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Cross-Compiling ROS2 Humble to WebAssembly for the Development of a Web Browser Supported Robotics Environment

Master Thesis

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Aachen, 31 March 2023

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Contents

List of abbreviations

General abbreviations

GUI	Graphical User Interface
LIFO	Last In, First Out
ROS	Robot Operating System
UI	User Interface
URDF	Universal Robotic Description Format
WASM	Web Assembly
emsdk	Emscripten SDK
SDK	Software Development Kit
JSON	JavaScript Object Notation
API	Application Programming Interface
VM	Virtual Machine
D3wasm	Doom 3 WebAssembly
MVP	Minimum Viable Product
DDS	Data-Distribution Service
OMG	Object Management Group
HTML	HyperText Markup Language
IDL	Interface Description Language
TCPROS	Transmission Control Protocol ROS
RTI	Real-Time Innovations
RTPS	Real-Time Publish Subscribe Protocol
DCPS	Data-Centric Publish Subscribe
QoS	Quality of Service
WebDDS	Web-Enabled DDS
RMW	ROS Middleware

1. Introduction

1.1. Robot Operating System 2

Robot Operating System (ROS) 2

1.2. Motivation

Web Assembly (WASM)

2. Relevant Works

TODO: Some intro

2.1. ROS on Web

The closest representation of the intended project is the work produced by Michael Allwright known as *ROS on Web*. Allwright shares the same goal as the author to develop the technology which allows for running ROS nodes entirely on the browser by cross-compiling C++ code to WebAssembly and using web workers to handle the internal communication [All23].

Equivalently, Allwright targeted the ROS 2 distribution. It is suspected that the *galactic* version was used for the demonstrations. The main demonstration of a running publisher and subscriber is illustrated in Figure 2.1.

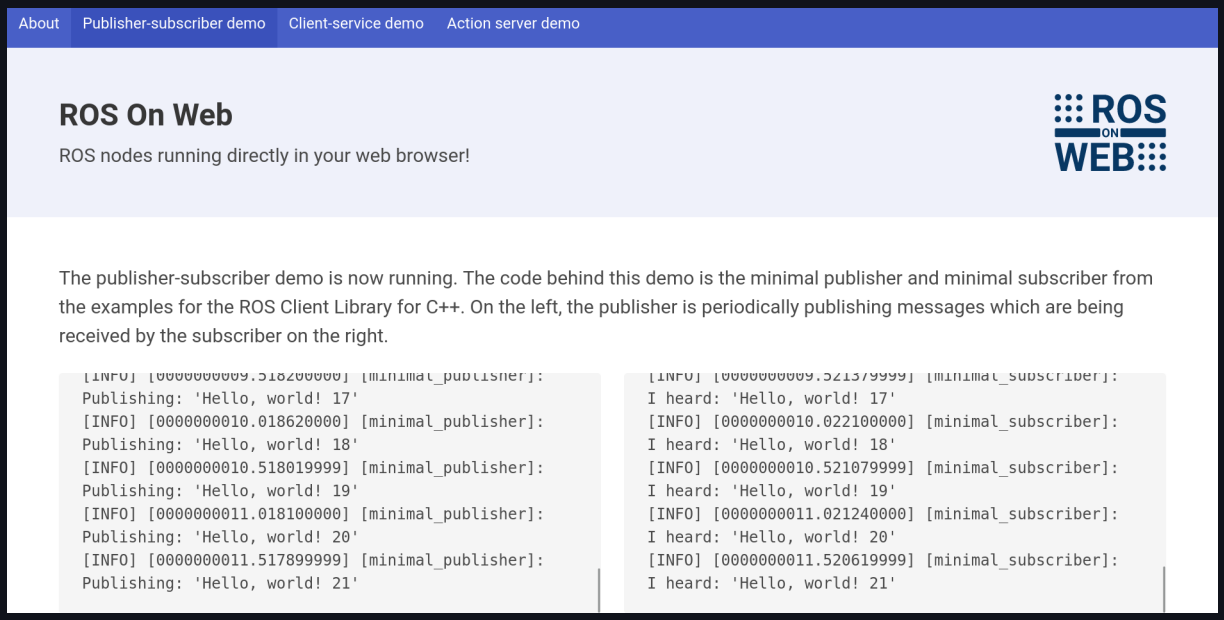


Figure 2.1. *ROS on Web* publisher and subscriber demonstration.

Nonetheless, the greatest disadvantage of *ROS on Web* lies in the fact that the project is not open source. Very little can be derived about how Allwright was able to achieve the demonstrations represented on the website. A few hints are given in the introductory page such as the replacement of the middleware with a custom design and the use of web workers. However, it is not possible to determine the manner in which these technologies were used. Hope remains that in the near future, the repositories for *ROS on Web* become publicly available as an extension of the ROS open source ecosystem.

2.2. roswasm_suite

Another project closely related to the author's developments is roswasm_suite currently maintained mainly by Nils Bore. This suite is a set of libraries which help the user to crosscompile C++ ROS nodes to WebAssembly [Bor]. It also includes a library of helpers to write web Graphical User Interface (GUI)s for ROS; one such example can be observed in Figure 2.2.

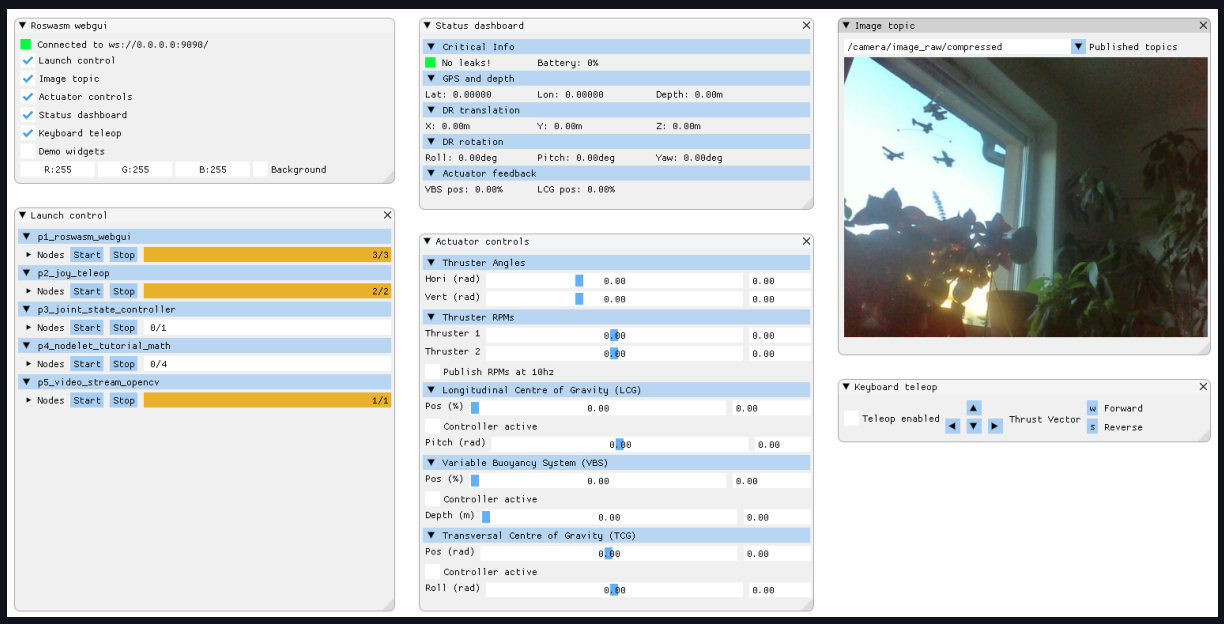


Figure 2.2. Example GUI for ROS using roswasm_gui.

Some of the biggest advantages of this roswasm_suite are that it is open source and actively maintained. The developers have a long history of continuous improvements to the packages, and as of 2023, they have managed to publish ten releases.

Nevertheless, these libraries do come with their set of disadvantages. First, the suite targets a ROS 1 distro and it depends on catkin tools to build the packages. Thus, the user is required to have a ROS 1 installation and the Emscripten Software Development Kit (SDK) before being able to use these libraries to launch ROS nodes on the browser.

2.3. Related Projects

There are several other works which do not directly align with the goals for this project but are pertinent in regards to the idea of developing a robotics environment which can be used on a web browser. Robot Web Tools maintains a collection of open source libraries and tools which can be used for robotic frameworks on the web [Ban].

2.3.1. Foxglove Studio

One of the most notorious examples of robotics applications on the browser consists of Foxglove Studio. The main focus of Foxglove Studio is visualization and debugging of robotic tasks [Sht]. Given that their products are based on observability and not on direct control of robotic systems, this allows them to expand their service area to a wider range of systems and platforms. For example, Foxglove Studio supports both ROS 1 and ROS 2 distributions and the application can be installed on Linux, Windows and MacOS or run directly in Google Chrome.

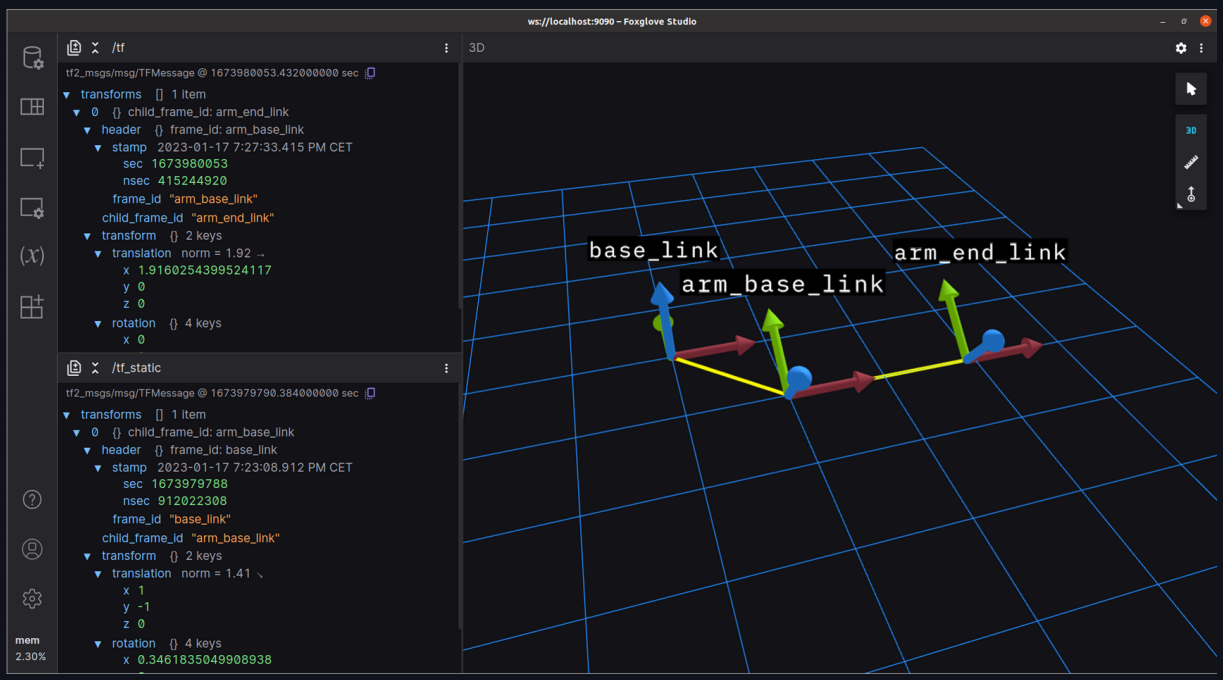


Figure 2.3. Visualizing ROS 2 Transforms with Foxglove Studio [Mil23b].

The wide range of visualization panels is one of the greatest strengths of Foxglove Studio. An example of a panel is shown in Figure 2.3 where ROS 2 transforms are drawn in a graphical display. Additional examples of panels include support for visualizing raw messages, image topics, plots, parameters, Universal Robotic Description Format (URDF) models, etc.

Another advantage of Foxglove Studio is that it is open source and actively maintained by community members. The application is also highly extensible with plugins to fit any specific needs of the users. Nevertheless, as a side effect of concentrating on observability, the application works as an add-on to an existing ROS installation and not as a replacement.

2.3.2. rosbridge_suite

On a similar note, the rosbridge_suite provides a set of packages which allow the user to interact with a ROS system via a JavaScript Object Notation (JSON) interface [Sch22]. Hypothetically, with these libraries, any non-ROS systems could interact with ROS by sending JSON messages. An instance of the rosbridge protocol can be seen in Figure 2.4.

```
{
    "op": "subscribe",
    (optional) "id": <string>,
    "topic": "/cmd_vel",
    "type": "geometry_msgs/Twist"
}
```

Figure 2.4. Example of rosbridge protocol emphasizing the JSON format.

The rosbridge_suite consists of four main packages:

- rosbridge_suite
- rosbridge_library
- rosbridge_server
- rosapi

From these packages, the rosbridge_library performs the conversions from JSON to ROS messages and vice versa. While the rosbridge_server provides the browsers with a WebSocket connection. A handful of Application Programming Interface (API)s enable clients to communicate with rosbridge; these APIs are implemented in JavaScript, Java, Python, and Rust.

Analogous to Foxglove Studio, rosbridge relies on an existing ROS installation. However, the capabilities of rosbridge are extensive and can be applied to real world scenarios; it also supports ROS 1 and ROS 2 distributions. Additionally, the community of contributors is highly involved in the maintenance of the client libraries.

2.3.3. ROS Control Center

The ROS Control Center is another web application which uses the rosbridge_suite to establish a WebSocket connection to a robotics system running ROS [Ber18]. A view of the control center is depicted in Figure 2.5.

With this ROS Control Center, the user is able to display information about running nodes, publish and subscribe to topics, call services, and change ROS parameters. Despite its potential, the control center does not offer explicit support for interacting with ROS 2 systems.

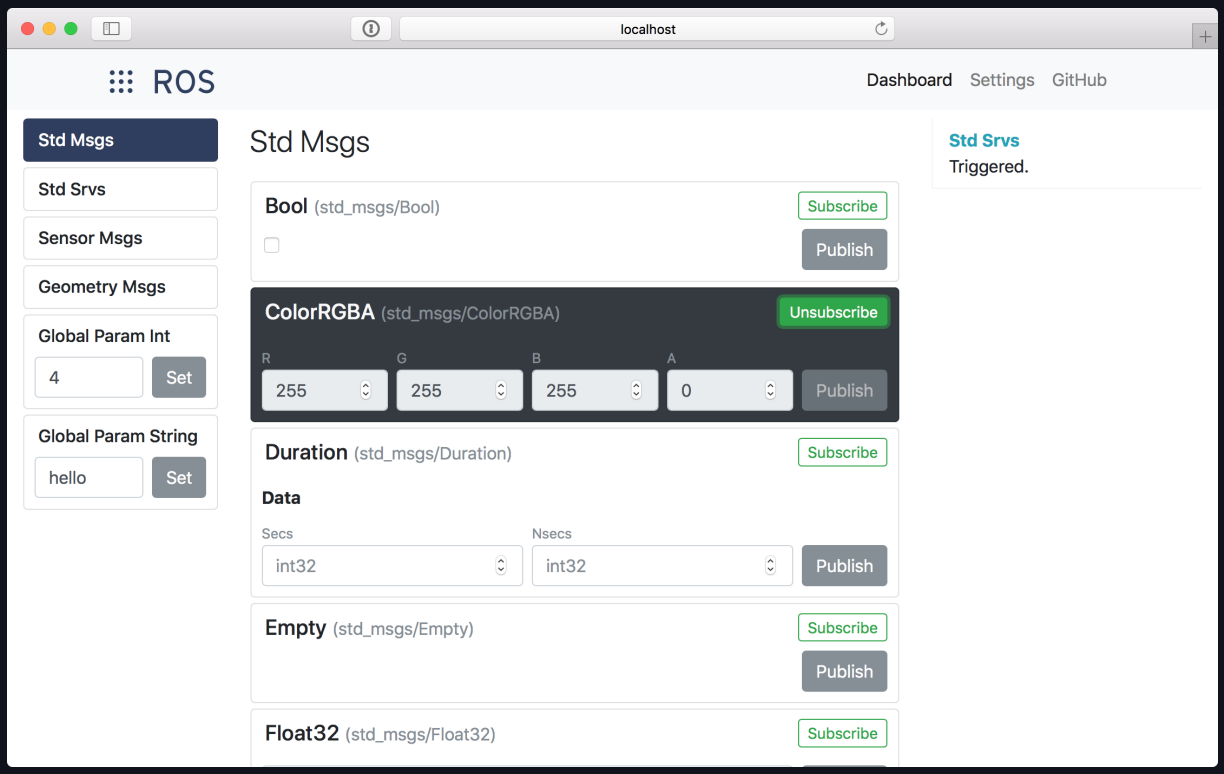


Figure 2.5. ROS control center running locally.

2.3.4. ROSWeb

ROSWeb combines all of the ROS widgets collected by Robot Web Tools into a single web application [Arr22]. As in the case of ROS Control Center (2.3.3), ROSWeb also depends on rosbridge to interact with ROS systems. Figure 2.6 demonstrates the ROSWeb application running on a Windows platform and communicating with a ROS system in a virtual machine running Ubuntu.

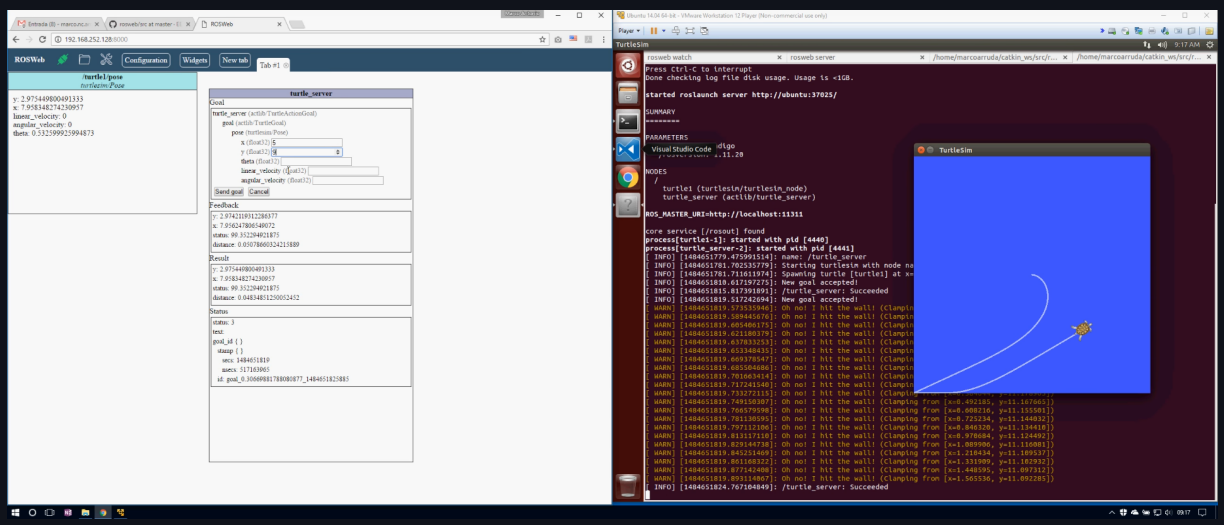


Figure 2.6. ROSWeb application interacting with a Virtual Machine (VM) running ROS.

A major advantage of ROSWeb application is its simplicity. The ROS widgets are interactive

and require minimal programming experience from the users. It also enables the users to easily save and modify workspaces to match their needs.

2.3.5. ROSboard

In contrast to the previous two models, ROSboard does not rely on rosbridge_suite to interact with ROS systems; instead, it has a custom Tornado implementation to function as a web server and WebSocket server [Ven21]. Figure 2.7 shows and example of the ROSboard application with different visualization widgets.

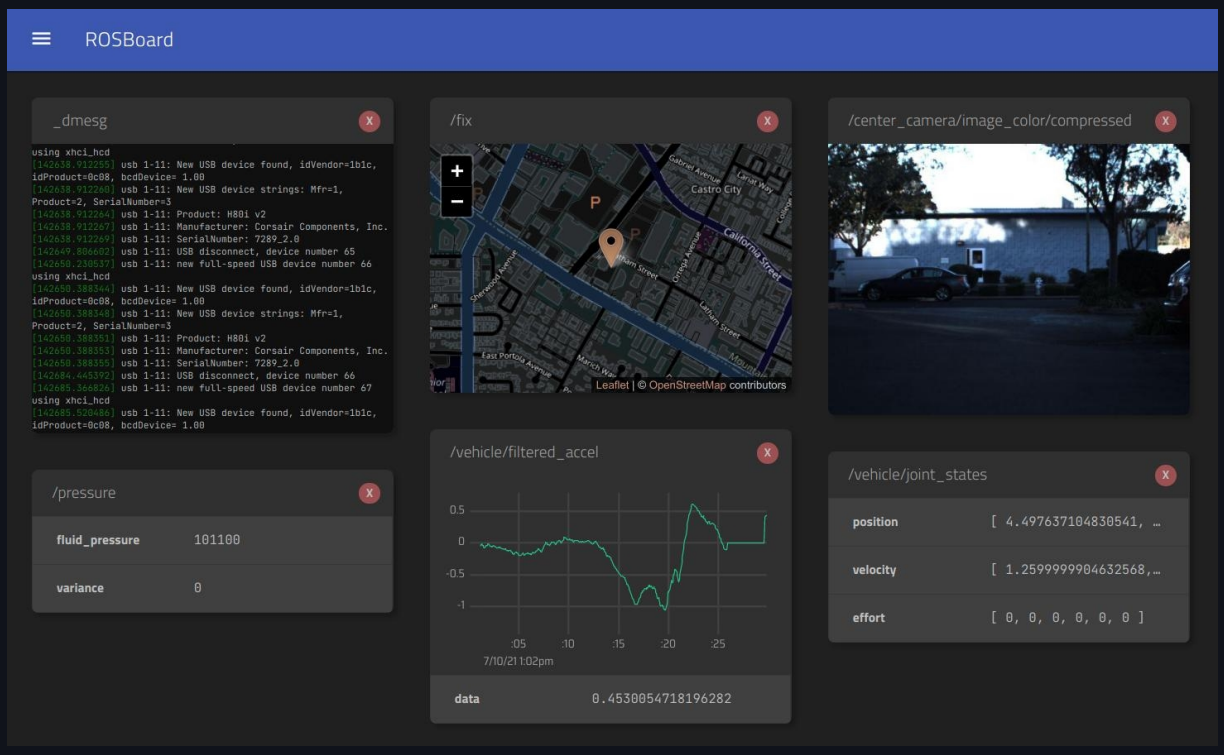


Figure 2.7. ROSboard application visualizing multiple message types.

ROSboard offers support for both ROS 1 and ROS 2 systems thanks to its tailored rospy2 library which is based on ROS 1's rospy but modified to ensure compatibility.

2.3.6. ROSLink

TODO: maybe too old to be relevant

2.4. WebAssembly

WebAssembly, also commonly referred to as simply WASM, is one of the newer technologies to enter the web arena. It was initially released in 2017 after representatives from the major browsers, Google Chrome, Microsoft Edge, Mozilla Firefox, and WebKit, agreed that the design of a Minimum Viable Product (MVP) was completed [Kri17].

In short, WebAssembly is a binary code format for a stack-based virtual machine [Ros23]. It is designed to be fast, safe, efficient, and portable; and it can be used inside or outside the browser. Inside the browser, WebAssembly works as a complement to JavaScript. Some of the use cases include: games, scientific visualizations, platform simulations, interactive educational software, virtual machines, developer tools, etc. [Tho23]. Because of its capabilities, it is believed to be an ideal target for the development of a robotics environment on the browser.

2.4.1. Applications

Before WebAssembly was officially released, one of the first demonstrations of its potential involved the game AngryBots developed by Unity Technologies. As illustrated in Figure 2.8, AngryBots is a first-person shooter game set in a space station filled with menacing robots.

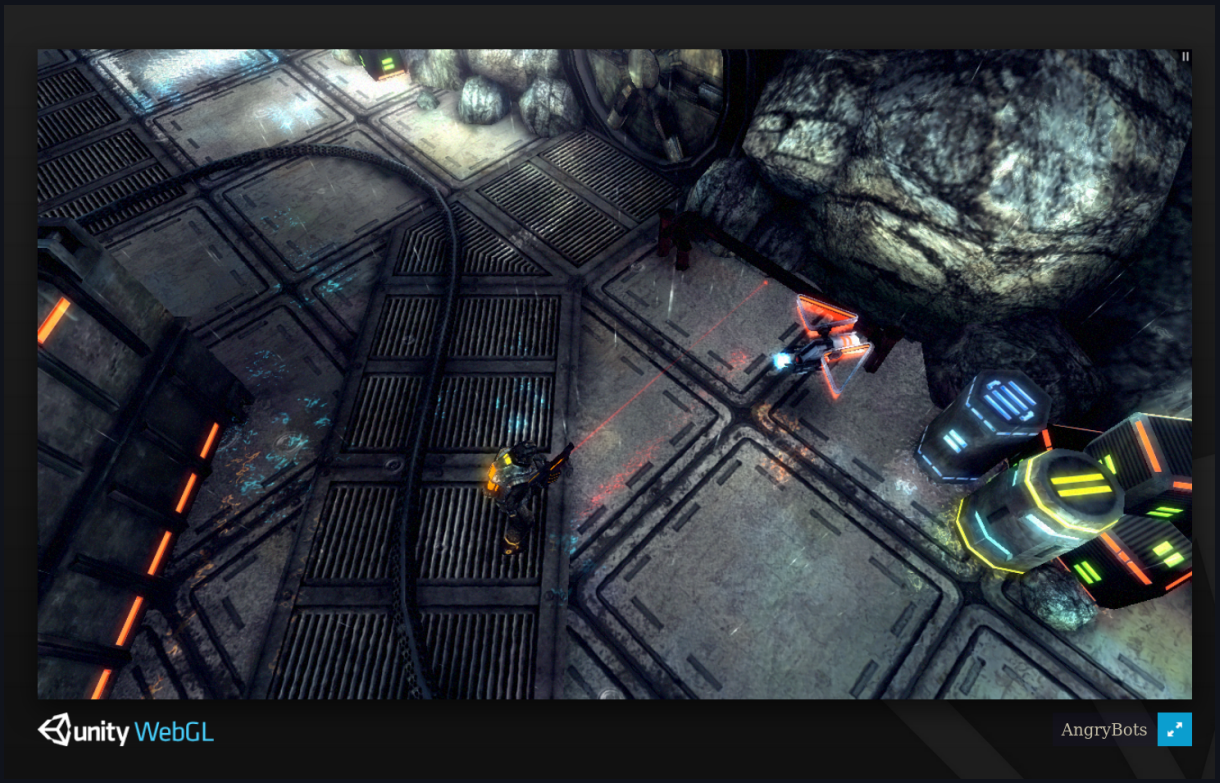


Figure 2.8. Demonstration of Angry ots in Unity WebGL [Ech16].

Similar to AngryBots, the Doom 3 Engine was ported to WebAssembly by using Emscripten. This experiment showed that very large and demanding C++ programs can be run inside a web

browser [Cuv22]. The game, pictured in Figure 2.9 is currently supported by all major desktop web browsers.

Figure 2.9. Online demonstration of the Doom 3 WebAssembly (D3wasm) project.

On a more classic note, the traditional Pong game has also been successfully ported to WebGL using Emscripten [Ben20]. Only a single player is supported in the current version of the game, as seen in Figure 2.10.

Aside from video games, WebAssembly has also been proven to work for other applications such as the web-based LaTeX editor shown in Figure 2.11, which uses a LaTeX compiler built with Emscripten; and the atmospheric simulation displayed in Figure 2.12. There exists several other use cases involving scientific visualizations and rendering.

All of the mentioned examples emphasize the ability of WebAssembly to be adapted to a wide range of applications. This feature is one of the most appealing characteristics for merging WebAssembly and robotics.

Figure 2.10. Classic Pong running on the browser.

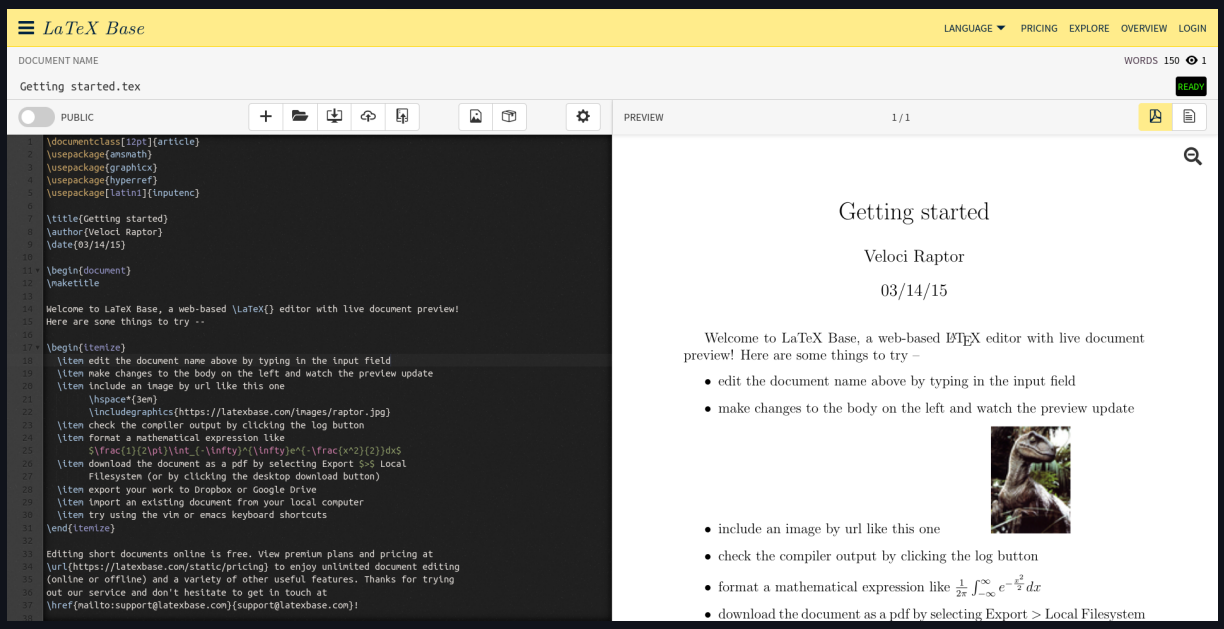


Figure 2.11. Web-based LaTeX editor built with Emscripten.

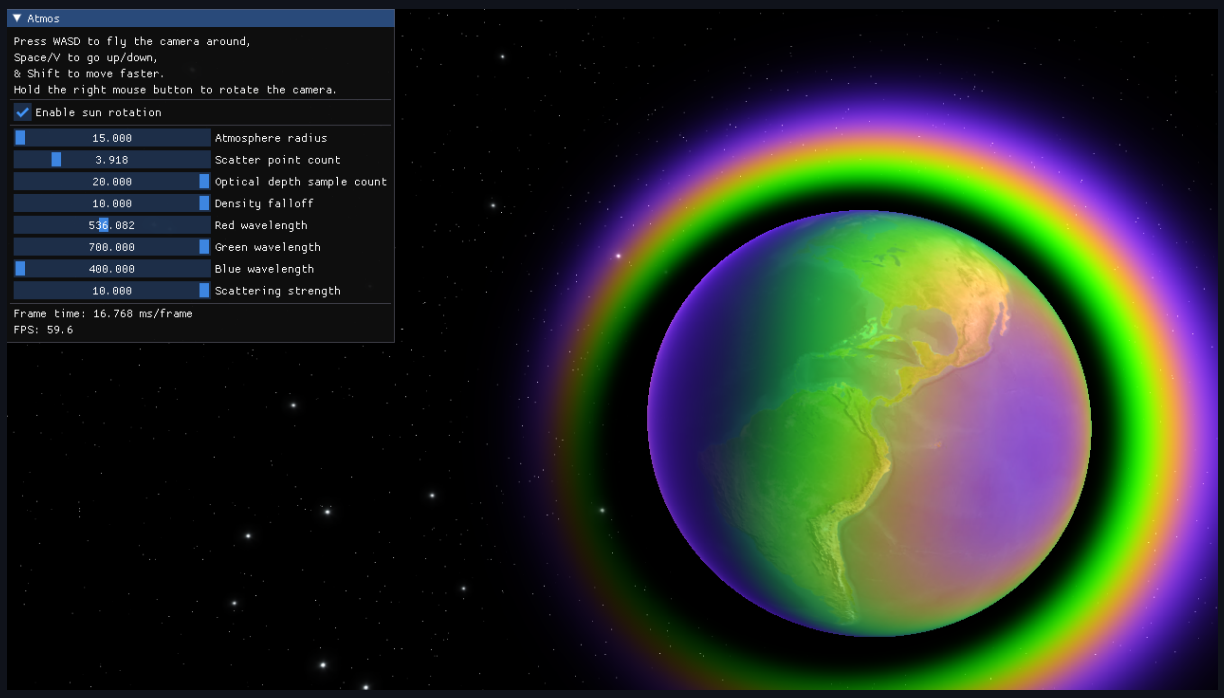


Figure 2.12. Atmospheric simulation [Mil23a].

3. Concept Realization

This section provides the major milestones from the project beginning with a brief description of the overall concept solution to the challenges presented in the Introduction, followed by the layers of implementation accomplished during the development phase.

3.1. Target Scenario

To introduce the concept, a "target scenario" is first considered. In this scenario, an intermediate ROS user should be able to reach a high level of usability with the tools developed in this project. First, an intermediate user is described as an individual who is familiar with the ROS ecosystem but does not have the need to maintain or test ROS packages across different platforms. In the target scenario, this intermediate user will be capable of performing the following tasks:

- install pre-compiled ROS 2 packages in the browser
- launch nodes including publishers, subscribers, servers, and clients
- interact with the environment to obtain information about running nodes, this would include echoing topics, listing parameters, reviewing log files, etc.
- visualize URDF files, transforms, point clouds, markers, etc.
- play and record bag files
- connect with robots via bluetooth

Outside of this scenario, another goal for this project includes making the developed tools available to the general public by distributing them as open-source software. This will allow other roboticists to compile their own packages and share them on the web.

3.2. Implementation Layers

The development of this project is subdivided into multiple levels for the users, the interactions that the users have with the tools developed, and the technical difficulty of developing the tools. These subdivisions are beneficial in providing the reader with an illustration of the progressing stages of development of this project.

Note

If the reader would like to follow along with the demonstrations provided in the following pages, it is recommended to visit ros2wasm.dev. Throughout the text, links will be provided to redirect the reader to specific examples.

3.2.1. User Levels

For the purpose of establishing target users for the developed tools, potential users were categorized based on expertise level with ROS and programming in general. A summary of these levels can be observed in Table 3.1.

Table 3.1. Target users categorized by expertise level.

	User	Description
1	Beginner	Complete beginners who have never used ROS or programmed in any language.
2	Student	University students with basic programming experience.
3	ROS User	Students and researchers who actively use ROS for projects.
4	Roboticist	Robotics software developers including contributors to the ROS ecosystem.

Commencing with Level 1, the *Beginner* category is reserved for students in secondary education who have had little to no experience with programming, and therefore are not familiar with ROS. The tools developed in this project would serve as an initial introduction to robotics for this category of users.

Level 2 consists of university students who have completed elementary programming courses but have not yet been introduced to ROS. For this type of user, this project will provide essential tutorials to become acquainted with the inner workings of ROS.

With a slightly higher level of expertise, Level 3 comprises students or other enthusiasts who are already familiar with ROS and have collaborated in projects which use ROS as the main system to handle communications of multiple robotics elements. This ROS user is equivalent to the intermediate user described in the target scenario (Section 3.1).

Lastly, the highest level of experience is dedicated to roboticists who actively use ROS and contribute to its development. For this category of users, the intention of this project will be to involve more contributors in order to more promptly meet the needs of most ROS users.

3.2.2. Interaction Levels

The GUI is an essential element in the development of this project because it determines the benefits the users will receive by utilizing these tools. Similarly, the interface the user experiences with the tools has been categorized in increasing levels of interaction. These categories are summarized in Table 3.2.

Table 3.2. User Interface (UI) segmented based on the level of interaction.

	Interface	Description
1	Non-interactive	A publisher runs automatically as soon as the site is loaded.
2	Minimal	User can start/stop a publisher by pressing a button.
3	Basic	User can select and run publisher and subscriber nodes simultaneously.
4	Intermediate	Publishers, subscribers, and services are available, and the user can request basic information about the environment.
5	Advanced	A complete GUI where the user has full control of the environment, can start/stop nodes, modify parameters, manage bag files, and visualize robots.
6	Complete	All ROS 2 features are available and packages can be built on the browser, plus the user can directly connect and interact with external robots.

As the name implies, the *non-interactive* Level 1 does not offer the user any sort of interaction with the ROS environment. With this non-interactive interface, the user can do nothing more than load and reload the page. As soon as the user loads the page, a node which has been pre-compiled will automatically start running. In the simplest case scenario, a publisher node would run and the published messages would be displayed on the window. Because the user has no ability to interact with the environment, this publisher node will continue to run uninterrupted. The scenario described is illustrated in Figure 3.1.

```
Publisher initializing.
[INFO] [168766.57900] [wasm_cpp]: Context initializing.
[INFO] [168767.91500] [wasm_publisher]: Publishing: 'Hello there! 0'
[INFO] [168768.98400] [wasm_publisher]: Publishing: 'Hello there! 1'
[INFO] [168769.94400] [wasm_publisher]: Publishing: 'Hello there! 2'
[INFO] [168770.90300] [wasm_publisher]: Publishing: 'Hello there! 3'
[INFO] [168771.96800] [wasm_publisher]: Publishing: 'Hello there! 4'
[INFO] [168772.92000] [wasm_publisher]: Publishing: 'Hello there! 5'
[INFO] [168773.97600] [wasm_publisher]: Publishing: 'Hello there! 6'
[INFO] [168774.93600] [wasm_publisher]: Publishing: 'Hello there! 7'
```

Figure 3.1. Output from non-interactive Level 1.

Example 1

A demonstration of a *non-interactive* user interface (Level 1) can be found at ros2wasm.dev/pages/demo01

NOTE: The page must be reloaded to restart the node.

By marginally expanding the interface, the *minimal* Level 2 provides the user with the ability to start and stop a pre-compiled node. This stage is accomplished by the addition of buttons to the website. Continuing with the example previously described, in this level the user can press a button to start a publisher node, view the output of any published messages, and stop the node at any point. Level 2 is exhibited in Figure 3.2

Figure 3.2. Interactive buttons to start and stop the publisher node.

Example 2

A demonstration of a *minimal* user interface (Level 2) can be found at ros2wasm.dev/pages/demo02

The *basic* Level 3 offers the user increasingly more control over the environment. In this level, the user has the ability to run more than one node simultaneously. This makes it possible to have publishers sending messages to a particular topic and subscribers retrieving the published messages accordingly. Nonetheless, the nodes are still pre-compiled and thus the user does not have the ability to change the topic names or any other parameters of the nodes. Figure 3.3 demonstrates a snapshot of Level 3.

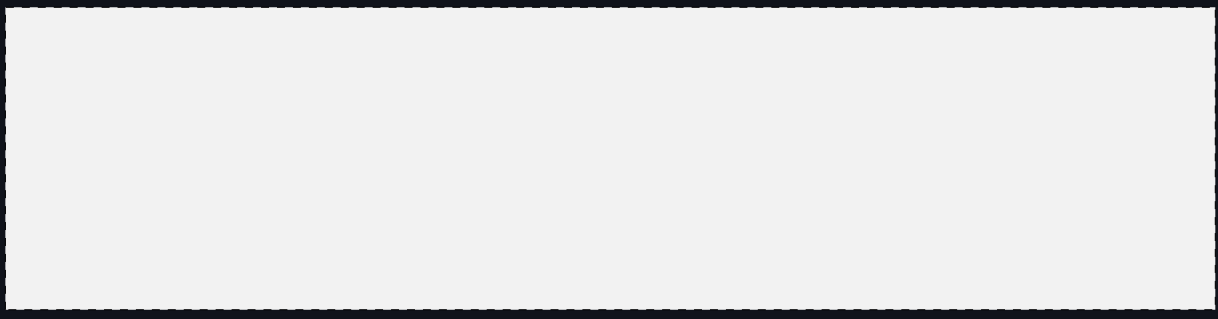


Figure 3.3. TODO Level 3 image

Example 3

A demonstration of a *basic* user interface (Level 3) can be found at ros2wasm.dev/pages/demo03

Stepping further into the list, the *intermediate* Level 4 introduces services, these include both the servers and the clients. Additionally, with this level the users now possess the ability to request information from the environment such as the type of nodes which are running at a given time, or which topics are available. A depiction of Level 4 is shown in Figure 3.4

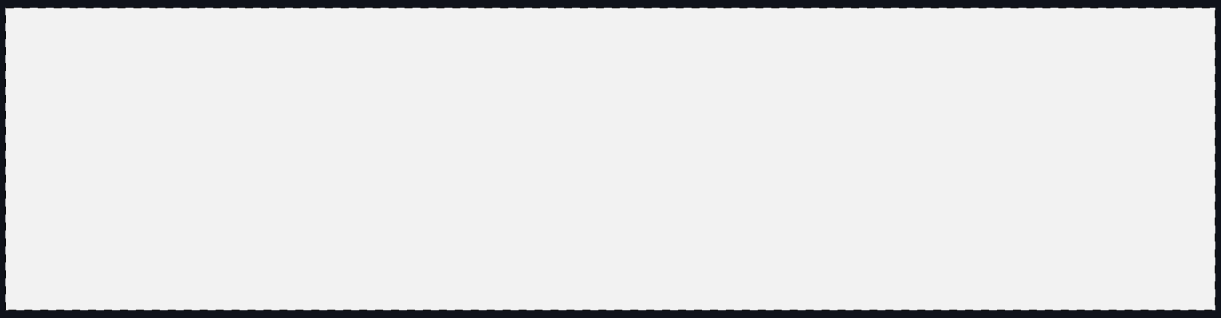


Figure 3.4. TODO Level 4 image

Example 4

A demonstration of an *intermediate* user interface (Level 4) can be found at ros2wasm.dev/pages/demo04

Finally arriving at the *advanced* Level 5, this level is more prominent because it introduces the integration of JupyterLite with the ROS environment. With JupyterLite, the user can directly interact with the ROS environment by using the ROS client libraries such as `rclpy`. A typical workspace in JupyterLite is pictured in Figure 3.5.

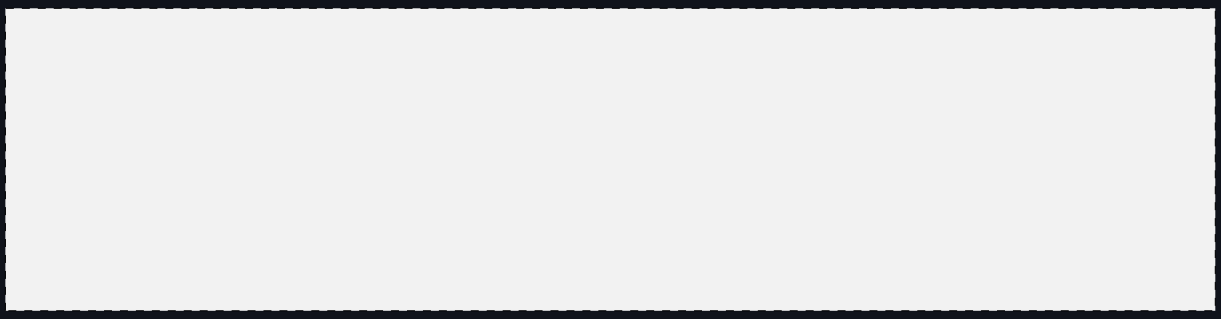


Figure 3.5. TODO Level 5 image

Lastly, Level 6 consists of a *complete* ROS environment also made available to the user through JupyterLite. The user would be able to install any additional ROS packages from `emscripten-forge`. An extension for JupyterLite could enable communications with external robots by using

the Web Bluetooth API. And a web compiler could be implemented to directly build packages within JupyterLite.

3.2.3. Complexity Levels

In regards to technical complexity of the project, a series of complexity levels is outlined in Table 3.3. The first four levels (1-4) must be accomplished in strict order, while levels 5-8 do not have any dependencies on the preceding levels to be able to function.

Table 3.3. Implementation categories with increasing technical complexity.

Level	Description
1	Replacement of the ROS middleware implementation.
2	A custom package and its dependencies can be cross-compiled to WebAssembly.
3	A publisher and subscriber can communicate with each other on the browser.
4	Multiple nodes and distinct topics can run simultaneously.
5	Manipulation of a physical robot via bluetooth or wifi.
6	Interaction with a ROS client library from JupyterLite.
7	Visualization of a robot with Amphion and Zethus.
8	Simulation of a robotics scenario with Gazebo.
9	Development workspace for creating and debugging ROS packages.

Although creating a replacement for the ROS middleware implementation denotes the lowest level on the list, its complexity must not be underestimated. Level 1 consists of creating custom middleware packages to handle discovery and communications between nodes. All other ROS packages depend on the middleware implementation, and because of this, creating a working replacement is crucial before any other features can be implemented.

Once the middleware packages have been introduced, the next level ensures that the core ROS packages can be cross-compiled. Level 2 involves the creation of a recipe to build all packages consistently. Minor modifications are needed in a few of the core packages to prevent compilation errors; for details, refer to TODO: add mods to appendix. And in order to set the custom middleware implementation as default, packages belonging to the other implementations must be ignored or removed.

Continuing the progression, Level 3 involves cross-compiling a package containing two executables, a publisher and a subscriber. Once these nodes are successfully loaded on the browser, communication between the nodes must be established by passing messages between web workers and the main thread.

Level 4 is simply an expansion of Level 3. In this case, the system handling communication between nodes can accommodate a multitude of different topics, message types, and node types. In other words, the communication system must be able to create and remove message queues at the time when they are requested by the individual nodes.

Starting with Level 5, the project begins to develop more practical applications. Manipulating a robot from the browser involves the addition of external libraries which enable communications to the hardware components of the robot. For example, a library which uses the Web Bluetooth API to establish a connection to a robot and sends commands commands to activate the robot's motors. This level also involves creating an interface which translates ROS messages to commands the robot can receive.

Level 6 requires Python support on the browser. This step consists of cross-compiling the ROS client library for Python (`rclpy`) in order to be able to import it from JupyterLite. The benefit of importing `rclpy` is that nodes could be created directly from the browser as shown in Figure 3.6.

```
import rclpy
web_node = rclpy.create_node("web_node")
```

Figure 3.6. Example of creating a node with rclpy.

Visualization of robots begins with Level 7. For this step, the Amphion and Zethus libraries are adapted to receive information from the ROS 2 nodes running on the browser. This entails replacing or modifying the dependency on `rosjslib` (the ROS 1 JavaScript library) which interacts with a native ROS 1 environment from the browser. Currently, `roslibjs` does not actively support ROS 2, but this is likely to change in the near future as more systems transition to ROS 2.

Unlike Amphion and Zethus, recent versions of Gazebo do support simulations for ROS 2 ecosystems. However, for Level 8, Gazebo's tools and libraries would need to be modified to run on the browser or communications must be established to Gazebo's cloud servers.

Lastly, Level 9 culminates with the implementation of all the previous levels plus additional developer tools such as compilers and debuggers running on the browser which would be equivalent to developing ROS packages in a local machine.

4. Methodology

In the spirit of reproducibility, this chapter describes the tools and procedures used in the development of this project. Starting with the hardware, the requirements for this project were minimal. An Intel® Core™ i7-1065G7 CPU 1.30 GHz processor with a memory capacity of 15.2 GiB of RAM was used. The operating system consisted of Ubuntu 22.04. A system with substandard specifications can also be adequate for development.

4.1. Development Environment

For the sake of simplicity and to isolate the development environment from global dependencies, a conda environment was created. This conda environment was used to build the ROS packages required. The essential packages installed in the development environment are shown in Table 4.1. For quick installation, an environment yaml file is provided at TODO

Table 4.1. Development environment dependencies

Package	Version
python	3.10
setuptools[1]	58.2.0
numpy	1.24
lark[2]	1.1
rosdep	0.22
cmake	3.25
colcon-core	0.12
colcon-ros	0.3
colcon-package-selection	0.2
colcon-devtools	0.2
nodejs	18.12

4.2. Compilation Tools

TODO: more details

Given that the colcon package is already well adapted to build ROS packages, colcon was widely used throughout this project with a few customizations.

There are currently four ways to port projects to WebAssembly [Ste23]:

[1] Version 58.2.0 of setuptools is the highest version that supports setup.py installs which many of the core ROS packages depend upon.
[2] The lark package is required for builtin_interfaces

- Writing WebAssembly directly
- Using AssemblyScript
- Targeting WebAssembly as output for Rust applications
- Using Emscripten for C/C++ applications

Since most ROS 2 packages are written in C/C++, the easiest solution was to use Emscripten. Emscripten is a compiler toolchain which takes C/C++ source code and outputs a wasm module, the JavaScript *glue* code and optionally an HyperText Markup Language (HTML) document, as illustrated in Figure 4.1. In terms of ROS packages, for each executable, for example a talker.cpp containing a publisher node, Emscripten will output three files per executable: talker.wasm, talker.js and talker.html.

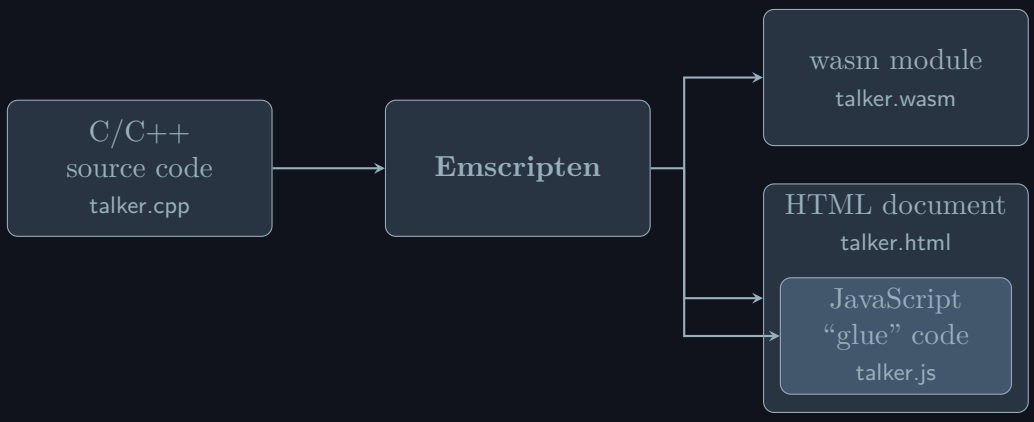


Figure 4.1. Transformation of C/C++ code to WebAssembly through Emscripten [Ste23].

In order to cross-compile the packages to WebAssembly, the Emscripten SDK (emsdk) version 3.1 was installed. The Emscripten toolchain was then provided to colcon as a cmake argument (See Appendix C.1 Line 109).

4.3. Package Building Process

Before any packages could be built, all of the ROS 2 core packages were cloned in a local workspace. To prevent compilation issues, packages related to the default middleware implementations were excluded by adding a COLCON_IGNORE file in their respective root directories; these include iceoryx, cyclonedds, fastrtps, and connextdds. A secondary purpose for excluding these packages is to ensure that the custom middleware implementation is the only implementation available at runtime. This custom middleware implementation must also be included in the current workspace before proceeding.

Additionally, a “blasm” script was created to aid in the building of packages given that the number of arguments quickly became exceedingly lengthy for manual input. The entire script is included in Appendix C.1 for reference. With this script, it is possible to build any package

and its dependencies, or to build a package individually. Care must be taken to ensure that the environment variables for the tools such as EMSDK_DIR are set accordingly. The list of options for this script are shown in Figure 4.2.

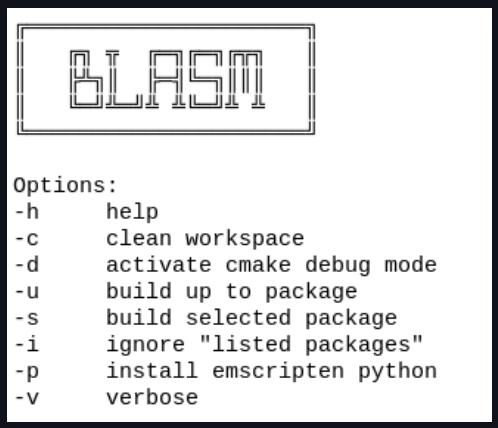


Figure 4.2. Blasm script options.

If the package compiles without errors, any executables in the package will be converted to *.wasm* and *.js* files to be run on the browser.

4.4. Debugging Tools

When working with new ROS packages, there are two main sources of errors: errors during compilation and errors at runtime. To tackle compilation errors, the first step is to obtain a full description of the error. The "blasm" script has the option to dynamically activate verbose (-v) mode as needed.

Secondly, for debugging errors at runtime, one of the most effective tools is the use of logs. Core ROS packages such as rcutils and rcpputils already include logging functionalities. Adapting these ROS logs into any newly created packages allows for efficient and quick debugging. Alternatively, customized logging functions could be implemented for an in-depth analysis at the expense of increasing the complexity of the package in question.

4.5. Post Processing

Once the executables have been successfully compiled, the generated JavaScript files are augmented with additional functions to enable communication between the main thread and the ROS packages. The added functions are described in Appendix C.2. (TODO: OR provide link to file on GitHub)

4.6. Testing Environment

Lastly, there are two phases of testing. The first phase consists of testing the packages directly from the terminal. For the early stages such as during the replacement of the middleware implementation, cross-compilation is not yet required; thus, it is possible to locally test the middleware packages by comparing their behavior with the default middleware implementations. This can be achieved in a separate conda environment with ROS 2 packages preinstalled by creating and installing an overlay which only includes the customized middleware implementation.

And the second phase involves testing the packages on a web browser. For this project, only Firefox and Chrome were subject to testing due to their popularity. The tools developed in this project may be suitable for other browsers, however, their full functionality is not guaranteed.

4.6.1. Package Management and Distribution

TODO: - Automating package building - Pipelines - robostack?

5. ROS 2 Middleware

A significant change from ROS 1 to ROS 2 is the shift from a custom transport layer consisting of Transmission Control Protocol ROS (TCPROS) to Data-Distribution Service (DDS). DDS is a publish-subscribe communication standard defined by Object Management Group (OMG). DDS uses Interface Description Language (IDL) for defining and serializing messages [Woo19]. In contrast to ROS 1, which requires a ROS master in order for nodes to discover and communicate with each other, ROS 2 discovery system is handled by DDS and each of the DDS vendors provides different options for customizing the communication layer.

One notable advantage of moving away from a custom transport protocol is that the ROS client libraries are now agnostic to the middleware interface; this means that the complexities of the DDS implementation are not exposed to the end user [Tho14]. As a consequence, multiple middleware interfaces can be implemented as long as they fulfill the following requirements:

- publishing and subscribing
- message serialization
- discovery

The interaction between the ROS user, the ROS client libraries, and the middleware layers is shown in Figure 5.1.

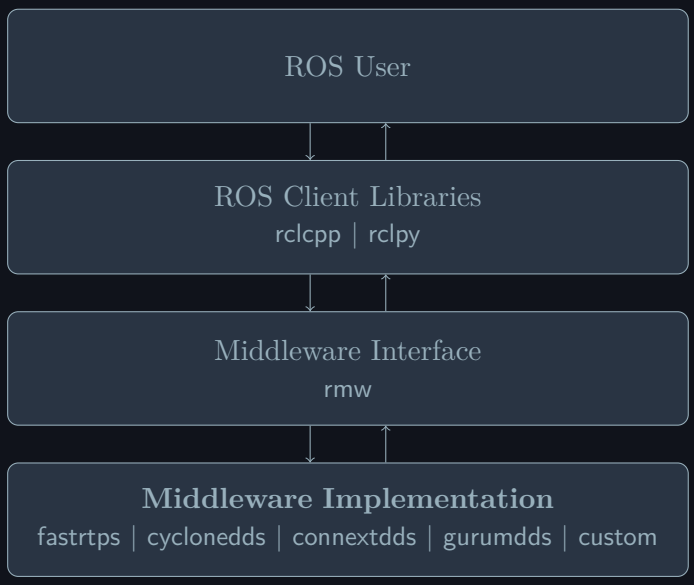


Figure 5.1. Relations between the user, the ROS client libraries and the middleware packages [Tho14].

5.1. Supported Implementations

Currently, ROS 2 releases provide full support for three middleware implementations: eProsima Fast DDS, Eclipse Cyclone DDS, and Real-Time Innovations (RTI) Connext DDS. The binaries also support Gurum DDS, but the implementation requires a separate installation [Lor22].

5.1.1. eProsima Fast DDS

eProsima Fast DDS, also known as Fast Real-Time Publish Subscribe Protocol (RTPS), is the default middleware implementation for ROS 2 packages. Some of the main advantages of Fast DDS is that it is free, open source, and it is developed for most platforms including Linux, Windows, Mac OS, and QNX. A rich set of Quality of Service (QoS) parameters is also available for tuning the communication protocols to any particular system. Fast DDS follows a Data-Centric Publish Subscribe (DCPS) model, which consists four elements: publishers, subscribers, topics, and domains [Pon20a]. This model introduces the concept of Data Writers and Data Readers which, as the names imply, have read and write permissions to the "Global Data Space" as specified by the DDS standard [Pon20b]. Figure 5.2 displays an example of the Fast DDS architecture and demonstrates how the different elements interact with each other.

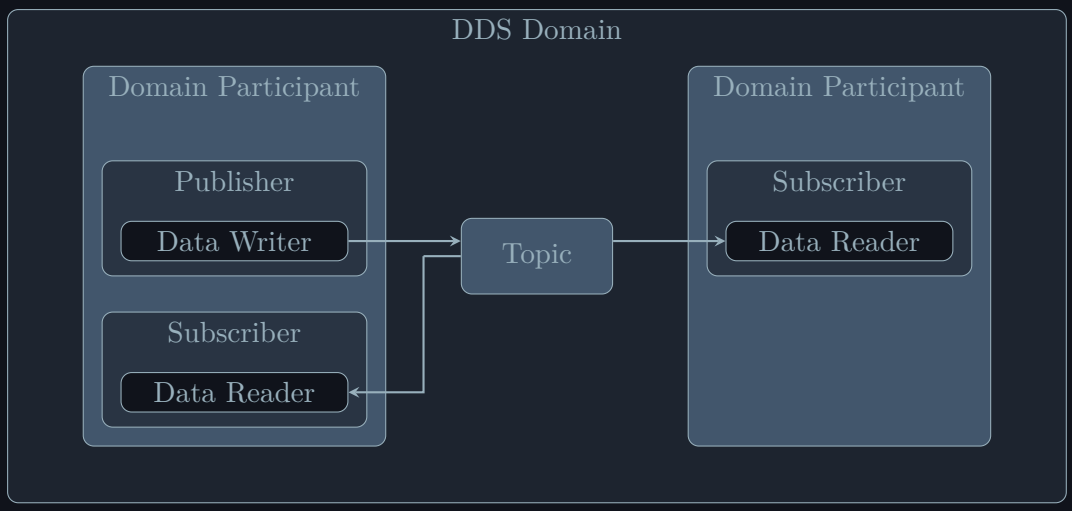


Figure 5.2. Instance of a typical Fast DDS domain model.

5.1.2. Eclipse Cyclone DDS

Similar to Fast DDS, Cyclone DDS is free and open source and supports the three major platforms, Linux, Windows, and Mac OS. Cyclone DDS offers a "data-centric" architecture with space- and time-decoupling with a zero configuration discovery system [Fou23]. Additionally, this implementation includes Python bindings to simplify the definition of data types.

5.1.3. RTI Connext DDS

Unlike the previously mentioned DDS implementations, RTI Connext DDS requires a separate installation plus the purchase of a license, however, free licenses are available for researchers and academics [Weo23]. RTI also offers a variety of tools to ROS users including admin consoles, system monitors, and recording and routing services [Put18].

5.1.4. Gurum Networks Gurum DDS

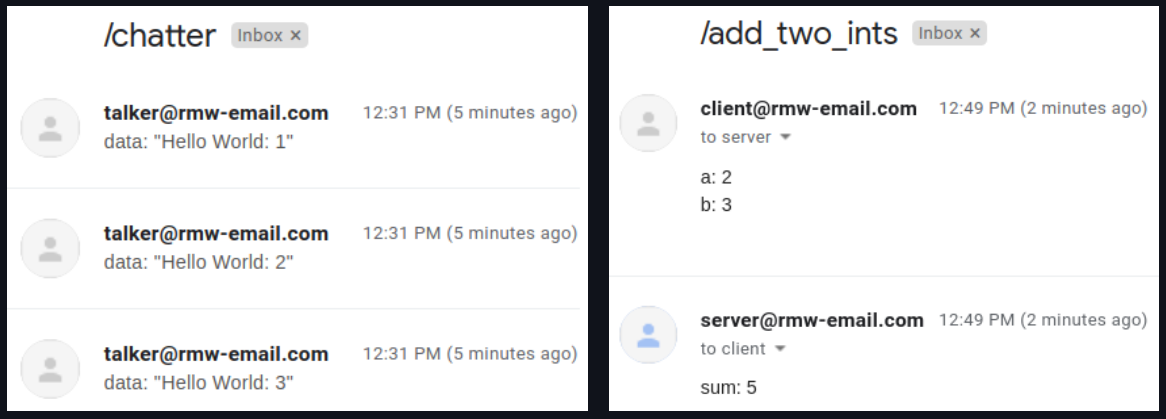
The last implementation which is supported by the ROS 2 binaries is GurumDDS. And as in the case of Connext DDS, GurumDDS also requires its own installation after the purchase of a license, although, free trials are available [Yun23].

5.2. Custom Middleware

Out of the aforementioned middleware implementations, none of them have targeted the web browser as the basis for the DDS Global Data Space. There exists a Web-Enabled DDS (WebDDS) standard, also specified by OMG, which dictates how a DDS system can be exposed to web clients via a WebDDS service [16]. However, this setup would still require a native DDS system. As an alternative to DDS, custom middleware packages can be implemented as long as they meet the basic requirements listed in Section 5.

5.2.1. Email

An excellent example of a middleware implementation which is not based on the DDS standard is rmw_email. With this implementation, all of the ROS 2 communications for publishing and subscribing to topics and to call and respond to services are handled by sending emails.



(a) Email publisher **(b)** Email service client and server

Figure 5.3. Email ROS Middleware (RMW) implementation.

The implementation consists of two parts: email for handling the communications and rmw_email which acts as an adapter to interface with rmw [Béd21]. Figure 5.3 shows a ROS publisher, a service client, and a service server using this email middleware. Although rmw_email does not reach the level of performance of the standard DDS implementations, it showcases the flexibility of the additional abstraction layer integrated in ROS 2 to support various middleware designs.

5.2.2. Zenoh

Continuing the trend of non-DDS middleware implementations, another approach involves the use of Eclipse Zenoh. Zenoh is a publication, subscription and query protocol to unify data which can be used in embedded micro-controllers or even data centers [Cor23]. Open Robotics has tested the potential of using Zenoh as a middleware for ROS 2 applications and concluded that it could alleviate some of the common problems encountered with the default DDS implementations by providing the users with hassle-free experience which does not require configuration and tuning unlike its DDS counterparts [Big22].

Similar to rmw_email, the interface between Zenoh and ROS 2 is handled by rmw_zenoh. As of 2023, rmw_zenoh still remains in the experimental phase. One notable aspect of this implementation, is the adaptation of Fast CDR to provide type support for Zenoh.

5.2.3. Minimal Middleware Implementation

The development of a custom middleware implementations consist of two major parts: the creation of a middleware "adapter" to communicate with the ROS 2 middleware interface, and the formation of the middleware implementation itself. An overview of a custom middleware architecture is demonstrated in Figure 5.4.

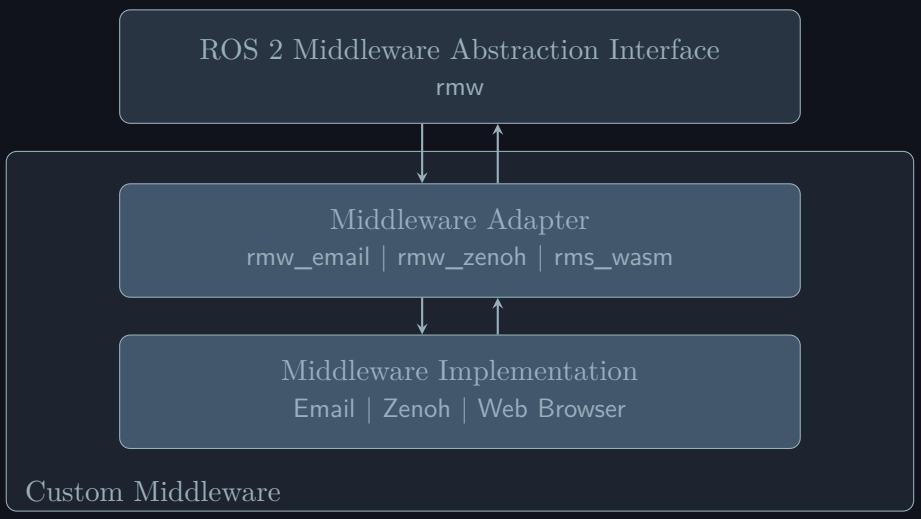


Figure 5.4. Architecture overview of a ROS 2 custom middleware implementation.

There are no standardized guidelines for how the middleware implementation should be formatted or what platforms it should support. The design of the implementation is highly dependent on the use case of the ROS application. The only design requirements are that the implementation should have the means to publish and subscribe data, perform message serialization from and to ROS message types, and have a discovery system to detect other participants in the specified domain. For this project, all of the communications are handled by the web browser and thus, the middleware is implemented in JavaScript.

For the creation of a middleware "adapter," rmw provides a set of primitives which are needed for higher level ROS APIs. Generating the adapter requires implementing all of the relevant interface functions defined by rmw. Figures 5.5 through 5.10 highlight a few of the necessary interface functions.

```
// Return a zero initialized context structure
rmw_context_t   rmw_get_zero_initialized_context (void) {...}

// Initialize the middleware with the given options and yield a context
rmw_ret_t   rmw_init (
    const rmw_init_options_t *options,
    rmw_context_t *context) {...}

// Shutdown the middleware for a given context
rmw_ret_t   rmw_shutdown (rmw_context_t *context) {...}

// Finalize a context
rmw_ret_t   rmw_context_fini (rmw_context_t *context) {...}

// Return a zero initialized init options structure
rmw_init_options_t  rmw_get_zero_initialized_init_options (void) {...}

// Initialize given init_options with the default values and implementation
    specific values
rmw_ret_t   rmw_init_options_init (
    rmw_init_options_t *init_options,
    rcutils_allocator_t allocator) {...}

// Copy the given source init options to the destination init options
rmw_ret_t   rmw_init_options_copy (
    const rmw_init_options_t *src,
    rmw_init_options_t *dst) {...}

// Finalize the given init_options
rmw_ret_t   rmw_init_options_fini (rmw_init_options_t *init_options) {...}
```

Figure 5.5. Functions for initialization and shutdown.

```
// Create a node and return a handle to that node
rmw_node_t *  rmw_create_node (
    rmw_context_t *context,
    const char *name,
    const char *namespace_,
    size_t domain_id,
    bool localhost_only) {...}

// Finalize a given node handle, reclaim the resources, and deallocate the node
    handle
rmw_ret_t   rmw_destroy_node (rmw_node_t *node) {...}

// Return a guard condition which is triggered when the ROS graph changes
const rmw_guard_condition_t *   rmw_node_get_graph_guard_condition (
    const rmw_node_t *node) {...}
```

Figure 5.6. Node functions.

```
// Create and return an rmw publisher
rmw_publisher_t *   rmw_create_publisher (
    const rmw_node_t *node,
    const rosidl_message_type_support_t *type_support,
    const char *topic_name,
    const rmw_qos_profile_t *qos_policies,
    const rmw_publisher_options_t *publisher_options) {...}

// Destroy publisher
rmw_ret_t   rmw_destroy_publisher (
    rmw_node_t *node,
    rmw_publisher_t *publisher) {...}

// Initialize a publisher allocation to be used with later publications
rmw_ret_t   rmw_init_publisher_allocation (
    const rosidl_message_type_support_t *type_support,
    const rosidl_runtime_c__Sequence__bound *message_bounds,
    rmw_publisher_allocation_t *allocation) {...}

// Destroy a publisher allocation object
rmw_ret_t   rmw_fini_publisher_allocation (
    rmw_publisher_allocation_t *allocation) {...}

// Return a rmw_publisher_options_t initialized with default values
rmw_publisher_options_t   rmw_get_default_publisher_options (void) {...}

//  Publish a given ros_message
rmw_ret_t   rmw_publish (
    const rmw_publisher_t *publisher,
    const void *ros_message,
    rmw_publisher_allocation_t *allocation) {...}
```

Figure 5.7. Publisher functions.

```
// Create and return an rmw subscription
rmw_subscription_t *  rmw_create_subscription (
    const rmw_node_t *node,
    const rosidl_message_type_support_t *type_support,
    const char *topic_name,
    const rmw_qos_profile_t *qos_policies,
    const rmw_subscription_options_t *subscription_options) {...}

// Destroy subscription
rmw_ret_t   rmw_destroy_subscription (
    rmw_node_t *node,
    rmw_subscription_t *subscription) {...}

// Retrieve the number of matched publishers to a subscription
rmw_ret_t   rmw_subscription_count_matched_publishers (
    const rmw_subscription_t *subscription,
    size_t *publisher_count) {...}

// Retrieve the actual qos settings of the subscription
rmw_ret_t   rmw_subscription_get_actual_qos (
    const rmw_subscription_t *subscription,
    rmw_qos_profile_t *qos) {...}

// Take an incoming message from a subscription
rmw_ret_t   rmw_take (
    const rmw_subscription_t *subscription,
    void *ros_message,
    bool *taken,
    rmw_subscription_allocation_t *allocation) {...}
```

Figure 5.8. Subscriber functions.

```
// Create an rmw service server that responds to requests
rmw_service_t *   rmw_create_service (
    const rmw_node_t *node,
    const rosidl_service_type_support_t *type_support,
    const char *service_name,
    const rmw_qos_profile_t *qos_policies) {...}

//  Destroy and unregister the service from this node
rmw_ret_t   rmw_destroy_service (
    rmw_node_t *node,
    rmw_service_t *service) {...}

// Attempt to take a request from this service's request buffer
rmw_ret_t   rmw_take_request (
    const rmw_service_t *service,
    rmw_service_info_t *request_header,
    void *ros_request,
    bool *taken) {...}

//  Send response to a client's request
rmw_ret_t   rmw_send_response (
    const rmw_service_t *service,
    rmw_request_id_t *request_header,
    void *ros_response) {...}
```

Figure 5.9. Service server functions.

Besides the essential functions for creating and destroying nodes, publishers, subscribers, and services, there exists additional functions to handle events, wait sets, guard conditions, QoS policies, and allocators. Additionally, there are utility functions and macros for handling errors, customizing log outputs and name validation. A full list of functions can be found in the rmw API documentation [Woo23] TODO: or appendix??.

```
// Create an rmw client to communicate with the specified service
rmw_client_t *  rmw_create_client (
    const rmw_node_t *node,
    const rosidl_service_type_support_t *type_support,
    const char *service_name,
    const rmw_qos_profile_t *qos_policies) {...}

// Destroy and unregister a service client
rmw_ret_t   rmw_destroy_client (
    rmw_node_t *node,
    rmw_client_t *client) {...}

// Send a service request to the rmw server
rmw_ret_t   rmw_send_request (
    const rmw_client_t *client,
    const void *ros_request,
    int64_t *sequence_id) {...}

// Attempt to get the response from a service request
rmw_ret_t   rmw_take_response (
    const rmw_client_t *client,
    rmw_service_info_t *request_header,
    void *ros_response,
    bool *taken) {...}

// Check if a service server is available for the given service client
rmw_ret_t   rmw_service_server_is_available (
    const rmw_node_t *node,
    const rmw_client_t *client,
    bool *is_available) {...}
```

Figure 5.10. Service client functions.

5.3. Substituting ROS 2 Middleware

There are two methods of using a particular middleware implementations when launching ROS applications other than the default implementation. The first method requires setting the environment variable RMW_IMPLEMENTATION to the implementation identifier of choice. An example of how to launch a publisher node with this method is shown in Figure 5.11.

```
RMW_IMPLEMENTATION=rmw_connextdds ros2 run demo_nodes_cpp talker
```

Figure 5.11. Launching a node with Connext DDS.

Nonetheless, the caveat of this first method is that the ROS 2 binaries installed must have support for the specified implementation [Sco22]. Alternatively, the second method involves rebuilding all of the desired ROS 2 packages from source and specify the RMW_IMPLEMENTATION as a CMake argument. When building from source, if the packages for multiple RMW implementations are available, all of them will be built starting with Fast DDS as the default. If Fast DDS is not available, then the default implementation will be selected by the next available implementation identifier in alphabetical order [Lor22]. To ensure that only a single implementation is available for use, the simplest solution is to explicitly ignore or remove the packages belonging to undesired implementations from the workspace.

6. ROS 2 Middleware Implementation for WebAssembly

The design of a custom middleware implementation, rms_wasm, that can be cross-compiled to WebAssembly modules is divided into three distinct packages as observed in Figure 6.1.

Figure 6.1. Architecture of custom middleware implementation to target WebAssembly.

6.1. rmw_wasm_cpp

The first package, rmw_wasm_cpp, works as the "adapter" between ROS 2 and the designed middleware. This package implements all of the functions required for rmw as described in Section 5.2.3. The source code for this package is entirely written in C++ and can be found: TODO:

TODO: add diagram

6.2. wasm_cpp

The role of wasm_cpp is to TODO: and to function as a bridge to JavaScript functions.

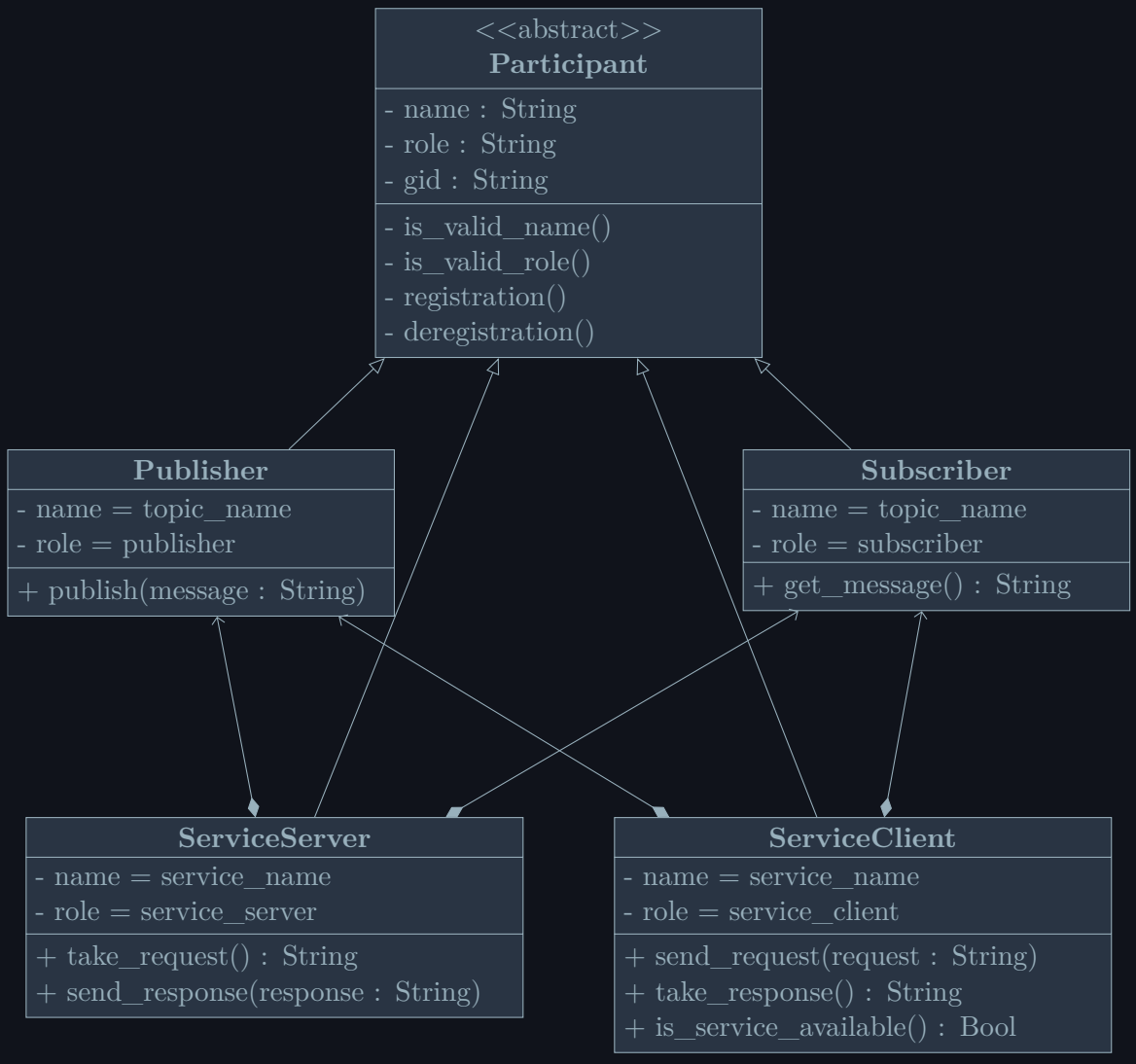


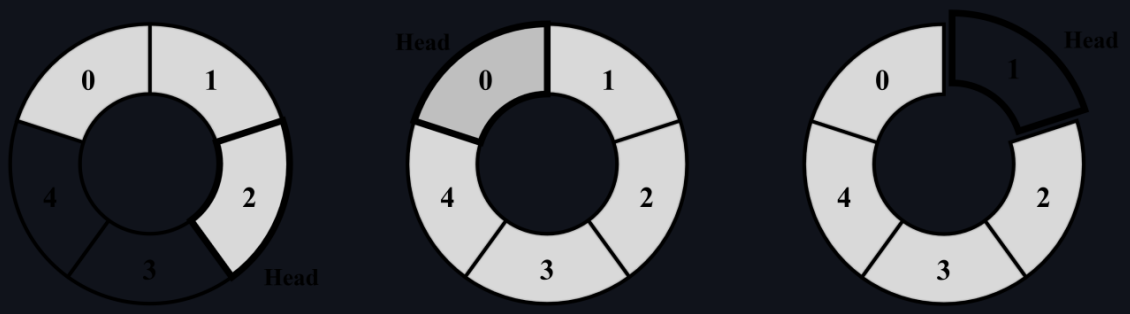
Figure 6.2. A class diagram

6.3. wasm_js

6.4. Design of Web Elements

6.5. Web Workers

6.6. Message Stacks



(a) Filling stack **(b)** Overwriting stack **(c)** Reading stack

Figure 6.3. Modified Circular Stack, Last In, First Out (LIFO)

- Web workers, what are they? why are they needed? - Communication channels - Registry of topics/-subs/pubs - Message handling width

7. Concept Assessment

- Survey - Performance measures - Limitations

8. Conclusion

8.1. Outlook

- Compiling on the browser - Packaging Gazebo - WASI

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C. Code

C.1. Build Script

```
#!/bin/bash

#------------------------------------------------------------
# HELP
#------------------------------------------------------------
Help()
{
    echo -e "Options:"
    echo "-h     help"
    echo "-c     clean workspace"
    echo "-d     activate cmake debug mode"
    echo "-u     build up to package"
    echo "-s     build selected package"
    echo "-i     ignore \'listed packages\'"
    echo "-p     install emscripten python"
    echo "-v     verbose"
    echo -e "\n"
}

#------------------------------------------------------------
# INSTALL PYTHON
#------------------------------------------------------------
InstallPython()
{
    # Install emscripten python
    CONDA_META_DIR="${PWD}/install/conda-meta"
    [[ -d "${CONDA_META_DIR}" ]] || mkdir -p "${CONDA_META_DIR}"
    micromamba install -p ./install python --platform=emscripten-32 \
        -c https://repo.mamba.pm/emscripten-forge -y
    mv ./install/bin/python3 ./install/bin/old_python3
}

#------------------------------------------------------------
# VARIABLES
#------------------------------------------------------------
VERBOSE=0
EMSDK_VERBOSE=0
verbose_args=""
package_args=""
package_ignore="--packages-ignore rosidl_generator_py"
```

```
debug_mode=OFF

export RMW_IMPLEMENTATION="rmw_wasm_cpp"

#-----------------------------------------------------------------
# OPTIONS
#-----------------------------------------------------------------

while getopts "hcvpu:s:i:" option; do
    case $option in
        h) # Display help
            Help
            exit;;

        c) # Clean workspace
            [[ -d "${PWD}/install" ]] && rm -rf "${PWD}/install"
            [[ -d "${PWD}/build" ]]   && rm -rf "${PWD}/build"
            [[ -d "${PWD}/log" ]]     && rm -rf "${PWD}/log"
            exit;;

        d) # Activate cmake debug
            debug_mode=ON
            echo "[BLASM]: CMake debug mode activated.";;

        v) # Make verbose
            VERBOSE=1
            EMSDK_VERBOSE=1
            verbose_args="--event-handlers console_direct+"
            echo "[BLASM]: Verbose activated.";;

        p) # Install emscripten python
            echo "[BLASM]: Installing python."
            package_ignore=""
            InstallPython;;

        u) # Build up to package
            package_args="--packages-up-to ${OPTARG}"
            echo "[BLASM]: Build up to ${OPTARG}.";;

        s) # Build selected package
            [[ -d "${PWD}/build/${OPTARG}" ]] && rm -rf "${PWD}/build/${OPTARG}"
            package_args="--packages-select ${OPTARG}"
            echo "[BLASM]: Build only ${OPTARG}.";;

        i) # Ignore "given packages"
            package_ignore="--packages-ignore ${OPTARG}"
            echo "[BLASM]: Ignore packages ${OPTARG}.";;
```

```
        \?) # Invalid option
            echo "Error: Invalid option."
            Help
            exit;;
    esac
done

#-----------------------------------------------------------------
# MAIN
#-----------------------------------------------------------------
[[ -z "${package_args}" ]] && { echo "No args given."; exit 1; }
[[ -d "${PWD}/src" ]] || { echo "Not a workspace directory"; exit 1; }

echo "[BLASM]: Commencing build."

colcon build \
    ${package_args} ${package_ignore} ${verbose_args} \
    --packages-skip-build-finished \
    --merge-install \
    --cmake-args \
        -DCMAKE_TOOLCHAIN_FILE="${EMSDK_DIR}/upstream/emscripten/cmake/Modules/
    Platform/Emscripten.cmake" \
        -DBUILD_TESTING=OFF \
        -DBUILD_SHARED_LIBS=ON \
        -DCMAKE_VERBOSE_MAKEFILE=${debug_mode} \
        -DCMAKE_FIND_ROOT_PATH_MODE_PACKAGE=ON \
        -DCMAKE_CROSSCOMPILING=TRUE \
        -DCMAKE_FIND_DEBUG_MODE=${debug_mode} \
        -DFORCE_BUILD_VENDOR_PKG=ON \
        -DPYBIND11_PYTHONLIBS_OVERWRITE=OFF
```

C.2. JavaScript Functions

```
// The Module object: Our interface to the outside world. We import
// and export values on it. There are various ways Module can be used:
// 1. Not defined. We create it here
// 2. A function parameter, function(Module) { ..generated code.. }
// 3. pre-run appended it, var Module = {}; ..generated code..
// 4. External script tag defines var Module.
// We need to check if Module already exists (e.g. case 3 above).
// Substitution will be replaced with actual code on later stage of the build,
// this way Closure Compiler will not mangle it (e.g. case 4. above).
// Note that if you want to run closure, and also to use Module
```

```
// after the generated code, you will need to define   var Module = {};
// before the code. Then that object will be used in the code, and you
// can continue to use Module afterwards as well.
var Module = typeof Module != 'undefined' ? Module : {};

function sleep(ms) {
     new Promise(resolve => setTimeout(resolve, ms));
}

let lastMessage = "data: empty";
let receivedNewMessage = false;
let topic = "";

self.onmessage = function(event) {
    // When a new message is received from main
    lastMessage = event.data;
    receivedNewMessage = true;
}

Module["registerParticipant"] = function registerParticipant(topic_name, role)
{
    topic = topic_name;
    let gid = Math.random().toString(16).slice(2)

    // Register new participant with main
    self.postMessage({
        command: "register",
        topic:   topic_name,
        role:    role,
        gid:     gid
    });

    return gid;
}

Module["deregisterParticipant"] = function deregisterParticipant(gid)
{
    // Deregister participant from main
    self.postMessage({
        command: "deregister",
        topic:   topic,
        gid:     gid
    });

    return;
}
```

```
Module["publishMessage"] = function publishMessage(message, topic_name)
{
    // Send message to main
    if (message.startsWith("data:")) {
        self.postMessage({
        command: "publish",
        topic:    topic_name,
        message: message
        });
    }

    // Assume it gets published
    return true;
}

Module["retrieveMessage"] = async function retrieveMessage(topic_name)
{
    receivedNewMessage = false;
    // Trigger main to send new message
    self.postMessage({
        command: "retrieve",
        topic:    topic_name
    });

    await sleep(100);

    return ( receivedNewMessage ? lastMessage : "" );
}
```