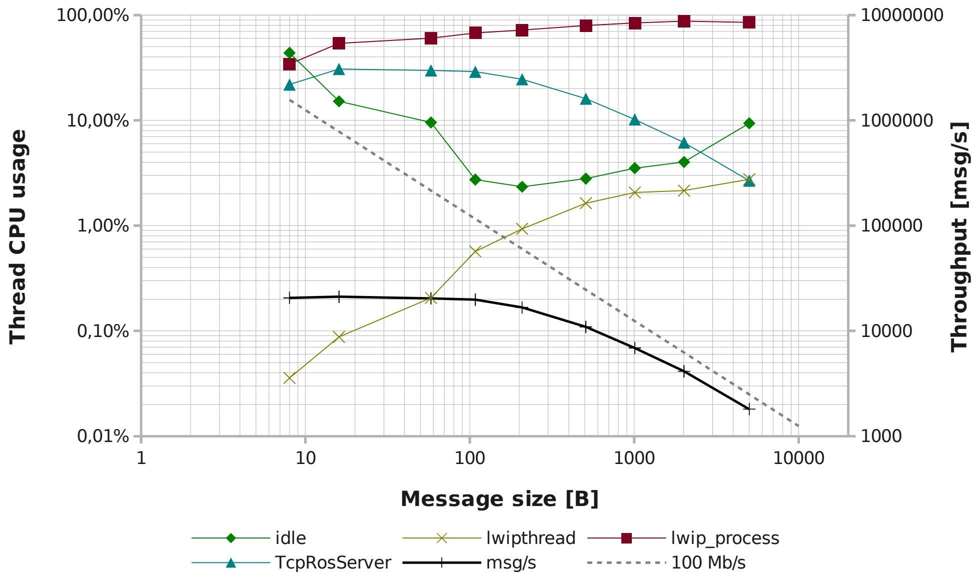
The board can receive messages at 10000 msg/s up to 500 B with an idle time higher than 50%, and an handler load less than 20%. There is a linear relationship between the LWIP processor and messaging threads, while the handler thread has a slight quadratic behavior due to the fragmented reception overhead.

Between 1000 B and 2000 B the LWIP threads require ≈70% of the CPU time, while the topic handler stays below 30%. The CPU is at full load.

Beyond 2000 B/s the 100 Mb/s is reached, indeed the CPU idle time grows a little.

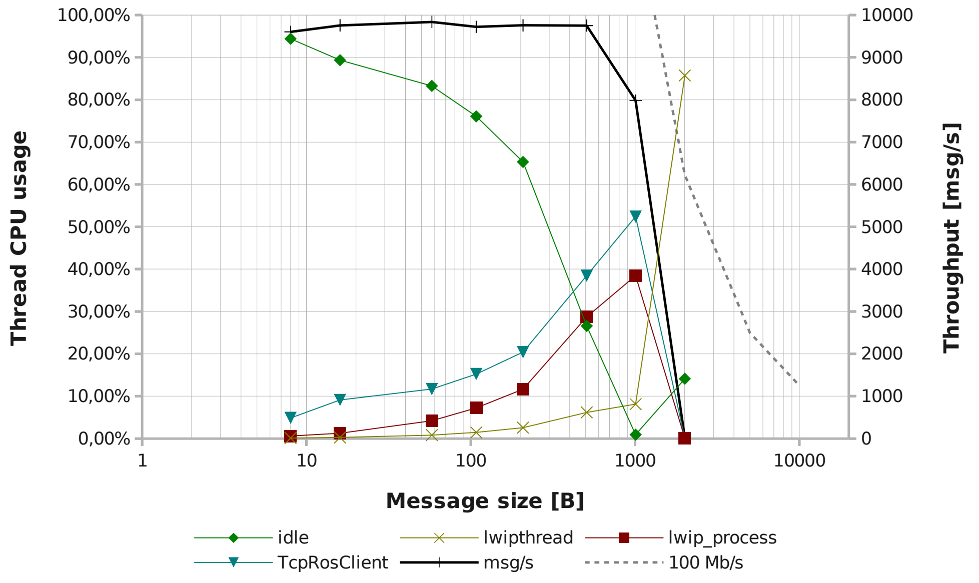


(a) log-lin

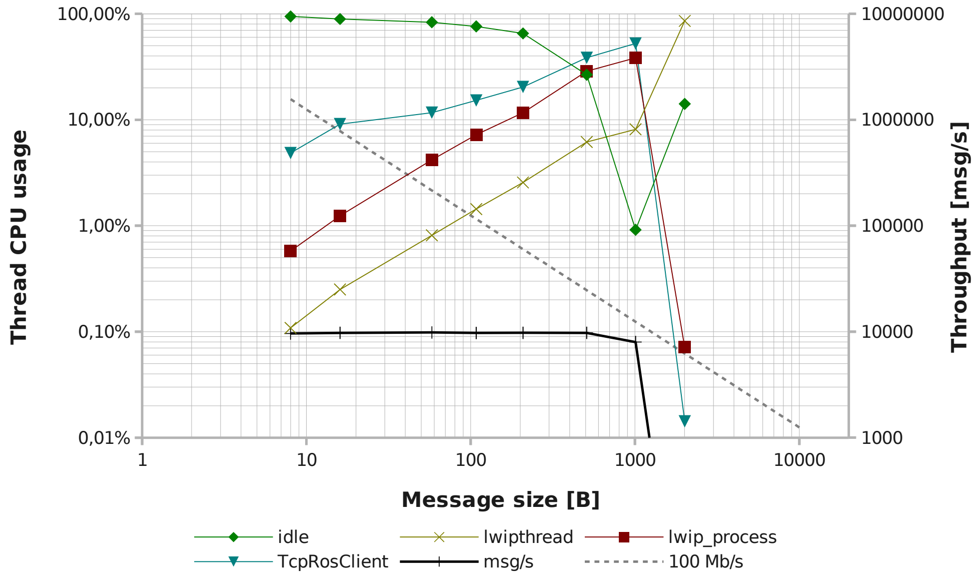


(b) log-log

Figure 6.3: Transmission performance on R2P_GW, on-the-fly

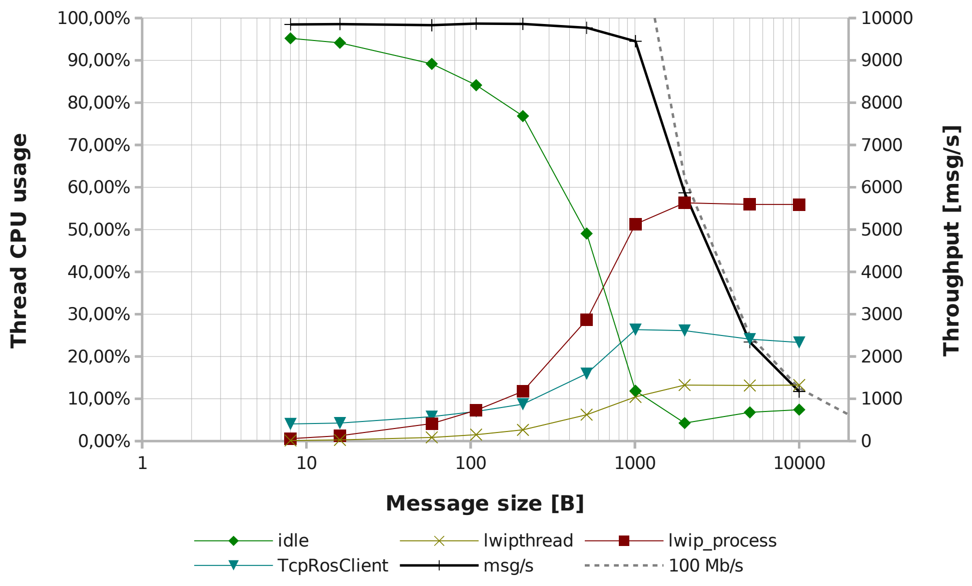


(a) log-lin

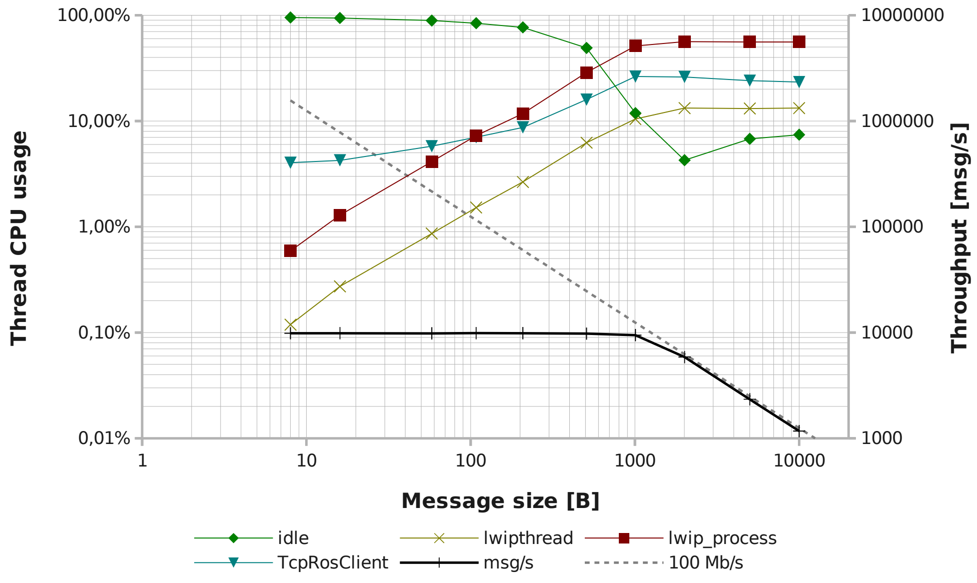


(b) log-log

Figure 6.4: Reception performance on R2P_GW, buffered messages



(a) log-lin



(b) log-log

Figure 6.5: Reception performance on R2P_GW, on-the-fly

6.1.3 Raspberry Pi

The *Raspberry Pi* [8] (model *B*, shown in **Figure 6.6**, abbreviated *RasPi*) is a low-cost computer designed for educational purposes, developed by the *Raspberry Pi Foundation* charity. Its main component is a *BCM2835* system-on-chip by *Broadcom*, which features an *ARM1176JZF-S* processor running at 700 Mhz (1 GHz boosts), and a *Videocore 4* GPU, capable of high-definition video resolutions and support for *OpenGL ES2.0*. It also mounts a *LAN9512* PHY by *SMSC*, with 100 Mb/s Ethernet capabilities.
The board provides the Ethernet RJ-45 socket, two USB-HS type A ports, HDMI and composite video outputs, stereo Line headphone socket, and a SD-HC card slot. Most of the BCM2835 signals (GPIO, UART, I2C, SPI, PWM, display, camera, and so on), are exposed by a set of pin headers and Camera Interface connectors. The model used for the benchmarks mounts 256 MiB of RAM.

The operating system chosen for our experiments is *Raspbian*, a *Debian*-based Linux distribution with specific support for the Raspberry Pi. The platform is controlled through a *SSH* connection, which makes negligible impact on the performance. No other user software or services are running, except the SSH connection and the benchmark executables.
Instead as single threads, like for the R2P_GW benchmarks, CPU usages were collected as aggregate values from `/proc/stat`. The benchmark application and µROSnode run at the *user* level, while the network stack runs at the *system* and *interrupt* levels.

Transmission performance

Similarly to R2P_GW, the RasPi generates `/benchmark/output` messages at the maximum speed achievable, by not introducing forced delays. Timeouts are disabled, and a single message actually resides in memory, being streamed by the message loop. The transmission results are similar to those of R2P_GW too, as seen in **Figure 6.7**; as expected, the curves are biased to a higher throughput.

The platform can saturate the host `rostopic` receiver at ≈20000 msg/s when the message size is not greater than ≈200 B. The CPU is used less than 50%, mainly by system processes (around 25%) and the topic handler (around 15%). As the message size increases from 8 B to 200 B, the impact of (software) interrupt requests grows, but stays below 10%.

Between 200 B and 500 B per message there is a sudden increase of the

Figure 6.6: Raspberry Pi model B

CPU usage, saturated by interrupts and system processes, which limits the throughput to ≈13000 msg/s. The topic handler usage stays around 15%, which means that the Linux network stack has a substantial effect in these circumstances.

With messages larger than 500 B there are no considerable changes in the CPU usage. At 10000 msg/s interrupts have a share of ≈40% and system calls of ≈55%, while the topic handler uses the CPU for less than 5%. The bandwidth gets close to 100 Mb/s, but it is still not reached at 10000 msg/s; indeed, the idle time stays around 1% without growing.

Reception performance

The reception performance was measured by streaming messages published by `rostopic` at ≈14000 msg/s, the maximum achievable by the host computer. As for R2P_GW, the reception was first evaluated by buffering each new incoming message, and then by processing the incoming message stream by skipping its contents.

The results with message buffering are depicted by **Figure 6.8**. Up to 100 B per message, the platform can receive all of the messages with low effort. The CPU is idle for more than 40% of the time, with the topic handler using less than 20% of the CPU time, and the system calls less than 40%. There is a strange decrease in the effect of system calls at a message size of 50 B, probably caused by some kernel optimization. The throughput stays at the maximum.

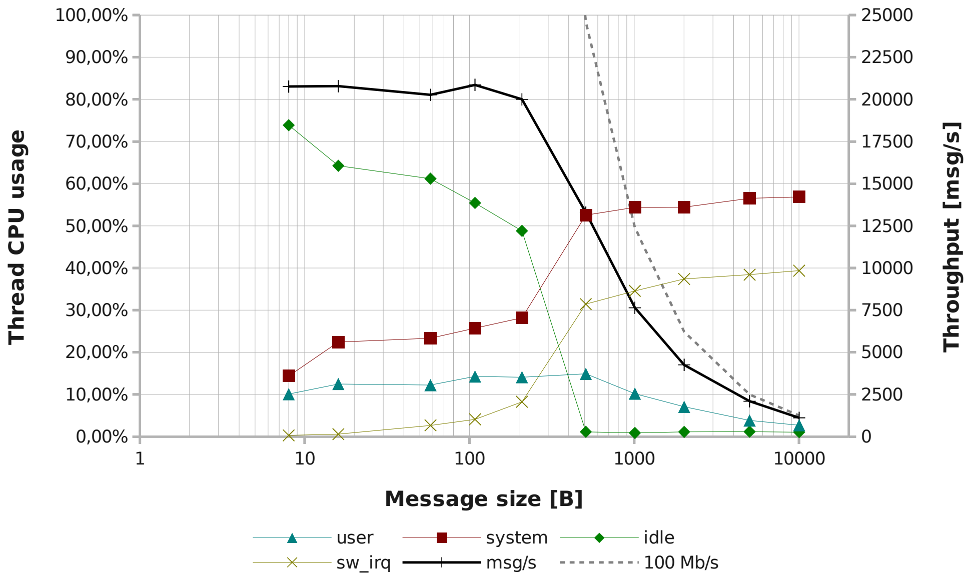
Between 100 B and 500 B, the CPU usage of interrupts increases over 40%, and the CPU becomes saturated. The topic handler and system calls do not show significant changes in their impact. After 200 B per message, the throughput starts decreasing, but is still above 13000 msg/s.

With a message size beyond 500 B, the bandwidth is completely used. Software interrupts use the CPU at ≈10%, while the effect of system calls keeps around 35%, and that of the topic handler decreases as low as ≈10%. The idle time goes back to almost 50%.

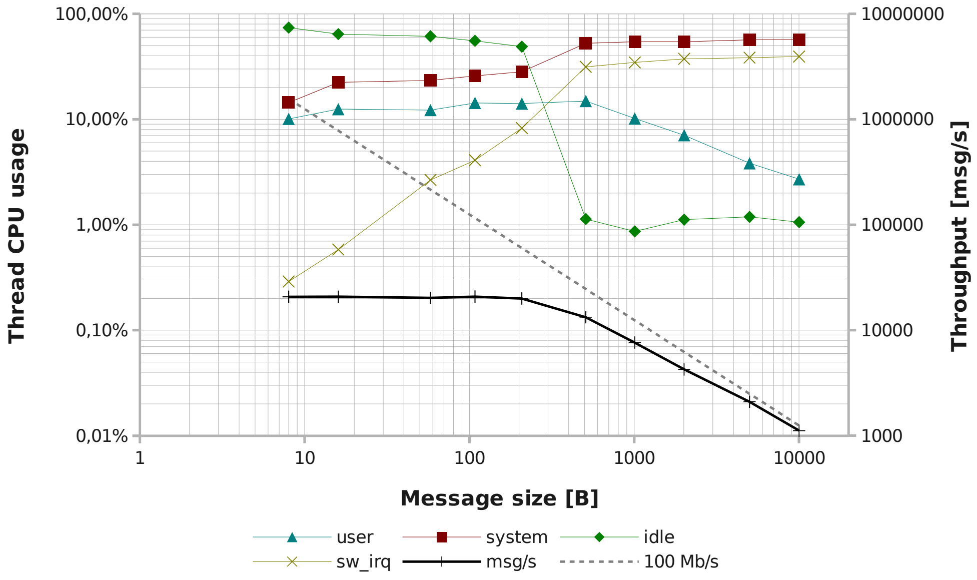
The performance results of on-the-fly reception are shown in **Figure 6.9**. Below 100 B per message, the platform can receive all of the messages with low effort. The CPU is idle for ≈60% of the time, primarily used by system calls for less than 30%, and the topic handler for ≈10%, the rest by (software) interrupts. Again, there is a strange decrease in usage by system calls at a size of 50 B.

Between 100 B and 500 B per message, where the CPU usage of system calls and interrupts increases up to ≈45% and ≈35% respectively, while the topic handler stays slightly above 10%. Here the plot shows the minimum peak of the idle time, around 10%.

With a message size greater than 500 B, the bandwidth reaches the 100 Mb/s limit, and the CPU load decreases. Software interrupts are steadily below 10% as well as the topic handler, which keeps decreasing. System calls go down to ≈30%, and the idle time almost reaches 60% again.

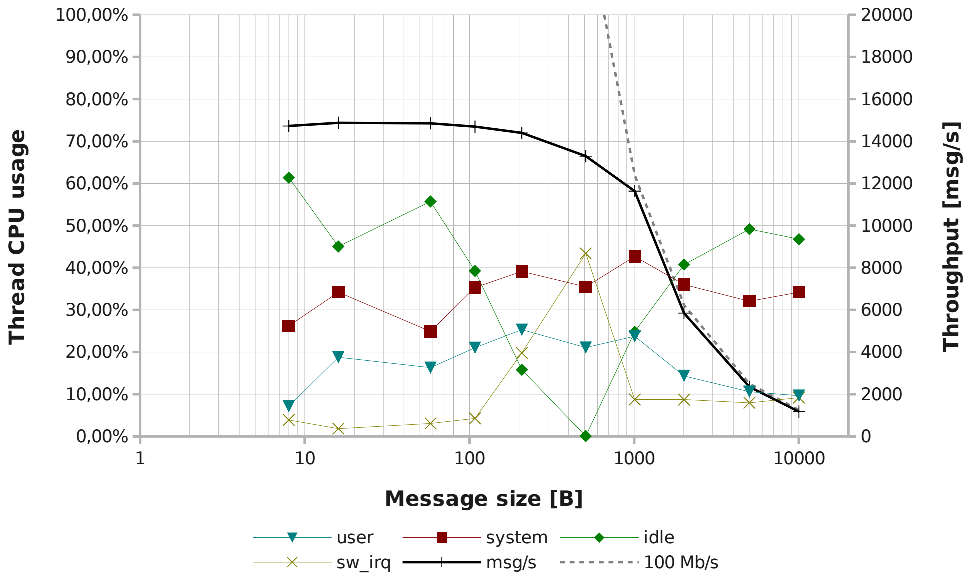


(a) log-lin

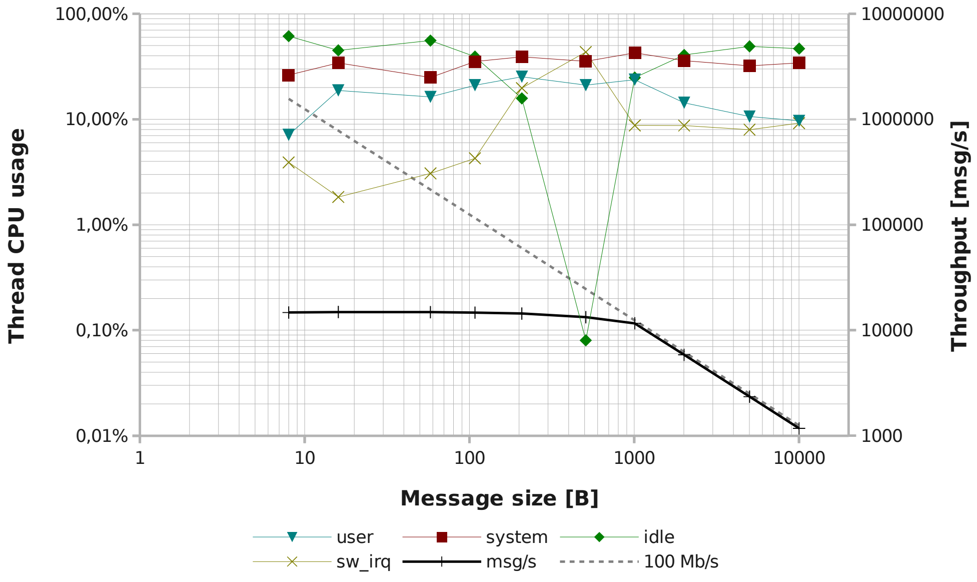


(b) log-log

Figure 6.7: Transmission performance on RasPi, on-the-fly

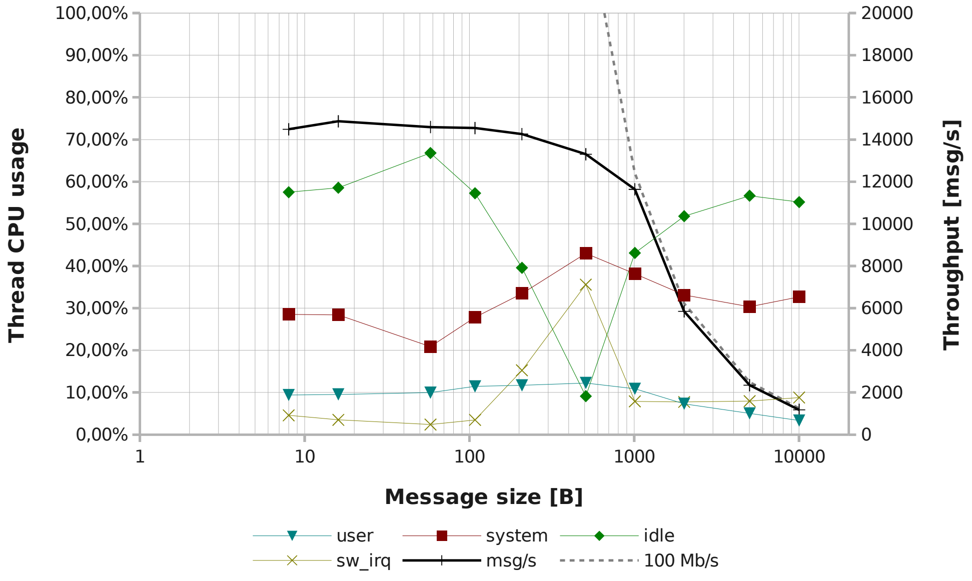


(a) log-lin

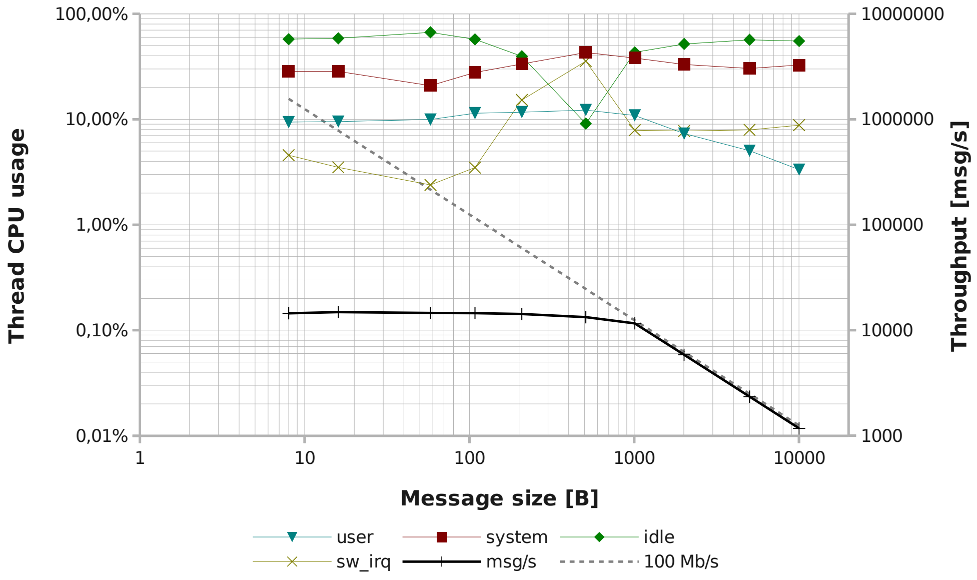


(b) log-log

Figure 6.8: Reception performance on RasPi, buffered messages



(a) log-lin



(b) log-log

Figure 6.9: Reception performance on RasPi, on-the-fly

6.2 Case study – Triskar2

µROSnode was used to teleoperate a robot, the *Triskar2* [21], by a remote ROS application. A µROSnode-based board acted as a gateway from a realtime *R2P* [2] CAN network, connecting sensors and actuators, to an Ethernet network, which is then linked to the remote host via Wi-Fi.

The gateway translates specific messages gathered from the CAN bus to native ROS messages, and vice versa. Thanks to the code generator tool supplied with µROSnode, the development of topic handlers was straightforward, needing only manual addition of few more lines in the handlers stubs, to republish messages between CAN and ROS.

6.2.1 Triskar2

Triskar2 is a highly modular, omnidirectional robot base developed by *AIRLab PoliMi*. Triskar2 is modular from the mechanical, the electronic, and the software points of view. Its small dimensions are suitable for indoor or cluttered environments. The robot base and the fully equipped robot are shown by **Figure 6.10**.

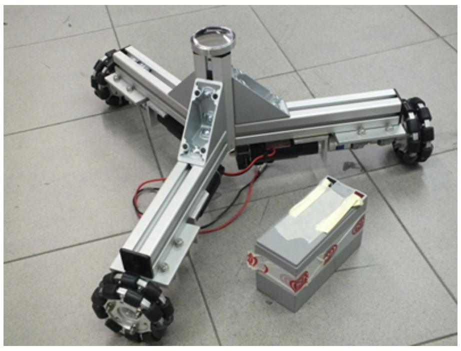
Mechanics

Triskar2 is a three-wheeled robot, with wheels spread at 120° on a circle, having their axes crossed at the center of the body frame. Its wheels, spun by motor modules (motor, transmission, encoder), are of *omni* type, to achieve three degrees of freedom.

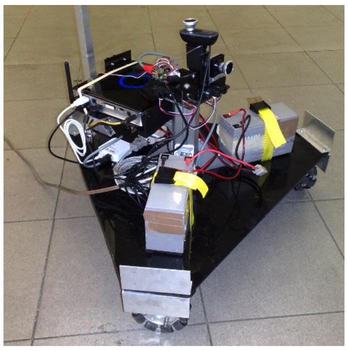
Its kinematics diagram is depicted in **Figure 6.11**. The body frame, which has origin in the middle of the robot, is aligned so that the y axis points forwards, the x axis rightwards, and the z axis upwards. The angle between the x axes of body and world frames, with respect to the z axis, is γ. Wheel angular positions are θ_1, θ_2, and θ_3. The only meaningful parameters, from the kinematics point of view, are the wheel radius, R, and the distance of the wheel origin from the body frame origin, L.

Direct kinematics:

$$\left\{ \begin{array}{rcrlrll} \dot{x} &=& R\cos\left(\frac{2}{6}\pi\right) & \dot{\theta}_1 & +R\cos\left(\frac{2}{6}\pi\right) & \dot{\theta}_2 & -R\ \dot{\theta}_3 \\ \dot{y} &=& -R\cos\left(\frac{1}{6}\pi\right) & \dot{\theta}_1 & +R\cos\left(\frac{1}{6}\pi\right) & \dot{\theta}_2 & \\ L\ \dot{\gamma} &=& -R & \dot{\theta}_1 & -R & \dot{\theta}_2 & -R\ \dot{\theta}_3 \end{array} \right. \tag{6.1}$$



(a) robot base



(b) fully equipped

Figure 6.10: The Triskar2 robot

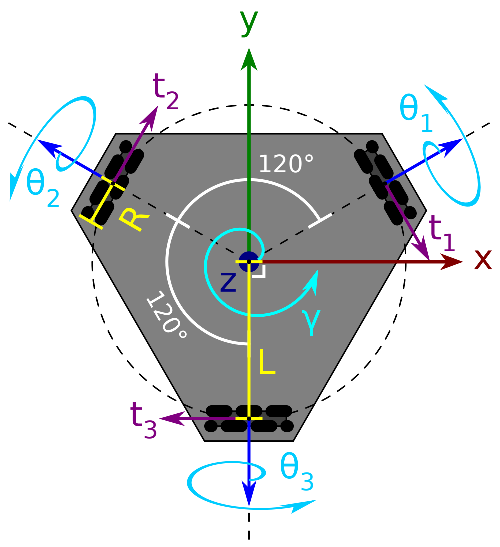


Figure 6.11: Kinematics diagram of Triskar2, top view

Inverse kinematics:

$$\left\{\begin{array}{lcccccc} R\ \dot{\theta}_1 & = & \cos\left(\frac{2}{6}\pi\right) & \dot{x} & -\cos\left(\frac{1}{6}\pi\right) & \dot{y} & -L\ \dot{\gamma} \\ R\ \dot{\theta}_2 & = & \cos\left(\frac{2}{6}\pi\right) & \dot{x} & +\cos\left(\frac{1}{6}\pi\right) & \dot{y} & -L\ \dot{\gamma} \\ R\ \dot{\theta}_3 & = & -1 & \dot{x} & & & -L\ \dot{\gamma} \end{array}\right. \tag{6.2}$$

Electronics

Triskar2 hosts the Rapid Robot Prototyping *Power* [17], *DC motor* [15], *IR* [16], and *Gateway* [29] modules. They are connected by a CAN bus, and can communicate with ROS through the µROSnode-based firmware running on the Gateway module, which in turn is linked to the on-board computer via Ether-

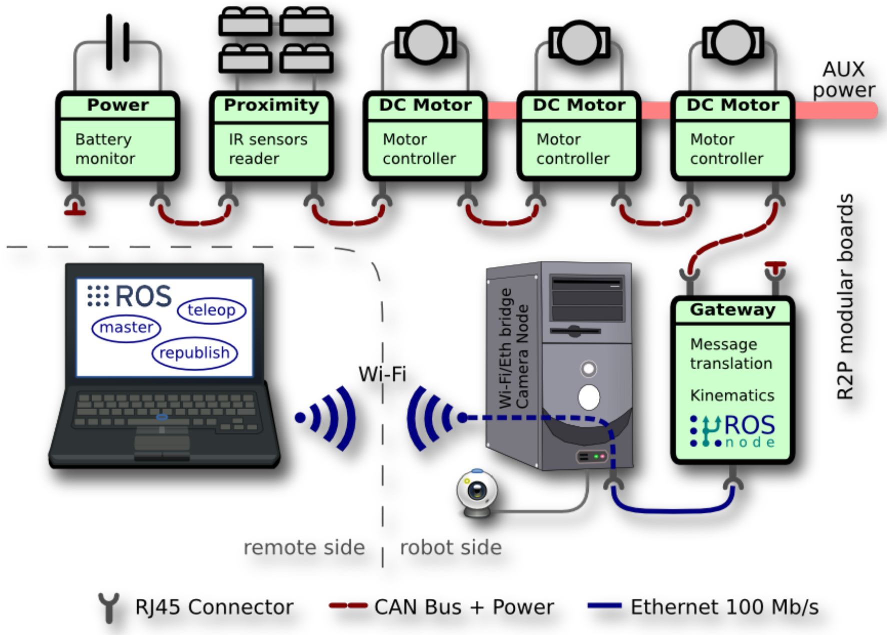


Figure 6.12: Devices and connections for the teleoperator application

net.
Two webcams, plugged to the on-board computer, provide vision capabilities in the forwards and upwards directions.
The robot optionally mounts a safety switch to shut down motors in case of emergency, and an USB-CAN debugger.
Figure 6.12 displays the devices and connections for the teleoperator application.

Computing

Triskar2 is fitted with a small-form-factor computer by *Zotac*, based on an *Intel Core i3 2330M* (dual core, 2.2 GHz), equipped with 6 GB RAM and *Wi-Fi* connectivity. The operating system is *Ubuntu 12.04*, hosting a full installation of *ROS Groovy*.

6.2.2 Software architecture

Our goal was to develop a first-person teleoperator application, to drive the robot from remote using ROS. We exploited the R2P Gateway module to act as a *bridge* between the underlying CAN-based network, involving sensors and actuators, and the IP-based network, managed by ROS.

Topics

Triskar2 spans two communication domains, R2P and ROS, both working in a *publish/subscribe* fashion. **Figure 6.13** summarizes the topics involved in the teleoperator application, highlighting their nature (R2P or ROS) and physical location (on the robot or on the remote host).

R2P Topics on the R2P side are exchanged among board modules through a CAN bus, which resides on the robot.
The teleoperator application needs the speed setpoints to be sent from the Gateway module to the motor boards via the `/speed123` topic, which groups the speed setpoints of the three motors.
The proximity sensor board sends the value of the four proximity sensors, one for each cardinal direction with respect to the body frame, to the gateway, via the `/irraw` topic.

ROS Topics on the ROS side are exchanged locally via 100 Mb/s Ethernet or shared-memory *nodelets*, and remotely via Wi-Fi.
The camera, mounted on the robot, streams frames to the remote host via the `/image_raw` topic, which uses the `compressed` format to save bandwidth. The uncompressed frames, republished by a local ROS node, are gathered by the teleoperator node via the `/triskar/front_camera` topic.
Velocity setpoints, changed by remote keyboard and mouse user interactions, are sent to the Gateway module via the `/triskar/velocity` topic.
On the other hand, the proximity values are received by the remote host from the Gateway module via the `/triskar/proximity` topic.

Gateway software

The R2P Gateway application translates R2P topic messages to ROS topic messages, and vice versa, performing the required mathematical transformations. Detailed listings can be found in Appendix B.4.

Teleoperator software

We created a ROS package, `triskar`, which provides the `teleop_node` ROS Node. It is written in Python, employing the *pygame* library [19] to draw the user interface and to manage user inputs. The teleoperator node only requires around 200 lines of code; its source code can be found in **Listing B.7**. This

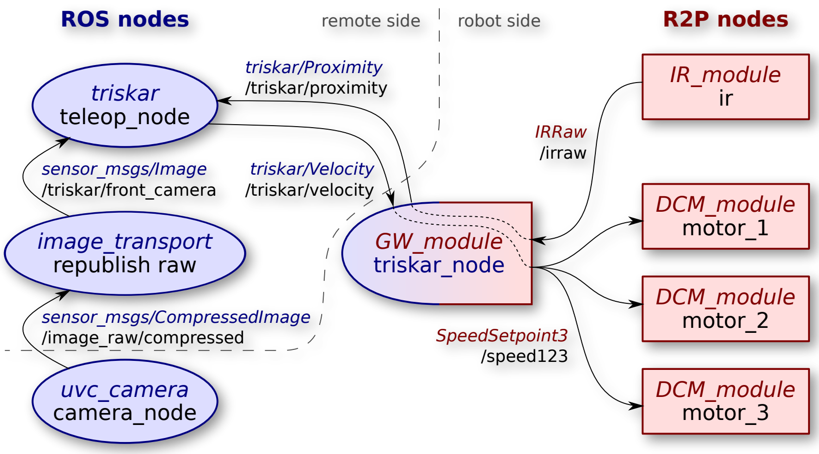


Figure 6.13: ROS and R2P topics of the Triskar2 teleoperator application

Key	Binding
W	Move forward
S	Move back
A	Strafe left
D	Strafe right
Q	Turn left
E	Turn right
Shift	Speed boost
Esc	Ungrab mouse

Mouse	Binding
Move forward	Move forward
Move back	Move back
Move left	Turn left
Move right	Turn right
Left button held	Integrate mouse impulses
Right button held	Strafe instead of turn

Table 6.3: User input bindings for the Triskar2 teleoperator application

node subscribes to the `/triskar/front_camera` topic, which streams frames captured from the front camera of Triskar2.
User inputs work like in *first person* games, which expolit a keyboard and a mouse to control the velocity of the *alter ego*; bindings are listed in **Table 6.3**.
A minimalistic user interface shows the current *forward* (vertical green line), *strafe* (horizontal red line), and *angular* (blue arc) setpoints, as displayed in **Figure 6.14**. Setpoints are sent to Triskar2 through the `/triskar/velocity` topic.
Movements of Triskar2 are inhibited in those directions where proximity sensors data, read from the `/triskar/proximities` topic, reveal the presence of obstacles.

6.2.3 Observations

The development of the Triskar2 gateway firmware did not require much effort. Since the target platform was already supported by µROSnode, we simply included the related makefile scripts into the `Makefile`.

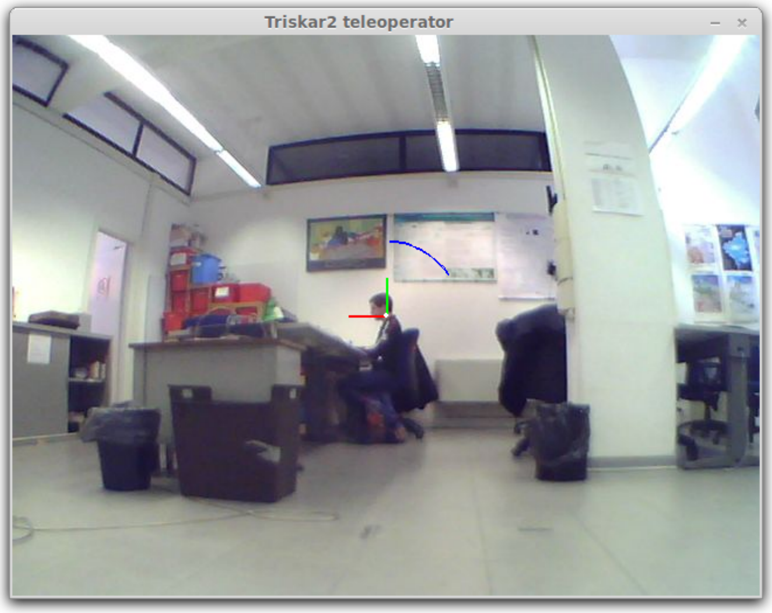


Figure 6.14: Screenshot of the Triskar2 teleoperator window

The codebase derived from the `benchmark-chibios+lwip` demo, supplied with µROSnode, which was integrated with the R2P middleware to control the R2P boards over a CAN bus.
The *urosMsgTypes* and *urosHandlers* software modules were regenerated by *urosgen*, provided with an appropriate configuration file. This task was accomplished in a few minutes.
As seen in Section 6.2.2, the development of topic handler routines was straightforward, and only required to translate messages between R2P and µROSnode (thus, ROS).
The whole firmware was completed in a few hours, including testing.

Chapter 7

Conclusions and future research directions

We were looking for a robotics software framework to program hardware modules for rapid prototyping of new robot designs. Since the state-of-the-art frameworks cannot easily blend high-level software with hardware platforms, we developed µROSnode, a software communication framework capable of integrating embedded systems with a ROS network. This way a robotics researcher, often accustomed to ROS for its simplicity and high availability of pre-made software packages, can natively connect to hardware modules running µROSnode.
Software development with µROSnode has proven to be easy, thanks to its simple software architecture, the well documented API, and the easy-to-use code generator.
Support for generic operating systems and IP network stacks, available through a lightweight abstraction layer, permits the use of µROSnode on multiple platforms, while sharing the same codebase and semantics.
The µROSnode codebase can be compiled for almost all of the embedded system platforms, by exploiting mature ANSI C89 support for such platforms. The small size of µROSnode in both program and working memories allows the development of firmware for advanced modern microcontrollers. The static stack analysis tool, supplied with µROSnode, assists the developer in optimization and control of stack usage.
Experimental results showed good performance even for a very simple platform, based on a recent microcontroller hosting an ARM-CM4 core. A platform of this type may be enough for simple specific-purpose hardware modules, where a few concurrent ROS topics are needed and message size is small. This allows the development of inexpensive robotics hardware modules, with the non-trivial

advantage of being natively connected to a ROS computation graph by an IP network.
Companies making robotics devices may take advantage of µROSnode to design ROS-ready components. µROSnode may be used to create a bridge to existing hardware, or directly inside the firmware of those devices already exposing Ethernet or Wi-Fi interfaces. µROSnode may also run on devices for educational or recreational applications working with ROS.

In order to provide a more flexible, higher-level codebase, µROSnode may support the C++ language in the future, by the means of wrapper classes around the C implementation, or even by a dedicated C++ version. Wrappers can be done fast, as C++ was designed on top of C, but an entire C++ version would provide a more idiomatic codebase. The C++ version may also provide an API closer to that of *roscpp*, which is already known by most of the ROS users.
While TCPROS is implemented by all of the ROS nodes (it is the fallback protocol), µROSnode currently lacks UDPROS support, which better suits low-latency communication and those applications where packet drops may be tolerated. Furthermore, UDP has higher efficiency than TCP over wireless communication.

Bibliography

[1] American National Standards Institute, 1430 Broadway, New York, NY 10018, USA. *American National Standard Programming Language C, ANSI X3.159-1989*, December 1989.

[2] Andrea Bonarini, Matteo Matteucci, Martino Migliavacca, and Davide Rizzi. R2P: an Open Source Modular Architecture for Rapid Prototyping of Robotics Applications. In *Proceedings of 1st IFAC Conference on Embedded Systems, Computational Intelligence and Telematics in Control (CESCIT'12)*, pages 68–73. Elsevier, 2012.

[3] Andrea Bonarini, Matteo Matteucci, Martino Migliavacca, Roberto Sannino, and Daniele Caltabiano. Modular Low-Cost Robotics: What Communication Infrastructure? In *Proceedings of 18th World Congress of the International Federation of Automatic Control (IFAC)*, pages 917–922. Elsevier, 2011.

[4] H. Bruyninckx. Open robot control software: the orocos project. In *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, volume 3, pages 2523–2528 vol.3.

[5] CMake.org. *CMake build system.*
`http://www.cmake.org/`

[6] Giovanni Di Sirio. *ChibiOS/RT Real-Time Operating System.*
`http://www.chibios.org/`

[7] Josh Faust. *The `turtlesim` ROS package.*
`http://www.ros.org/wiki/turtlesim`

[8] Raspberry Pi Foundation. *Raspberry Pi.*
`http://www.raspberrypi.org/`

[9] GNU. *GNU Compiler Collection.*
`http://gcc.gnu.org/`

[10] GNU. *Language Standards Supported by GCC.*
http://gcc.gnu.org/onlinedocs/gcc/Standards.html

[11] Brian Hall. *Beej's Guide to Network Programming.* Jorgensen Publishing, October 2011.
http://beej.us/guide/bgnet/

[12] Albert S. Huang, Edwin Olson, and David Moore. LCM: Lightweight Communications and Marshalling. In *Int. Conf. on Intelligent Robots and Systems (IROS)*, Taipei, Taiwan, Oct. 2010.

[13] iRobot Corporation. *Create Programmable Robot.*
http://www.irobot.com/en/us/robots/Educators/Create.aspx

[14] ISO/IEC JTC 1. *14977:1996 – Information technology – Syntactic metalanguage – Extended BNF.*
http://standards.iso.org/ittf/PubliclyAvailableStandards/s026153_ISO_IEC_14977_1996(E).zip

[15] Martino Migliavacca. *Rapid Robot Prototyping – DC motor module.*
http://github.com/openrobots-dev/R2P_DCM_module

[16] Martino Migliavacca. *Rapid Robot Prototyping – IR module.*
http://github.com/openrobots-dev/R2P_IR_module

[17] Martino Migliavacca. *Rapid Robot Prototyping – Power supply module.*
http://github.com/openrobots-dev/R2P_PS_module

[18] Martino Migliavacca. *Rapid Robot Prototyping – Sonar module.*
http://github.com/openrobots-dev/R2P_Sonar_module

[19] Pete Shinners. *pygame.*
http://www.pygame.org/

[20] Politecnico di Milano – AIRLab. *TiltOne.*
http://airwiki.elet.polimi.it/index.php/TiltOne

[21] Politecnico di Milano – AIRLab. *Triskar2.*
http://airwiki.elet.polimi.it/index.php/Triskar2

[22] Morgan Quigley, Ken Conley, Brian P. Gerkey, Josh Faust, Tully Foote, Jeremy Leibs, Rob Wheeler, and Andrew Y. Ng. ROS: an open-source Robot Operating System. In *ICRA Workshop on Open Source Software*, 2009.

[23] Radu Bogdan Rusu. *ROS Introduction – Overview.*
http://www.ros.org/wiki/Events/CoTeSys-ROS-School

[24] D. J. Rosenkrantz and R. E. Stearns. Properties of deterministic top-down grammars. In *Proceedings of the first annual ACM symposium on Theory of computing*, STOC '69, page 165, 1969.

[25] ROS.org. *Documentation.*
`http://www.ros.org/wiki`

[26] Herbert Schildt, American National Standards Institute, International Organization for Standardization, International Electrotechnical Commission, and ISO/IEC JTC 1. *The annotated ANSI C standard: American National Standard for Programming Languages C: ANSI/ISO 9899-1990.* Osborne/McGraw-Hill, Berkeley, CA, USA, 1990.

[27] SICK Group. *LMS100 Laser Measurement System.*
`http://www.sick.com/group/EN/home/products/product_news/laser_measurement_systems/Pages/lms100.aspx`

[28] UserLand Software. *XML-RPC Specification.*
`http://www.xmlrpc.com/spec`

[29] Andrea Zoppi and Martino Migliavacca. *Rapid Robot Prototyping – CAN-to-Ethernet gateway module.*
`http://github.com/openrobots-dev/R2P_GW_module`

[30] Andrea Zoppi and Martino Migliavacca. *μROSnode.*
`http://github.com/openrobots-dev/uROSnode`

Appendix A

ROS-related API documentation

This appendix describes the μROSnode API, close to that of ROS, used to communicate with the *Master Node*, the *Parameter Server*, and the common *Slave Nodes*, via XML-RPC.

Furthermore, the μROSnode Node singleton API manages (un)registration of message types, topics, and services.

A.1 ROS Master API

A.1.1 registerService()

Registers the caller as a provider of the specified service.

```
uros_err_t urosRpcCallRegisterService(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *service,
  const UrosString      *service_api,
  const UrosString      *caller_api,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`service` [*in*] Fully-qualified name of service. Non-empty string pointer.
`service_api` [*in*] ROSRPC Service URI. Non-empty string pointer.
`caller_api` [*in*] XML-RPC URI of caller node. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any ignore ]
```

A.1.2 unregisterService()

Unregisters the caller as a provider of the specified service.

```
uros_err_t urosRpcCallUnregisterService(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *service,
  const UrosString      *service_api,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`service` [*in*] Fully-qualified name of service. Non-empty string pointer.
`service_api` [*in*] API URI of service to unregister. Unregistration will only occur if current registration matches. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:
`[ int code,str statusMessage,int numUnregistered ]`
Number of unregistrations (either `0` or `1`). If this is zero it means that the caller was not registered as a service provider. The call still succeeds as the intended final state is reached.

A.1.3 registerSubscriber()

Subscribes the caller to the specified topic. In addition to receiving a list of current publishers, the subscriber will also receive notifications of new publishers via the `publisherUpdate()` API.

```
uros_err_t urosRpcCallRegisterSubscriber(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *topic,
  const UrosString      *topic_type,
  const UrosString      *caller_api,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`topic` [*in*] Fully-qualified name of topic. Non-empty string pointer.
`topic_type` [*in*] Datatype for topic. Must be a package-resource name, i.e. the `.msg` name. Non-empty string pointer.
`caller_api` [*in*] API URI of subscriber to register. Will be used for new publisher notifications. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:
`[ int code,str statusMessage,[str publisherN]]`

A.1.4 unregisterSubscriber()

Unregisters the caller as a publisher of the topic.

```
uros_err_t urosRpcCallUnregisterSubscriber(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *topic,
  const UrosString      *caller_api,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
topic [*in*] Fully-qualified name of topic. Non-empty string pointer.
caller_api [*in*] API URI of service to unregister. Unregistration will only occur if current registration matches. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:
`[ int code,str statusMessage,int numUnsubscribed ]`
If `numUnsubscribed` is zero it means that the caller was not registered as a subscriber. The call still succeeds as the intended final state is reached.

A.1.5 registerPublisher()

Registers the caller as a publisher the topic.

```
uros_err_t urosRpcCallRegisterPublisher(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *topic,
  const UrosString      *topic_type,
  const UrosString      *caller_api,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
topic [*in*] Fully-qualified name of topic to register. Non-empty string pointer.
topic_type [*in*] Datatype for topic. Must be a package-resource name, i.e. the `.msg` name. Non-empty string pointer.
caller_api [*in*] API URI of publisher to register. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:
`[ int code,str statusMessage,[str subscriberApiN]]`

A.1.6 unregisterPublisher()

Unregisters the caller as a publisher of the topic.

```
uros_err_t urosRpcCallUnregisterPublisher(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *topic,
  const UrosString      *caller_api,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
topic [*in*] Fully-qualified name of topic to unregister. Non-empty string pointer.

`caller_api` [*in*] API URI of publisher to unregister. Unregistration will only occur if current registration matches. Non-empty string pointer.

`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,int numUnregistered ]
```

If `numUnregistered` is zero it means that the caller was not registered as a publisher. The call still succeeds as the intended final state is reached.

A.1.7 lookupNode()

Gets the XML-RPC URI of the node with the associated name. This API is for looking information about publishers and subscribers. Use `lookupService()` instead to lookup ROS-RPC URIs.

```
uros_err_t urosRpcCallLookupNode(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *node,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`node` [*in*] Name of node to lookup. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,str URI ]
```

A.1.8 getPublishedTopics()

Gets the list of topics that can be subscribed to. This does not return topics that have no publishers.

```
uros_err_t urosRpcCallGetPublishedTopics(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *subgraph,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`subgraph` [*in*] Restrict topic names to match within the specified subgraph. Subgraph namespace is resolved relative to the caller's namespace. Use empty string to specify all names. Valid string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,[[str topicN,str typeN]]]
```

A.1.9 getTopicTypes()

Retrieves list topic names and their types.

```
uros_err_t urosRpcCallGetTopicTypes(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,[[str topicN,str typeN]]]
```

A.1.10 getSystemState()

Retrieves list representation of system state.

```
uros_err_t urosRpcCallGetSystemState(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code, str statusMessage, [
  [ str topicN,   [str topicN_publisherM] ],
  [ str topicN,   [str topicN_subscriberM] ],
  [ str serviceN, [str serviceN_providerM] ]
] ]
```

A.1.11 getUri()

Gets the URI of the the Master.

```
uros_err_t urosRpcCallGetUri(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,str masterURI ]
```

A.1.12 lookupService()

Looks up all the providers of a particular service.

```
uros_err_t urosRpcCallLookupService(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *service,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`service` [*in*] Fully-qualified name of service. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,str serviceURI ]
```

A.2 ROS Parameter Server API

A.2.1 deleteParam()

Deletes a parameter.

```
uros_err_t urosRpcCallDeleteParam(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *key,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`key` [*in*] Parameter name. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any ignore ]
```

A.2.2 setParam()

Sets a parameter. If value is a dictionary it will be treated as a parameter tree, where `key` is the parameter namespace.

```
uros_err_t urosRpcCallSetParam(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *key,
  const UrosRpcParam    *value,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`key` [*in*] Parameter name. Non-empty string pointer.
`value` [*in*] Parameter value.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any ignore ]
```

A.2.3 getParam()

Retrieve a parameter value from server.

```
uros_err_t urosRpcCallGetParam(
  const UrosAddr         *addrp,
  const UrosString       *caller_id,
  const UrosString       *key,
  UrosRpcResponse        *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
key [*in*] Parameter name. If `key` is a namespace, it will return a parameter tree. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any parameterValue ]
```

A.2.4 searchParam()

Searches for a parameter key on the server. Search starts in caller's namespace and proceeds upwards through parent namespaces until Parameter Server finds a matching key.

Its behavior is to search for the first partial match. For example, imagine that there are two `robot_description` parameters:

```
/robot_description
    /arm
    /base
/pr2
    /robot_description
        /base
```

If starting in the namespace `/pr2/foo` and search for `robot_description`, searchParam() will match `/pr2/robot_description`.
If searching for `robot_description/arm` it will return `/pr2/robot_description/arm`, even though that parameter does not exist (yet).

```
uros_err_t urosRpcCallSearchParam(
  const UrosAddr         *addrp,
  const UrosString       *caller_id,
  const UrosString       *key,
  UrosRpcResponse        *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
key [*in*] Parameter name to search for. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,str foundKey ]
```

A.2.5 subscribeParam()

Retrieves a parameter value from the server, and subscribes to updates to that parameter.

```
uros_err_t urosRpcCallSubscribeParam(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *caller_api,
  const UrosString      *key,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
key [*in*] Parameter name. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any parameterValue ]
```

If `code` is not `1`, `parameterValue` should be ignored. `parameterValue` is an empty dictionary if the parameter has not been set yet.

A.2.6 unsubscribeParam()

Retrieves a parameter value from server and subscribe to updates to that parameter.

```
uros_err_t urosRpcCallUnsubscribeParam(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *caller_api,
  const UrosString      *key,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
key [*in*] Parameter name. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,int numUnsubscribed ]
```

If `numUnsubscribed` is zero, it means that the caller was not subscribed to the parameter.

A.2.7 hasParam()

Checks if a parameter is stored on the server.

```
uros_err_t urosRpcCallHasParam(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *key,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.

caller_id [*in*] ROS caller ID. Non-empty string pointer.
key [*in*] Parameter name. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,bool hasParam ]
```

A.2.8 getParamNames()

Gets the list of all parameter names stored on the server.

```
uros_err_t urosRpcCallGetParamNames(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,[str paramaterNameN]]
```

A.3 ROS Slave API

A.3.1 getBusStats()

Retrieves transport/topic statistics.

```
uros_err_t urosRpcCallGetBusStats(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

addrp [*in*] Pointer to the Master API connection address.
caller_id [*in*] ROS caller ID. Non-empty string pointer.
resp [*out*] Pointer to the response object. Format:

```
[ int code, str statusMessage, [ publishStats, subscribeStats, serviceStats ] ]

publishStats:   [ [ topicName, messageDataSent, pubConnectionData ]... ]
subscribeStats: [ [ topicName, subConnectionData ]... ]
serviceStats:   [ numRequests, bytesReceived, bytesSent ] (proposed)

pubConnectionData: [ connectionId, bytesSent, numSent, connected ]*
subConnectionData: [ connectionId, bytesReceived, dropEstimate, connected ]*
```

`dropEstimate` is `-1` for no estimate.

A.3.2 getBusInfo()

Retrieves transport/topic connection information.

```
uros_err_t urosRpcCallGetBusInfo(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code, str statusMessage, busInfo ]
```

```
[ [ connectionIdN, destinationIdN, directionN, transportN, topicN, connectedN ] ]
```

`connectionId` is defined by the node and is opaque
`destinationId` is the XMLRPC URI of the destination
`direction` is one of `'i'`, `'o'`, or `'b'` (in, out, both)
`transport` is the transport type (e.g. `'TCPROS'`)
`topic` is the topic name
`connected` indicates connection status

A.3.3 getMasterUri()

Gets the URI of the Master node.

```
uros_err_t urosRpcCallGetMasterUri(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,str masterURI ]
```

A.3.4 shutdown()

Stops the Slave server.

```
uros_err_t urosRpcCallShutdown(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *msg,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`msg` [*in*] A message describing why the node is being shutdown. Valid string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any ignore ]
```

A.3.5 getPid()

Get the PID of the Slave server.

```
uros_err_t urosRpcCallGetPid(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,int serverProcessPID ]
```

A.3.6 getSubscriptions()

Retrieves a list of topics that this node subscribes to.

```
uros_err_t urosRpcCallGetSubscriptions(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,[[str topicN,str topicTypeN]]]
```

A.3.7 getPublications()

Retrieves a list of topics that this node publishes.

```
uros_err_t urosRpcCallGetPublications(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,[[str topicN,str topicTypeN]]]
```

A.3.8 paramUpdate()

Callback from Master with updated value of subscribed parameter.

```
uros_err_t urosRpcCallParamUpdate(
  const UrosAddr        *addrp,
  const UrosString      *caller_id,
  const UrosString      *parameter_key,
  const UrosRpcParam    *parameter_value,
  UrosRpcResponse       *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`parameter_key` [*in*] Parameter name, globally resolved. Non-empty string pointer.
`parameter_value` [*in*] New parameter value.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any ignore ]
```

A.3.9 publisherUpdate()

Callback from Master of current publisher list for the specified topic.

```
uros_err_t urosRpcCallPublisherUpdate(
  const UrosAddr            *addrp,
  const UrosString          *caller_id,
  const UrosString          *topic,
  const UrosRpcParamList    *publishers,
  UrosRpcResponse           *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.
`topic` [*in*] Topic name. Non-empty string pointer.
`publishers` [*in*] List of current publishers for topic in the form of XMLRPC URIs.
`resp` [*out*] Pointer to the response object. Format:

```
[ int code,str statusMessage,any ignore ]
```

A.3.10 requestTopic()

Publisher node API method called by a subscriber node. This requests that source allocate a channel for communication. Subscriber provides a list of desired protocols for communication. Publisher returns the selected protocol along with any additional params required for establishing connection. For example, for a TCP/IP-based connection, the source node may return a port number of TCP/IP server.

```
uros_err_t urosRpcCallRequestTopic(
  const UrosAddr            *addrp,
  const UrosString          *caller_id,
  const UrosString          *topic,
  const UrosRpcParamList    *protocols,
  UrosRpcResponse           *resp
);
```

`addrp` [*in*] Pointer to the Master API connection address.
`caller_id` [*in*] ROS caller ID. Non-empty string pointer.

topic [*in*] Topic name. Non-empty string pointer.
protocols [*in*] List of desired protocols for communication in order of preference. Each protocol is a list of the form:
```
[ protocolName,protocolParam1,protocolParam2,... ]
```
resp [*out*] Pointer to the response object. Format:
```
[ int code,str statusMessage,[str protocolParamN]]
```

A.4 Node API

The following API are used to manage the current state of the Node singleton, by (un)registering topics, services, and parameters, as well as resolving the address of a specific topic or service publisher.

A.4.1 urosNodePublishTopic()

Issues a `publishTopic()` call to the XML-RPC Master.

Warning: The access to the topic registry is thread-safe, but delays of the XML-RPC communication will delay also any other threads trying to publish/unpublish any topics.

Preconditions:
- the topic is not published;
- the TPCORS `service` flag must be clear.

```
uros_err_t urosNodePublishTopic(
  const UrosString      *namep,
  const UrosString      *typep,
  uros_proc_f           procf,
  uros_topicflags_t     flags
);
```

namep [*in*] Pointer to the topic name string.
typep [*in*] Pointer to the topic message type name string.
procf [*in*] Topic handler function.
flags [*in*] Topic flags.

A.4.2 urosNodeUnpublishTopic()

Issues an `unpublishTopic()` call to the XML-RPC Master.

Warning: The access to the topic registry is thread-safe, but delays of the XML-RPC communication will delay also any other threads trying to publish/unpublish any topics.

Preconditions:
- the topic is published.

Postconditions: If successful, the topic descriptor is dereferenced by the topic registry, and will be freed:
- by this function, if there are no publishing TCPROS threads; or
- by the last publishing TCPROS thread which references the topic.

```
uros_err_t urosNodeUnpublishTopic(
  const UrosString      *namep
);
```

namep [*in*] Pointer to a string which names the topic.

A.4.3 urosNodeSubscribeTopic()

Issues a `registerSubscriber()` call to the XML-RPC Master, and connects to known publishers.

Warning: The access to the topic registry is thread-safe, but delays of the XML-RPC communication will delay also any other threads trying to subscribe/unsubscribe to any topics.

Preconditions:

- the topic is not subscribed;
- the TPCROS service flag must be clear.

Postconditions:

- connects to known publishers listed by a successful response.

```
uros_err_t urosNodeSubscribeTopic(
  const UrosString      *namep,
  const UrosString      *typep,
  uros_proc_f           procf,
  uros_topicflags_t     flags
);
```

namep	[*in*]	Pointer to the topic name string.
typep	[*in*]	Pointer to the topic message type name string.
procf	[*in*]	Topic handler function.
flags	[*in*]	Topic flags.

A.4.4 urosNodeUnsubscribeTopic()

Issues an `unregisterSubscriber()` call to the XML-RPC Master.

Warning: The access to the topic registry is thread-safe, but delays of the XML-RPC communication will delay also any other threads trying to subscribe/unsubscribe to any topics.

Preconditions:

- the topic is published;
- the TCPROS `service` flag must be clear.

Postconditions: If successful, the topic descriptor is dereferenced by the topic registry, and will be freed:

- by this function, if there are no publishing TCPROS threads; or
- by the last publishing TCPROS thread which references the topic.

```
uros_err_t urosNodeUnsubscribeTopic(
  const UrosString      *namep
);
```

namep [*in*] Pointer to a string which names the topic.

A.4.5 urosNodePublishService()

Issues a `registerService()` call to the XML-RPC Master.

Warning: The access to the service registry is thread-safe, but delays of the XML-RPC communication will delay also any other threads trying to subscribe/unsubscribe to any services.

Preconditions:

- the service is published;
- the TCPROS service flag must be clear.

Postconditions: If successful, the topic descriptor is dereferenced by the topic registry, and will be freed:

- by this function, if there are no publishing TCPROS threads; or
- by the last publishing TCPROS thread which references the topic.

```
uros_err_t urosNodePublishService(
  const UrosString      *namep,
  const UrosString      *typep,
  uros_proc_f           procf,
  uros_topicflags_t     flags
);
```

namep	[*in*]	Pointer to the service name string.
typep	[*in*]	Pointer to the service type name string.
procf	[*in*]	Service handler function.
flags	[*in*]	Topic flags.

A.4.6 urosNodeUnpublishService()

Issues an unregisterService() call to the XML-RPC Master.

Warning: The access to the service registry is thread-safe, but delays of the XML-RPC communication will delay also any other threads trying to publish/unpublish any services.

Preconditions:

- the service is published.

Postconditions: If successful, the service descriptor is dereferenced by the topic registry, and will be freed:

- by this function, if there are no publishing TCPROS threads; or
- by the last publishing TCPROS thread which references the service.

```
uros_err_t urosNodeUnpublishService(
  const UrosString      *namep
);
```

namep	[*in*]	Pointer to a string which names the service.

A.4.7 urosNodeCallService()

Gets the service URI from the Master node. If found, it executes the service call once, and the result is returned.

Note: Only a *single* call will be executed. Persistent TCPROS service connections need custom handlers.

Preconditions:

- the TCPROS `service` flag must be set, `persistent` clear.

```
uros_err_t urosNodeCallService(
  const UrosString      *namep,
  const UrosString      *typep,
  uros_tcpsrvcall_t     callf,
  uros_topicflags_t     flags,
  void                  *resobjp
);
```

namep [*in*] Pointer to the service name string.
typep [*in*] Pointer to the service type name string.
callf [*in*] Service call handler.
flags [*in*] TCPROS flags.
resobjp [*out*] Pointer to the allocated response object. The service result will be written there only if the call is successful.

A.4.8 urosNodeSubscribeParam()

Issues a `subscribeParam()` call to the XML-RPC Master, and connects to known publishers.

Warning: The access to the parameter registry is thread-safe, but delays of the XML-RPC communication will delay also any other threads trying to subscribe/unsubscribe to any parameters.

Preconditions:

- the parameter has not been registered yet.

```
uros_err_t urosNodeSubscribeParam(
  const UrosString      *namep
);
```

namep [*in*] Pointer to the parameter name string.

A.4.9 urosNodeUnsubscribeParam()

Issues an `unsubscribeParam()` call to the XML-RPC Master, and connects to known publishers.

Preconditions:

- the parameter has been registered.

Postconditions:

- if successful, the parameter descriptor is unreferenced and deleted by the parameter registry.

namep [*in*] Pointer to a string which names the parameter to be unregistered.

A.4.10 urosNodeResolveTopicPublisher()

Requests the TCPROS URI of a topic published by a node.

```
uros_err_t urosNodeResolveTopicPublisher(
  const UrosAddr        *apiaddrp,
  const UrosString      *namep,
  UrosAddr              *tcprosaddrp
);
```

apiaddrp [*in*] XML-RPC API address of the target node.

namep [*in*] Pointer to the topic name string.

tcprosaddrp [*in*] Pointer to an allocated **UrosAddr** descriptor, which will hold the TCPROS API address of the requested topic provider.

A.4.11 urosNodeResolveServicePublisher()

Requests the TCPROS URI of a service published by a node.

```
uros_err_t urosNodeResolveServicePublisher(
  const UrosString      *namep,
  UrosAddr              *pubaddrp
);
```

namep [*in*] Pointer to the topic name string.

pubaddrp [*in*] Pointer to an allocated **UrosAddr** descriptor, which will hold the TCPROS API address of the requested service provider.

Appendix B

Useful listings

This appendix contains miscellaneous listings, for a better understanding of XML-RPC and TCPROS protocols, as well as the µROSnode license, and some demonstration configuration files for the code generator and the static stack analysis tool.

B.1 Disclaimer

The following is the µROSnode source code disclaimer, based on a 2-clause *BSD* license.

```
Copyright (c) 2012-2013, Politecnico di Milano. All rights reserved.

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http://airlab.elet.polimi.it/
http://www.openrobots.com/

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WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE
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(INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES;
LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND
ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT
(INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS
SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
```

Listing B.1: Source code disclaimer of μROSnode

B.2 XML-RPC grammar

No official grammar specification exists, but a *Document Type Definition* (*DTD*) and an *XML Schema* (*XSD*) can be outlined, although none of them can synthesize all of the XML-RPC grammar rules.

B.2.1 Document Type Definition

```
<!--
Copyright 2001-2002 Elliotte Rusty Harold
http://cafeconleche.org/books/xmljava/chapters/ch02s05.html
-->

<!ELEMENT methodCall (methodName, params)>
<!ELEMENT methodName (#PCDATA)>
<!ELEMENT params     (param*)>
<!ELEMENT param      (value)>
<!ELEMENT value      (
  i4 | int | string | double | dateTime.iso8601 | base64 | struct | array
)>

<!ELEMENT i4               (#PCDATA)>
<!ELEMENT int              (#PCDATA)>
<!ELEMENT string           (#PCDATA)>
<!ELEMENT dateTime.iso8601 (#PCDATA)>
<!ELEMENT double           (#PCDATA)>
<!ELEMENT base64           (#PCDATA)>

<!ELEMENT array            (data)>
<!ELEMENT data             (value*)>
<!ELEMENT struct           (member+)>
<!ELEMENT member           (name, value)>
<!ELEMENT name             (#PCDATA)>

<!ELEMENT methodResponse   (params | fault)>
<!ELEMENT fault            (value)>
```

Listing B.2: Document Type Definition of XML-RPC (unofficial)

B.2.2 XML Schema

```
<?xml version="1.0"?>
<!--
Copyright 2001-2002 Elliotte Rusty Harold
http://cafeconleche.org/books/xmljava/chapters/ch02s05.html
-->

<xsd:schema xmlns:xsd="http://www.w3.org/2001/XMLSchema">
  <!--
  The only two possible root elements are methodResponse and methodCall, so
  these are the only two I use a top-level declaration for.
  -->

  <xsd:element name="methodCall">
    <xsd:complexType>
      <xsd:all>
        <xsd:element name="methodName">
          <xsd:simpleType>
            <xsd:restriction base="ASCIIString">
              <xsd:pattern value="([A-Za-z0-9]|/|\.|:|_)*"/>
            </xsd:restriction>
          </xsd:simpleType>
        </xsd:element>
        <xsd:element name="params" minOccurs="0" maxOccurs="1">
          <xsd:complexType>
            <xsd:sequence>
              <xsd:element name="param"  type="ParamType"
                           minOccurs="0" maxOccurs="unbounded"/>
            </xsd:sequence>
          </xsd:complexType>
         </xsd:element>
      </xsd:all>
    </xsd:complexType>
  </xsd:element>

  <xsd:element name="methodResponse">
    <xsd:complexType>
      <xsd:choice>
        <xsd:element name="params">
          <xsd:complexType>
            <xsd:sequence>
              <xsd:element name="param" type="ParamType"/>
            </xsd:sequence>
          </xsd:complexType>
        </xsd:element>
        <xsd:element name="fault">
          <!-- What can appear inside a fault is very restricted -->
          <xsd:complexType>
            <xsd:sequence>
```

```
              <xsd:element name="value">
                <xsd:complexType>
                  <xsd:sequence>
                    <xsd:element name="struct">
                      <xsd:complexType>
                        <xsd:sequence>
                          <xsd:element name="member" type="MemberType">
                          </xsd:element>
                          <xsd:element name="member" type="MemberType">
                          </xsd:element>
                        </xsd:sequence>
                      </xsd:complexType>
                    </xsd:element>
                  </xsd:sequence>
                </xsd:complexType>
              </xsd:element>
            </xsd:sequence>
          </xsd:complexType>
         </xsd:element>
      </xsd:choice>
    </xsd:complexType>
  </xsd:element>

  <xsd:complexType name="ParamType">
    <xsd:sequence>
      <xsd:element name="value" type="ValueType"/>
    </xsd:sequence>
  </xsd:complexType>

  <xsd:complexType name="ValueType" mixed="true">
    <!--
    I need to figure out how to say that this is either a simple xsd:string
    type or that it contains one of these elements; but that otherwise it
    does not have mixed content.
    -->
    <xsd:choice>
      <xsd:element name="i4"               type="xsd:int"/>
      <xsd:element name="int"              type="xsd:int"/>
      <xsd:element name="string"           type="ASCIIString"/>
      <xsd:element name="double"           type="xsd:decimal"/>
      <xsd:element name="Base64"           type="xsd:base64Binary"/>
      <xsd:element name="boolean"          type="NumericBoolean"/>
      <xsd:element name="dateTime.iso8601" type="xsd:dateTime"/>
      <xsd:element name="array"            type="ArrayType"/>
      <xsd:element name="struct"           type="StructType"/>
    </xsd:choice>
  </xsd:complexType>

  <xsd:complexType name="StructType">
    <xsd:sequence>
      <xsd:element name="member" type="MemberType" maxOccurs="unbounded"/>
    </xsd:sequence>
  </xsd:complexType>

  <xsd:complexType name="MemberType">
    <xsd:sequence>
      <xsd:element name="name"  type="xsd:string"/>
      <xsd:element name="value" type="ValueType"/>
    </xsd:sequence>
  </xsd:complexType>

  <xsd:complexType name="ArrayType">
    <xsd:sequence>
      <xsd:element name="data">
        <xsd:complexType>
          <xsd:sequence>
            <xsd:element name="value"  type="ValueType"
                         minOccurs="0" maxOccurs="unbounded"/>
          </xsd:sequence>
        </xsd:complexType>
      </xsd:element>
    </xsd:sequence>
  </xsd:complexType>

  <xsd:simpleType name="ASCIIString">
    <xsd:restriction base="xsd:string">
      <xsd:pattern value="([ -~]|\n|\r|\t)*"/>
    </xsd:restriction>
  </xsd:simpleType>

  <xsd:simpleType name="NumericBoolean">
    <xsd:restriction base="xsd:boolean">
      <xsd:pattern value="0|1"/>
    </xsd:restriction>
  </xsd:simpleType>

</xsd:schema>

<!--
The three XML-RPC requirements that cannot be specified in the W3C XML Schema
Language are:

- one of the two members in a fault struct must have the name faultCode and
  an int value and the other must have the name faultString and a string
  value;

- a value element can contain either an ASCII string or a type element such
  as int, but not a type element and an ASCII string;

- strings can contain binary data, except for '&' and '<', which are encoded
  as "&amp;" and "&lt;", respectively.
-->
```

Listing B.3: XML Schema of XML-RPC (unofficial)

B.3 TCPROS syntax

The following is an unofficial EBNF syntax [14] of TCPROS streams.

```
(* Unofficial TCPROS EBNF syntax *)

length      = ? little-endian uint32_t ?;
text        = { ? printable characters ? };
string      = length, text;

header      = length, { eq_field };
eq_field    = length, text, '=', text;

stream      = tpc_stream | srv_stream;  (* root symbol *)

(* Topic stream *)
tpc_stream  = header, { message };
message     = length, contents;
contents    = ? defined by the message descriptor ?;

(* Service stream *)
srv_stream  = header, { transaction };
transaction = request, ok_byte, response;
request     = message;
ok_byte     = ? uint8_t ?;
response    = message | string;
```

Listing B.4: Unofficial EBNF syntax of TCPROS streams

B.4 Case study

This section contains some useful listings extracted from the *Triskar2 teleoperator* application.

B.4.1 Triskar2 message types

The following are the types for velocity and proximity messages of Triskar2.

```
float32 strafe    # Strafe speed (X axis, m/s)
float32 forward   # Forward speed (Y axis, m/s)
float32 angular   # Angular speed (Z axis, rad/s)
```

Listing B.5: Contents of `triskar/msg/Velocity.msg`

```
uint32 NUM_SENSORS  = 4     # Number of proximity sensors

uint32 EAST         = 0     # East index
uint32 NORTH        = 1     # North index
uint32 WEST         = 2     # West index
uint32 SOUTH        = 3     # South index

float32[4] proximities      # Normalized proximities (1.0 far, 0.0 near)
```

Listing B.6: Contents of `triskar/msg/Proximity.msg`

B.4.2 Triskar2 teleoperator node

The following is the complete source code of the teleoperator ROS Node, used to control Triskar2 from remote the *first person* way.

```python
#!/usr/bin/env python
"""
Triskar2 teleoperator node
"""

import math, sys, os, time

import pygame
from pygame.locals import *

import roslib; roslib.load_manifest("triskar")
import rospy
from sensor_msgs.msg import Image
from triskar.msg import Velocity, Proximity

from filters import ExpFilter, SmoothedVec3


# Global constants
SCREEN_SIZE         = ( 640, 480 )
MOUSE_SENS          = ( 0.02, 0.02 )
SP_IMPULSE_SPEED    = ( ( 0.25, 0.25, 0.5 ), ( 1.0, 1.0, 1.0 ) )    # Normal, fast
ROS_TO_SURF_ENC     = { "mono8":"P", "rgb8":"RGB", "bgr8":"BGR", "rgba8":"RGBA" }
EAST = 0; NORTH = 1; WEST = 2; SOUTH = 3
PROXIMITY_THRESHOLD = ( 0.1, 0.1, 0.1, 0.1 )    # Don't move where lower

# Global variables
screen              = None
camera_frame        = None
mouse_grabbed       = False
proximities         = [ 1.0, 1.0, 1.0, 1.0 ]


def camera_frame_cb(msg):
    """ Camera frame callback """
    global camera_frame
    size = (msg.width, msg.height)
    encoding = ROS_TO_SURF_ENC[msg.encoding]
    frame = pygame.image.frombuffer(msg.data, size, encoding)
    frame = pygame.transform.smoothscale(frame, screen.get_size())
    camera_frame = frame.convert()


def proximity_cb(msg):
    """ Proximity sensors callback """
    proximities = msg.proximities[:]


def center_mouse(screenSize):
    """ Centers the mouse """
    pygame.event.set_blocked(MOUSEMOTION)
    pygame.mouse.set_pos((screenSize[0] / 2, screenSize[1] / 2))
    pygame.event.set_allowed(MOUSEMOTION)


def grab_mouse(grabbed):
    """ Grabs/ungrabs the mouse """
    global mouse_grabbed
    if grabbed and not mouse_grabbed:
        mouse_grabbed = True
        pygame.mouse.set_visible(False)
    elif not grabbed and mouse_grabbed:
        mouse_grabbed = False
        pygame.mouse.set_visible(True)


def handle_inputs(sp_accum, sp_impulse):
    """ Processes mouse inputs """

    # Configure mouse movements (accumulated if left button held)
    for i in range(3): sp_impulse[i] = 0.0
    sp_temp = [ 0.0, 0.0, 0.0 ]
    mouse_buttons = pygame.mouse.get_pressed()
    if mouse_buttons[0]:
        mouse_scale = ( 0.1 * MOUSE_SENS[0], 0.1 * MOUSE_SENS[1] )
    else:
        mouse_scale = MOUSE_SENS
        for i in range(3): sp_accum[i] = 0.0

    # Process events since the last call
    for e in pygame.event.get():
        if e.type is QUIT:
            rospy.signal_shutdown("User closed the teleoperator window")
        elif e.type is KEYDOWN:
            grab_mouse(not e.key is K_ESCAPE)
        elif e.type is KEYUP:
            if not e.key is K_ESCAPE: grab_mouse(True)
        elif e.type is MOUSEBUTTONDOWN:
            grab_mouse(True)
        elif e.type is MOUSEBUTTONUP:
            grab_mouse(True)
        elif e.type is MOUSEMOTION and mouse_grabbed:
            screenSize = screen.get_size()
            center_mouse(screenSize)
            sp_temp[1] -= float(e.rel[1]) * mouse_scale[1]      # Fwd / Bwd
            if mouse_buttons[2]: sp_temp[0] += float(e.rel[0]) * mouse_scale[0]  # Strafe
            else:                sp_temp[2] -= float(e.rel[0]) * mouse_scale[0]  # Turn

    # Process keyboard impulses
    keys = pygame.key.get_pressed()
    mods = pygame.key.get_mods()
    gear = int(bool(mods & KMOD_SHIFT))
    if keys[K_d]: sp_impulse[0] += SP_IMPULSE_SPEED[gear][0]
    if keys[K_a]: sp_impulse[0] -= SP_IMPULSE_SPEED[gear][0]
    if keys[K_w]: sp_impulse[1] += SP_IMPULSE_SPEED[gear][1]
    if keys[K_s]: sp_impulse[1] -= SP_IMPULSE_SPEED[gear][1]
    if keys[K_q]: sp_impulse[2] += SP_IMPULSE_SPEED[gear][2]
    if keys[K_e]: sp_impulse[2] -= SP_IMPULSE_SPEED[gear][2]

    # Apply mouse movements (either accumulated motion or impulses)
    if mouse_buttons[0]:
        for i in range(3): sp_accum[i] += sp_temp[i]
    else:
        for i in range(3): sp_impulse[i] += sp_temp[i]

    # Block movements towards constrained directions
    if proximities[EAST] < PROXIMITY_THRESHOLD[EAST]:
        sp_accum[0]   = min(0.0, sp_accum[0])
        sp_impulse[0] = min(0.0, sp_impulse[0])
    if proximities[WEST] < PROXIMITY_THRESHOLD[WEST]:
        sp_accum[0]   = max(0.0, sp_accum[0])
        sp_impulse[0] = max(0.0, sp_impulse[0])
    if proximities[NORTH] < PROXIMITY_THRESHOLD[NORTH]:
        sp_accum[1]   = min(0.0, sp_accum[1])
        sp_impulse[1] = min(0.0, sp_impulse[1])
    if proximities[SOUTH] < PROXIMITY_THRESHOLD[SOUTH]:
        sp_accum[1]   = max(0.0, sp_accum[1])
        sp_impulse[1] = max(0.0, sp_impulse[1])


def draw_circle_arc(surface, color, pos, radius, start, stop, width=0):
    """ Draws a centered arc """
    rect = ((pos[0] - radius, pos[1] - radius), (2 * radius, 2 * radius))
    if start > stop: (start, stop) = (stop, start)
    pygame.draw.arc(screen, 0x0000FF, rect, start, stop, width)


def render_scene(screen, setpoint):
    """ Renders the current screen frame """
    screen.fill(0x808080)
    screen.blit(camera_frame, ( 0, 0 ))

    c = screen.get_size()
    c = ( c[0] / 2, c[1] / 2 )
    r = min([ 64, c[0], c[1] ])
    pygame.draw.line(screen, 0xFF0000, c, (int(c[0] + r * setpoint[0]), c[1]), 2)
    pygame.draw.line(screen, 0x00FF00, c, (c[0], int(c[1] - r * setpoint[1])), 2)
    draw_circle_arc(screen, 0x0000FF, c, r, math.pi/2, math.pi/2 + setpoint[2], 2)
    pygame.draw.circle(screen, 0xFFFFFF, c, 2)


def main():
    # Initialize pygame stuff
    global screen, camera_frame
    pygame.init()
    clock = pygame.time.Clock()
    screen = pygame.display.set_mode(SCREEN_SIZE)
    screen.fill(0x808080)
    pygame.display.flip()
    pygame.display.set_caption("Triskar2 teleoperator")
    pygame.mouse.set_visible(True)
    camera_frame = pygame.Surface(( 1, 1 )).convert()   # Fake camera frame placeholder

    # Initialize ROS stuff
    rospy.init_node("teleop_node")
    pubVelocity = rospy.Publisher("triskar/velocity", Velocity)
    pubVelocity.publish(Velocity(0.0, 0.0, 0.0))
    rospy.Subscriber("triskar/front_camera", Image, camera_frame_cb)
    rospy.Subscriber("triskar/proximity", Proximity, proximity_cb)

    # Initialize setpoints
    sp_impulse = [ 0.0, 0.0, 0.0 ]
    sp_accum = [ 0.0, 0.0, 0.0 ]
    sp_smooth = SmoothedVec3(ExpFilter(1.0 / 60, 1.0, 0.000001), sp_accum)

    while not rospy.is_shutdown():
        # Process inputs
        handle_inputs(sp_accum, sp_impulse)
        if rospy.is_shutdown(): break
        sp = sp_smooth.process([ sp_impulse[i] + sp_accum[i] for i in range(3) ])
        pubVelocity.publish(Velocity(sp[0], sp[1], sp[2]))

        # Render the scene
        render_scene(screen, sp)
        pygame.display.flip()
        clock.tick(60)

    # Stop the robot
    pubVelocity.publish(Velocity(0.0, 0.0, 0.0))


# Call the 'main' function when this script is executed
if __name__ == "__main__":
    try: main()
    except rospy.ROSInterruptException: pass
```

Listing B.7: Source code of the Triskar2 teleoperator node (`triskar/teleop_node`)

B.4.3 Triskar2 `urosgen` configuration

The following is the `urosgen` configuration for the Triskar2 µROSnode-based firmware.

```
# urosgen.py configuration file for Triskar2

[Options]
author                      = Andrea Zoppi <texzk@email.it>
licenseFile                 = ../../COPYING
includeDir                  = ../include
sourceDir                   = ../src
nodeName                    = triskar_node
fieldComments               = false

msgOnStack                  = true
inOnStack                   = true
outOnStack                  = true

[PubTopics]
/triskar/proximity          = triskar/Proximity

[SubTopics]
/triskar/velocity           = triskar/Velocity

[PubServices]

[CallServices]
```

Listing B.8: `urosgen` configuration file for the Triskar2 µROSnode-based firmware

B.4.4 Triskar2 gateway handler routines

The following are the topic handlers for the Triskar2 teleoperator application, which translate R2P messages to ROS messages, and vice versa.

```c
uros_err_t sub_tpc__triskar__velocity(UrosTcpRosStatus *tcpstp) {

  /* Message allocation and initialization.*/
  UROS_TPC_INIT_S(msg__triskar__Velocity);
  SpeedSetpoint3 *r2p_msg;

  /* Subscribed messages loop.*/
  while (!urosTcpRosStatusCheckExit(tcpstp)) {
    /* Receive the next message.*/
    UROS_MSG_RECV_LENGTH();
    UROS_MSG_RECV_BODY(&msg, msg__triskar__Velocity);

    /* Republish the received ROS message to R2P DC motor modules.*/
    r2p_msg = lpubSpeeds.alloc();
    if (r2p_msg != NULL) {
      velocity_to_setpoints(msg, *r2p_msg);
      lpubSpeeds.broadcast(r2p_msg);
      palTogglePad(GPIOC, GPIOC_LED2);
    }

    /* Dispose the contents of the message.*/
    clean_msg__triskar__Velocity(&msg);
  }
  tcpstp->err = UROS_OK;

_finally:
  /* Message deinitialization and deallocation.*/
  UROS_TPC_UNINIT_S(msg__triskar__Velocity);
  return tcpstp->err;
}
```

Listing B.9: Publication handler function for the `/triskar/velocity` ROS topic

```
uros_err_t pub_tpc__triskar__proximity(UrosTcpRosStatus *tcpstp) {

  /* Message allocation and initialization.*/
  UROS_TPC_INIT_S(msg__triskar__Proximity);
  IRRaw *r2p_msg;
  Subscriber<IRRaw, 8> lsubProximity("IRRaw");
  Node mwNode("mwNode");
  Middleware::instance().newNode(&mwNode);
  mwNode.subscribe(&lsubProximity);

  /* Published messages loop.*/
  while (!urosTcpRosStatusCheckExit(tcpstp)) {
    /* Republish the received R2P raw proximity message to ROS.*/
    mwNode.spin(MS2ST(1000));
    r2p_msg = lsubProximity.get();
    if (r2p_msg != NULL) {
      irraw_to_proximities(*r2p_msg, msg);
      lsubProximity.release(r2p_msg);

      /* Send the message.*/
      UROS_MSG_SEND_LENGTH(&msg, msg__triskar__Proximity);
      UROS_MSG_SEND_BODY(&msg, msg__triskar__Proximity);

      /* Dispose the contents of the message.*/
      clean_msg__triskar__Proximity(&msg);
    }
  }
  tcpstp->err = UROS_OK;

_finally:
  /* Message deinitialization and deallocation.*/
  UROS_TPC_UNINIT_S(msg__triskar__Proximity);
  return tcpstp->err;
}
```

Listing B.10: Subscription handler function for the `/triskar/proximity` ROS topic

B.5 Code generator configuration demo

The following is a demonstration configuration file for the code generator, `urosgen.py`. All of the possible options are listed and commented. The chosen data types involve all of the code generator features.

```
# urosgen.py configuration file, for demonstration purposes.

# This is the options section. All the options are assigned below. An undefined
# option is assigned its default value. Run urosgen.py without arguments to see
# their default values.
[Options]

# Author of the generated files
author              = Your Name <your.email@example.com>

# Optional license text file to comment at the beginning of generated files
licenseFile         = ../../../COPYING

# Name of the generated node
nodeName            = uros_demo_node

# Paths of the generated files, relative to this configuration file
includeDir          = .                     # Header files path (must exist!)
sourceDir           = .                     # Source files path (must exist!)

# File names for "<filename>.h" and "<filename>.c" generation
msgTypesFilename    = urosMsgTypes          # Message types file name
handlersFilename    = urosHandlers          # Handlers file name

# Generation switches
genMsgTypesHeader   = true
genMsgTypesSource   = true
genHandlersHeader   = true
genHandlersSource   = true

# Allocates the message/service values on the stack instead of into the heap
msgOnStack          = false                 # All the topic messages
inOnStack           = false                 # All the service requests (in)
outOnStack          = true                  # All the service responses (out)

# Base name of handler variables. Depending on the stack/heap options, they
# will be declared as: [*namep = NULL] if in heap, [name] if on stack.
msgVarBaseName      = msg                   # Topic message variable name
inVarBaseName       = inmsg                 # Service request variable name
outVarBaseName      = outmsg                # Service response variable name

# Generates comments above the declaration of each structure field
fieldComments       = true

# Generated function names
regTypesFuncName          = urosMsgTypesRegStaticTypes
regPubTopicsFuncName      = urosHandlersPublishTopics
unregPubTopicsFuncName    = urosHandlersUnpublishTopics
regSubTopicsFuncName      = urosHandlersSubscribeTopics
unregSubTopicsFuncName    = urosHandlersUnsubscribeTopics
regPubServicesFuncName    = urosHandlersPublishServices
unregPubServicesFuncName  = urosHandlersUnpublishServices


# List of published topics, in the form: <name> = <type>
[PubTopics]
output      = stereo_msgs/DisparityImage    # 3 levels deep type
rosout      = rosgraph_msgs/Log             # A common type


# List of subscribed topics, in the form: <name> = <type>
[SubTopics]
input       = stereo_msgs/DisparityImage    # Just to check
constants   = bond/Constants                # This type defines only constants
rosin       = rosgraph_msgs/Log             # Just to check


# List of published services, in the form: <name> = <type>
[PubServices]
reconfigure = dynamic_reconfigure/Reconfigure # 3 levels deep type


# List of services called by the node, in the form: <name> = <type>
[CallServices]
reconfigure = dynamic_reconfigure/Reconfigure # Just to check
```

Listing B.11: Documented demo configuration file for `urosgen.py`, with complex types

B.6 Stack usage analyzer configuration demo

The following is the configuration file for the static stack analysis tool, `urosstan.py`, used to analyze the *turtlesim* [7] demonstration project for the R2P_GW [29] project.

```
# urosstan.py demo configuration file for turtlesim

# List of options for urosstan.py
[Options]

# Output directory (must exist!), relative to this configuration file
outDir = ../build/obj

# Reference Makefile location, relative to this configuration file
makefileDir = ..

# Known graph leafs (terminators), in the form: <function> = <usage>
# where <function> is unmangled (see GKD/SU) and globally defined
[Terminators]
_port_switch = 36   # sizeof(intctx), no FPU, naked


# List of starting functions, in the form: <function> = <usage_bias>
[EntryPoints]
main = 36
lwip_thread = 36
urosThreadPoolWorkerThread = 36
urosNodeThread = 240
urosRpcSlaveServerThread = 240
urosRpcSlaveListenerThread = 240
urosTcpRosListenerThread = 240

pub_tpc__rosout = 240
pub_tpc__turtleX__pose = 240
pub_tpc__turtleX__color_sensor = 240

sub_tpc__turtleX__command_velocity = 240

pub_srv__clear = 240
pub_srv__kill = 240
pub_srv__spawn = 240
pub_srv__turtleX__set_pen = 240
pub_srv__turtleX__teleport_absolute = 240
pub_srv__turtleX__teleport_relative = 240


# List of source units to be analyzed, in the form:
# <*.c[pp]> = <*.gkd> | <*.su> | <*.nm>
# where paths are relative to the Makefile
[SourceUnits]
"../../../../os/ports/GCC/ARMCMx/crt0.c" = "./build/obj/crt0.o.gkd" |
"./build/obj/crt0.su" | "./build/obj/crt0.o.nm"
"../../../../os/ports/GCC/ARMCMx/STM32F4xx/vectors.c" = "./build/obj/vectors.o.gkd" |
"./build/obj/vectors.su" | "./build/obj/vectors.o.nm"
"../../../../os/ports/GCC/ARMCMx/chcore.c" = "./build/obj/chcore.o.gkd" |
"./build/obj/chcore.su" | "./build/obj/chcore.o.nm"
"../../../../os/ports/GCC/ARMCMx/chcore_v7m.c" = "./build/obj/chcore_v7m.o.gkd" |
"./build/obj/chcore_v7m.su" | "./build/obj/chcore_v7m.o.nm"
"../../../../os/ports/common/ARMCMx/nvic.c" = "./build/obj/nvic.o.gkd" |
"./build/obj/nvic.su" | "./build/obj/nvic.o.nm"
"../../../../os/kernel/src/chsys.c" = "./build/obj/chsys.o.gkd" |
"./build/obj/chsys.su" | "./build/obj/chsys.o.nm"
"../../../../os/kernel/src/chdebug.c" = "./build/obj/chdebug.o.gkd" |
"./build/obj/chdebug.su" | "./build/obj/chdebug.o.nm"
"../../../../os/kernel/src/chlists.c" = "./build/obj/chlists.o.gkd" |
"./build/obj/chlists.su" | "./build/obj/chlists.o.nm"
"../../../../os/kernel/src/chvt.c" = "./build/obj/chvt.o.gkd" |
"./build/obj/chvt.su" | "./build/obj/chvt.o.nm"
"../../../../os/kernel/src/chschd.c" = "./build/obj/chschd.o.gkd" |
"./build/obj/chschd.su" | "./build/obj/chschd.o.nm"
"../../../../os/kernel/src/chthreads.c" = "./build/obj/chthreads.o.gkd" |
"./build/obj/chthreads.su" | "./build/obj/chthreads.o.nm"
"../../../../os/kernel/src/chdynamic.c" = "./build/obj/chdynamic.o.gkd" |
"./build/obj/chdynamic.su" | "./build/obj/chdynamic.o.nm"
"../../../../os/kernel/src/chregistry.c" = "./build/obj/chregistry.o.gkd" |
"./build/obj/chregistry.su" | "./build/obj/chregistry.o.nm"
"../../../../os/kernel/src/chsem.c" = "./build/obj/chsem.o.gkd" |
"./build/obj/chsem.su" | "./build/obj/chsem.o.nm"
"../../../../os/kernel/src/chmtx.c" = "./build/obj/chmtx.o.gkd" |
"./build/obj/chmtx.su" | "./build/obj/chmtx.o.nm"
"../../../../os/kernel/src/chcond.c" = "./build/obj/chcond.o.gkd" |
"./build/obj/chcond.su" | "./build/obj/chcond.o.nm"
"../../../../os/kernel/src/chevents.c" = "./build/obj/chevents.o.gkd" |
"./build/obj/chevents.su" | "./build/obj/chevents.o.nm"
"../../../../os/kernel/src/chmsg.c" = "./build/obj/chmsg.o.gkd" |
"./build/obj/chmsg.su" | "./build/obj/chmsg.o.nm"
"../../../../os/kernel/src/chmboxes.c" = "./build/obj/chmboxes.o.gkd" |
"./build/obj/chmboxes.su" | "./build/obj/chmboxes.o.nm"
"../../../../os/kernel/src/chqueues.c" = "./build/obj/chqueues.o.gkd" |
"./build/obj/chqueues.su" | "./build/obj/chqueues.o.nm"
"../../../../os/kernel/src/chmemcore.c" = "./build/obj/chmemcore.o.gkd" |
"./build/obj/chmemcore.su" | "./build/obj/chmemcore.o.nm"
"../../../../os/kernel/src/chheap.c" = "./build/obj/chheap.o.gkd" |
"./build/obj/chheap.su" | "./build/obj/chheap.o.nm"
"../../../../os/kernel/src/chmempools.c" = "./build/obj/chmempools.o.gkd" |
"./build/obj/chmempools.su" | "./build/obj/chmempools.o.nm"
"../../../../test/test.c" = "./build/obj/test.o.gkd" |
"./build/obj/test.su" | "./build/obj/test.o.nm"
"../../../../test/testthd.c" = "./build/obj/testthd.o.gkd" |
"./build/obj/testthd.su" | "./build/obj/testthd.o.nm"
"../../../../test/testsem.c" = "./build/obj/testsem.o.gkd" |
"./build/obj/testsem.su" | "./build/obj/testsem.o.nm"
"../../../../test/testmtx.c" = "./build/obj/testmtx.o.gkd" |
"./build/obj/testmtx.su" | "./build/obj/testmtx.o.nm"
```

```
"../../../../test/testmsg.c" = "./build/obj/testmsg.o.gkd" | "./build/obj/testmsg.su" | "./build/obj/testmsg.o.nm"
"../../../../test/testmbox.c" = "./build/obj/testmbox.o.gkd" | "./build/obj/testmbox.su" | "./build/obj/testmbox.o.nm"
"../../../../test/testevt.c" = "./build/obj/testevt.o.gkd" | "./build/obj/testevt.su" | "./build/obj/testevt.o.nm"
"../../../../test/testheap.c" = "./build/obj/testheap.o.gkd" | "./build/obj/testheap.su" | "./build/obj/testheap.o.nm"
"../../../../test/testpools.c" = "./build/obj/testpools.o.gkd" | "./build/obj/testpools.su" | "./build/obj/testpools.o.nm"
"../../../../test/testdyn.c" = "./build/obj/testdyn.o.gkd" | "./build/obj/testdyn.su" | "./build/obj/testdyn.o.nm"
"../../../../test/testqueues.c" = "./build/obj/testqueues.o.gkd" | "./build/obj/testqueues.su" | "./build/obj/testqueues.o.nm"
"../../../../test/testbmk.c" = "./build/obj/testbmk.o.gkd" | "./build/obj/testbmk.su" | "./build/obj/testbmk.o.nm"
"../../../../os/hal/src/hal.c" = "./build/obj/hal.o.gkd" | "./build/obj/hal.su" | "./build/obj/hal.o.nm"
"../../../../os/hal/src/adc.c" = "./build/obj/adc.o.gkd" | "./build/obj/adc.su" | "./build/obj/adc.o.nm"
"../../../../os/hal/src/can.c" = "./build/obj/can.o.gkd" | "./build/obj/can.su" | "./build/obj/can.o.nm"
"../../../../os/hal/src/ext.c" = "./build/obj/ext.o.gkd" | "./build/obj/ext.su" | "./build/obj/ext.o.nm"
"../../../../os/hal/src/gpt.c" = "./build/obj/gpt.o.gkd" | "./build/obj/gpt.su" | "./build/obj/gpt.o.nm"
"../../../../os/hal/src/i2c.c" = "./build/obj/i2c.o.gkd" | "./build/obj/i2c.su" | "./build/obj/i2c.o.nm"
"../../../../os/hal/src/icu.c" = "./build/obj/icu.o.gkd" | "./build/obj/icu.su" | "./build/obj/icu.o.nm"
"../../../../os/hal/src/mac.c" = "./build/obj/mac.o.gkd" | "./build/obj/mac.su" | "./build/obj/mac.o.nm"
"../../../../os/hal/src/mmc_spi.c" = "./build/obj/mmc_spi.o.gkd" | "./build/obj/mmc_spi.su" | "./build/obj/mmc_spi.o.nm"
"../../../../os/hal/src/mmcsd.c" = "./build/obj/mmcsd.o.gkd" | "./build/obj/mmcsd.su" | "./build/obj/mmcsd.o.nm"
"../../../../os/hal/src/pal.c" = "./build/obj/pal.o.gkd" | "./build/obj/pal.su" | "./build/obj/pal.o.nm"
"../../../../os/hal/src/pwm.c" = "./build/obj/pwm.o.gkd" | "./build/obj/pwm.su" | "./build/obj/pwm.o.nm"
"../../../../os/hal/src/rtc.c" = "./build/obj/rtc.o.gkd" | "./build/obj/rtc.su" | "./build/obj/rtc.o.nm"
"../../../../os/hal/src/sdc.c" = "./build/obj/sdc.o.gkd" | "./build/obj/sdc.su" | "./build/obj/sdc.o.nm"
"../../../../os/hal/src/serial.c" = "./build/obj/serial.o.gkd" | "./build/obj/serial.su" | "./build/obj/serial.o.nm"
"../../../../os/hal/src/serial_usb.c" = "./build/obj/serial_usb.o.gkd" | "./build/obj/serial_usb.su" | "./build/obj/serial_usb.o.nm"
"../../../../os/hal/src/spi.c" = "./build/obj/spi.o.gkd" | "./build/obj/spi.su" | "./build/obj/spi.o.nm"
"../../../../os/hal/src/tm.c" = "./build/obj/tm.o.gkd" | "./build/obj/tm.su" | "./build/obj/tm.o.nm"
"../../../../os/hal/src/uart.c" = "./build/obj/uart.o.gkd" | "./build/obj/uart.su" | "./build/obj/uart.o.nm"
"../../../../os/hal/src/usb.c" = "./build/obj/usb.o.gkd" | "./build/obj/usb.su" | "./build/obj/usb.o.nm"
"../../../../os/hal/platforms/STM32F4xx/stm32_dma.c" = "./build/obj/stm32_dma.o.gkd" | "./build/obj/stm32_dma.su" | "./build/obj/stm32_dma.o.nm"
"../../../../os/hal/platforms/STM32F4xx/hal_lld.c" = "./build/obj/hal_lld.o.gkd" | "./build/obj/hal_lld.su" | "./build/obj/hal_lld.o.nm"
"../../../../os/hal/platforms/STM32F4xx/adc_lld.c" = "./build/obj/adc_lld.o.gkd" | "./build/obj/adc_lld.su" | "./build/obj/adc_lld.o.nm"
"../../../../os/hal/platforms/STM32F4xx/ext_lld_isr.c" = "./build/obj/ext_lld_isr.o.gkd" | "./build/obj/ext_lld_isr.su" | "./build/obj/ext_lld_isr.o.nm"
"../../../../os/hal/platforms/STM32/can_lld.c" = "./build/obj/can_lld.o.gkd" | "./build/obj/can_lld.su" | "./build/obj/can_lld.o.nm"
"../../../../os/hal/platforms/STM32/ext_lld.c" = "./build/obj/ext_lld.o.gkd" | "./build/obj/ext_lld.su" | "./build/obj/ext_lld.o.nm"
"../../../../os/hal/platforms/STM32/gpt_lld.c" = "./build/obj/gpt_lld.o.gkd" | "./build/obj/gpt_lld.su" | "./build/obj/gpt_lld.o.nm"
"../../../../os/hal/platforms/STM32/icu_lld.c" = "./build/obj/icu_lld.o.gkd" | "./build/obj/icu_lld.su" | "./build/obj/icu_lld.o.nm"
"../../../../os/hal/platforms/STM32/mac_lld.c" = "./build/obj/mac_lld.o.gkd" | "./build/obj/mac_lld.su" | "./build/obj/mac_lld.o.nm"
"../../../../os/hal/platforms/STM32/pwm_lld.c" = "./build/obj/pwm_lld.o.gkd" | "./build/obj/pwm_lld.su" | "./build/obj/pwm_lld.o.nm"
"../../../../os/hal/platforms/STM32/sdc_lld.c" = "./build/obj/sdc_lld.o.gkd" | "./build/obj/sdc_lld.su" | "./build/obj/sdc_lld.o.nm"
"../../../../os/hal/platforms/STM32/GPIOv2/pal_lld.c" = "./build/obj/pal_lld.o.gkd" | "./build/obj/pal_lld.su" | "./build/obj/pal_lld.o.nm"
"../../../../os/hal/platforms/STM32/I2Cv1/i2c_lld.c" = "./build/obj/i2c_lld.o.gkd" | "./build/obj/i2c_lld.su" | "./build/obj/i2c_lld.o.nm"
"../../../../os/hal/platforms/STM32/OTGv1/usb_lld.c" = "./build/obj/usb_lld.o.gkd" | "./build/obj/usb_lld.su" | "./build/obj/usb_lld.o.nm"
"../../../../os/hal/platforms/STM32/RTCv2/rtc_lld.c" = "./build/obj/rtc_lld.o.gkd" | "./build/obj/rtc_lld.su" | "./build/obj/rtc_lld.o.nm"
"../../../../os/hal/platforms/STM32/SPIv1/spi_lld.c" = "./build/obj/spi_lld.o.gkd" | "./build/obj/spi_lld.su" | "./build/obj/spi_lld.o.nm"
"../../../../os/hal/platforms/STM32/USARTv1/serial_lld.c" = "./build/obj/serial_lld.o.gkd" | "./build/obj/serial_lld.su" | "./build/obj/serial_lld.o.nm"
"../../../../os/hal/platforms/STM32/USARTv1/uart_lld.c" = "./build/obj/uart_lld.o.gkd" | "./build/obj/uart_lld.su" | "./build/obj/uart_lld.o.nm"
"../../../../os/various/lwip_bindings/lwipthread.c" = "./build/obj/lwipthread.o.gkd" | "./build/obj/lwipthread.su" | "./build/obj/lwipthread.o.nm"
"../../../../os/various/lwip_bindings/arch/sys_arch.c" = "./build/obj/sys_arch.o.gkd" | "./build/obj/sys_arch.su" | "./build/obj/sys_arch.o.nm"
"../../../../ext/lwip/src/netif/etharp.c" = "./build/obj/etharp.o.gkd" | "./build/obj/etharp.su" | "./build/obj/etharp.o.nm"
"../../../../ext/lwip/src/core/dhcp.c" = "./build/obj/dhcp.o.gkd" | "./build/obj/dhcp.su" | "./build/obj/dhcp.o.nm"
"../../../../ext/lwip/src/core/dns.c" = "./build/obj/dns.o.gkd" | "./build/obj/dns.su" | "./build/obj/dns.o.nm"
"../../../../ext/lwip/src/core/init.c" = "./build/obj/init.o.gkd" | "./build/obj/init.su" | "./build/obj/init.o.nm"
"../../../../ext/lwip/src/core/mem.c" = "./build/obj/mem.o.gkd" | "./build/obj/mem.su" | "./build/obj/mem.o.nm"
"../../../../ext/lwip/src/core/memp.c" = "./build/obj/memp.o.gkd" | "./build/obj/memp.su" | "./build/obj/memp.o.nm"
"../../../../ext/lwip/src/core/netif.c" = "./build/obj/netif.o.gkd" | "./build/obj/netif.su" | "./build/obj/netif.o.nm"
"../../../../ext/lwip/src/core/pbuf.c" = "./build/obj/pbuf.o.gkd" | "./build/obj/pbuf.su" | "./build/obj/pbuf.o.nm"
"../../../../ext/lwip/src/core/raw.c" = "./build/obj/raw.o.gkd" | "./build/obj/raw.su" | "./build/obj/raw.o.nm"
"../../../../ext/lwip/src/core/stats.c" = "./build/obj/stats.o.gkd" | "./build/obj/stats.su" | "./build/obj/stats.o.nm"
"../../../../ext/lwip/src/core/sys.c" = "./build/obj/sys.o.gkd" | "./build/obj/sys.su" | "./build/obj/sys.o.nm"
"../../../../ext/lwip/src/core/tcp.c" = "./build/obj/tcp.o.gkd" |
"./build/obj/tcp.su" | "./build/obj/tcp.o.nm"
"../../../../ext/lwip/src/core/tcp_in.c" = "./build/obj/tcp_in.o.gkd" |
"./build/obj/tcp_in.su" | "./build/obj/tcp_in.o.nm"
"../../../../ext/lwip/src/core/tcp_out.c" = "./build/obj/tcp_out.o.gkd" |
"./build/obj/tcp_out.su" | "./build/obj/tcp_out.o.nm"
"../../../../ext/lwip/src/core/udp.c" = "./build/obj/udp.o.gkd" |
"./build/obj/udp.su" | "./build/obj/udp.o.nm"
"../../../../ext/lwip/src/core/ipv4/autoip.c" = "./build/obj/autoip.o.gkd" |
"./build/obj/autoip.su" | "./build/obj/autoip.o.nm"
"../../../../ext/lwip/src/core/ipv4/icmp.c" = "./build/obj/icmp.o.gkd" |
"./build/obj/icmp.su" | "./build/obj/icmp.o.nm"
"../../../../ext/lwip/src/core/ipv4/igmp.c" = "./build/obj/igmp.o.gkd" |
"./build/obj/igmp.su" | "./build/obj/igmp.o.nm"
"../../../../ext/lwip/src/core/ipv4/inet.c" = "./build/obj/inet.o.gkd" |
"./build/obj/inet.su" | "./build/obj/inet.o.nm"
"../../../../ext/lwip/src/core/ipv4/inet_chksum.c" = "./build/obj/inet_chksum.o.gkd" |
"./build/obj/inet_chksum.su" | "./build/obj/inet_chksum.o.nm"
"../../../../ext/lwip/src/core/ipv4/ip.c" = "./build/obj/ip.o.gkd" |
"./build/obj/ip.su" | "./build/obj/ip.o.nm"
"../../../../ext/lwip/src/core/ipv4/ip_addr.c" = "./build/obj/ip_addr.o.gkd" |
"./build/obj/ip_addr.su" | "./build/obj/ip_addr.o.nm"
"../../../../ext/lwip/src/core/ipv4/ip_frag.c" = "./build/obj/ip_frag.o.gkd" |
"./build/obj/ip_frag.su" | "./build/obj/ip_frag.o.nm"
"../../../../ext/lwip/src/core/def.c" = "./build/obj/def.o.gkd" |
"./build/obj/def.su" | "./build/obj/def.o.nm"
"../../../../ext/lwip/src/core/timers.c" = "./build/obj/timers.o.gkd" |
"./build/obj/timers.su" | "./build/obj/timers.o.nm"
"../../../../ext/lwip/src/api/api_lib.c" = "./build/obj/api_lib.o.gkd" |
"./build/obj/api_lib.su" | "./build/obj/api_lib.o.nm"
"../../../../ext/lwip/src/api/api_msg.c" = "./build/obj/api_msg.o.gkd" |
"./build/obj/api_msg.su" | "./build/obj/api_msg.o.nm"
"../../../../ext/lwip/src/api/err.c" = "./build/obj/err.o.gkd" |
"./build/obj/err.su" | "./build/obj/err.o.nm"
"../../../../ext/lwip/src/api/netbuf.c" = "./build/obj/netbuf.o.gkd" |
"./build/obj/netbuf.su" | "./build/obj/netbuf.o.nm"
"../../../../ext/lwip/src/api/netdb.c" = "./build/obj/netdb.o.gkd" |
"./build/obj/netdb.su" | "./build/obj/netdb.o.nm"
"../../../../ext/lwip/src/api/netifapi.c" = "./build/obj/netifapi.o.gkd" |
"./build/obj/netifapi.su" | "./build/obj/netifapi.o.nm"
"../../../../ext/lwip/src/api/sockets.c" = "./build/obj/sockets.o.gkd" |
"./build/obj/sockets.su" | "./build/obj/sockets.o.nm"
"../../../../ext/lwip/src/api/tcpip.c" = "./build/obj/tcpip.o.gkd" |
"./build/obj/tcpip.su" | "./build/obj/tcpip.o.nm"
"../../../../os/various/evtimer.c" = "./build/obj/evtimer.o.gkd" |
"./build/obj/evtimer.su" | "./build/obj/evtimer.o.nm"
"../../../../os/various/chprintf.c" = "./build/obj/chprintf.o.gkd" |
"./build/obj/chprintf.su" | "./build/obj/chprintf.o.nm"
"../../../../os/various/shell.c" = "./build/obj/shell.o.gkd" |
"./build/obj/shell.su" | "./build/obj/shell.o.nm"
"../../src/urosBase.c" = "./build/obj/urosBase.o.gkd" |
"./build/obj/urosBase.su" | "./build/obj/urosBase.o.nm"
"../../src/urosConn.c" = "./build/obj/urosConn.o.gkd" |
"./build/obj/urosConn.su" | "./build/obj/urosConn.o.nm"
"../../src/urosNode.c" = "./build/obj/urosNode.o.gkd" |
"./build/obj/urosNode.su" | "./build/obj/urosNode.o.nm"
"../../src/urosRpcCall.c" = "./build/obj/urosRpcCall.o.gkd" |
"./build/obj/urosRpcCall.su" | "./build/obj/urosRpcCall.o.nm"
"../../src/urosRpcParser.c" = "./build/obj/urosRpcParser.o.gkd" |
"./build/obj/urosRpcParser.su" | "./build/obj/urosRpcParser.o.nm"
"../../src/urosRpcSlave.c" = "./build/obj/urosRpcSlave.o.gkd" |
"./build/obj/urosRpcSlave.su" | "./build/obj/urosRpcSlave.o.nm"
"../../src/urosRpcStreamer.c" = "./build/obj/urosRpcStreamer.o.gkd" |
"./build/obj/urosRpcStreamer.su" | "./build/obj/urosRpcStreamer.o.nm"
"../../src/urosTcpRos.c" = "./build/obj/urosTcpRos.o.gkd" |
"./build/obj/urosTcpRos.su" | "./build/obj/urosTcpRos.o.nm"
"../../src/urosThreading.c" = "./build/obj/urosThreading.o.gkd" |
"./build/obj/urosThreading.su" | "./build/obj/urosThreading.o.nm"
"../../src/lld/chibios/uros_lld_base.c" = "./build/obj/uros_lld_base.o.gkd" |
"./build/obj/uros_lld_base.su" | "./build/obj/uros_lld_base.o.nm"
"../../src/lld/chibios/uros_lld_threading.c" = "./build/obj/uros_lld_threading.o.gkd" |
"./build/obj/uros_lld_threading.su" | "./build/obj/uros_lld_threading.o.nm"
"../../src/lld/lwip/uros_lld_conn.c" = "./build/obj/uros_lld_conn.o.gkd" |
"./build/obj/uros_lld_conn.su" | "./build/obj/uros_lld_conn.o.nm"
"./src/board.c" = "./build/obj/board.o.gkd" |
"./build/obj/board.su" | "./build/obj/board.o.nm"
"./src/main.c" = "./build/obj/main.o.gkd" |
"./build/obj/main.su" | "./build/obj/main.o.nm"
"./src/usbcfg.c" = "./build/obj/usbcfg.o.gkd" |
"./build/obj/usbcfg.su" | "./build/obj/usbcfg.o.nm"
"./src/urosUser.c" = "./build/obj/urosUser.o.gkd" |
"./build/obj/urosUser.su" | "./build/obj/urosUser.o.nm"
"./src/urosMsgTypes.c" = "./build/obj/urosMsgTypes.o.gkd" |
"./build/obj/urosMsgTypes.su" | "./build/obj/urosMsgTypes.o.nm"
"./src/urosHandlers.c" = "./build/obj/urosHandlers.o.gkd" |
"./build/obj/urosHandlers.su" | "./build/obj/urosHandlers.o.nm"
"./src/app.c" = "./build/obj/app.o.gkd" |
"./build/obj/app.su" | "./build/obj/app.o.nm"
```

Listing B.12: Documented demo configuration file for `urosstan.py`, turtlesim *running on* ChibiOS/RT