Programming for Robotics - Introduction to ROS

Presentation · February 2017

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Programming for Robotics
Introduction to ROS

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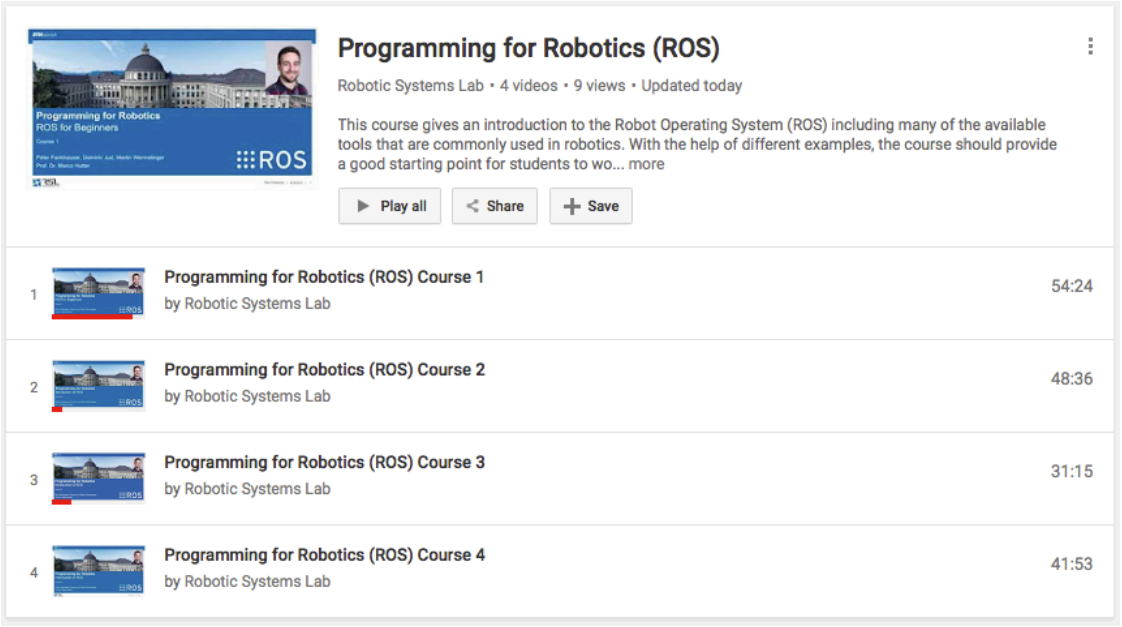
ROS

Presentation videos

https://www.youtube.com/playlist?list=PLE-BQwvVGf8HOvwXPgtDfWoxd4Cc6ghiP



Course Material & Exercises

http://www.rsl.ethz.ch/education-students/lectures/ros.html

Course material

	Topics	Material
20.2.	– ROS architecture & philosophy – ROS master, nodes, and topics – Console commands – Catkin workspace and build system – Launch-files – Gazebo simulator	– Video recording – Lecture 1 (PDF, 3.2 MB) Updated 22.02.2017 – Exercise 1 (PDF, 290 KB) Updated 22.02.2017
23.2.	– ROS package structure – Integration and programming with Eclipse – ROS C++ client library (roscpp) – ROS subscribers and publishers – ROS parameter server – RViz visualization	– Lecture 2 (PDF, 4.1 MB) Updated 24.02.2017 – Exercise 2 (PDF, 210 KB) Updated 22.02.2017 – Husky Highlevel Controller Template (ZIP, 3 KB) Updated 22.02.2017 – Example Solution Exercise 2 (ZIP, 5 KB) Updated 24.02.2017
24.2.	– TF Transformation System – rqt User Interface – Robot models (URDF) – Simulation descriptions (SDF)	– Lecture 3 (PDF, 5.5 MB) Updated 24.02.2017 – Exercise 3 (PDF, 227 KB) Updated 23.02.2017 – ROS Worlds (ZIP, 1 KB) Updated 13.02.2017
27.2.	– ROS services – ROS actions (actionlib) – ROS time – ROS bags – Debugging strategies	– Lecture 4 (PDF, 966 KB) Updated 26.02.2017 – Exercise 4 (PDF, 384 KB) Updated 26.02.2017 – ROS Bag (BAG, 158.9 MB) Updated 13.02.2017
2.3.	– Case study: Using ROS in complex real-world applications	– Exercise 5 (PDF, 127 KB) Updated 13.02.2017

Overview

- **Part 1**
  - ROS architecture & philosophy
  - ROS master, nodes, and topics
  - Console commands
  - Catkin workspace and build system
  - Launch-files
  - Gazebo simulator
- **Part 2**
  - ROS package structure
  - Integration and programming with Eclipse
  - ROS C++ client library (roscpp)
  - ROS subscribers and publishers
  - ROS parameter server
  - RViz visualization
- **Part 3**
  - TF Transformation System
  - rqt User Interface
  - Robot models (URDF)
  - Simulation descriptions (SDF)
- **Part 4**
  - ROS services
  - ROS actions (actionlib)
  - ROS time
  - ROS bags
  - Debugging strategies
- **Part 5**
  - Case study

Overview Part 1

- ROS architecture & philosophy
- ROS master, nodes, and topics
- Console commands
- Catkin workspace and build system
- Launch-files
- Gazebo simulator

What is ROS?

ROS = Robot Operating System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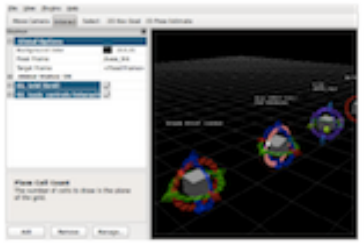
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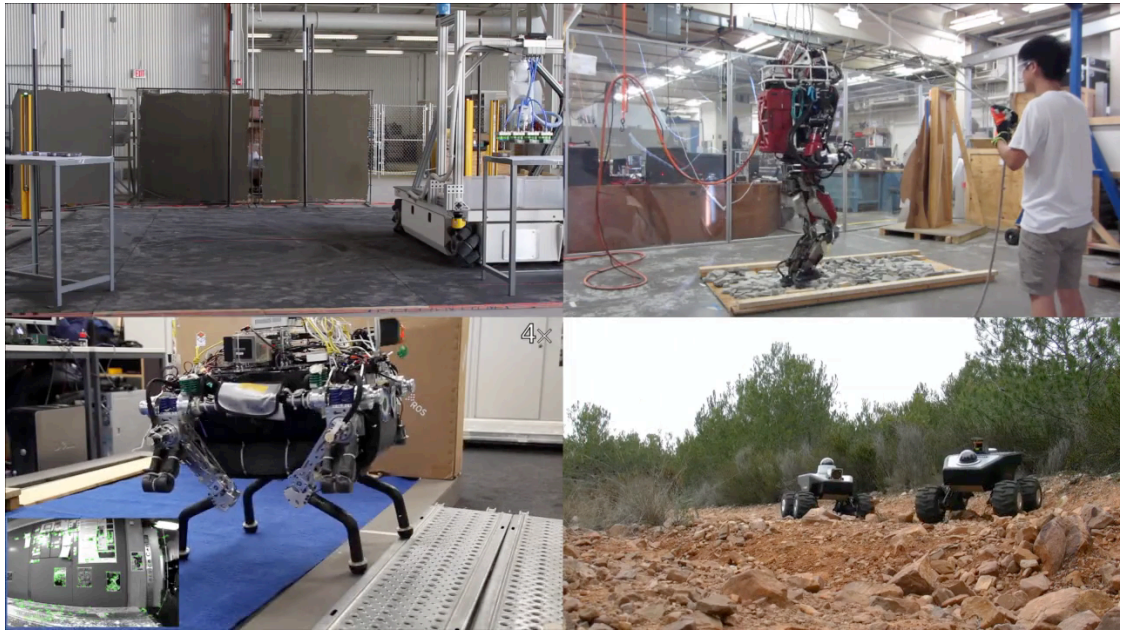
ros.org

Plumbing	Tools	Capabilities	Ecosystem
▪ Process management ▪ Inter-process communication ▪ Device drivers	▪ Simulation ▪ Visualization ▪ Graphical user interface ▪ Data logging	▪ Control ▪ Planning ▪ Perception ▪ Mapping ▪ Manipulation	▪ Package organization ▪ Software distribution ▪ Documentation ▪ Tutorials

History of ROS

- Originally developed in 2007 at the Stanford Artificial Intelligence Laboratory
- Since 2013 managed by OSRF
- Today used by many robots, universities and companies
- De facto standard for robot programming



ros.org

ROS Philosophy

- **Peer to peer**
  Individual programs communicate over defined API (ROS *messages*, *services*, etc.).
- **Distributed**
  Programs can be run on multiple computers and communicate over the network.
- **Multi-lingual**
  ROS modules can be written in any language for which a client library exists (C++, Python, MATLAB, Java, etc.).
- **Light-weight**
  Stand-alone libraries are wrapped around with a thin ROS layer.
- **Free and open-source**
  Most ROS software is open-source and free to use.

ROS Workspace Environment

- Defines context for the current workspace
- Default workspace loaded with

```
> source /opt/ros/indigo/setup.bash
```

Overlay your *catkin workspace* with

```
> cd ~/catkin_ws
> source devel/setup.bash
```

Check your workspace with

```
> echo $ROS_PACKAGE_PATH
```

This is already setup in the provided installation.

See setup with

```
> cat ~/.bashrc
```

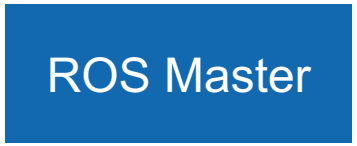
More info

http://wiki.ros.org/indigo/Installation/Ubuntu

http://wiki.ros.org/catkin/workspaces

ROS Master

- Manages the communication between nodes
- Every node registers at startup with the master



Start a master with

```
> roscore
```

More info
http://wiki.ros.org/Master

ROS Nodes

- Single-purpose, executable program
- Individually compiled, executed, and managed
- Organized in *packages*

Run a node with

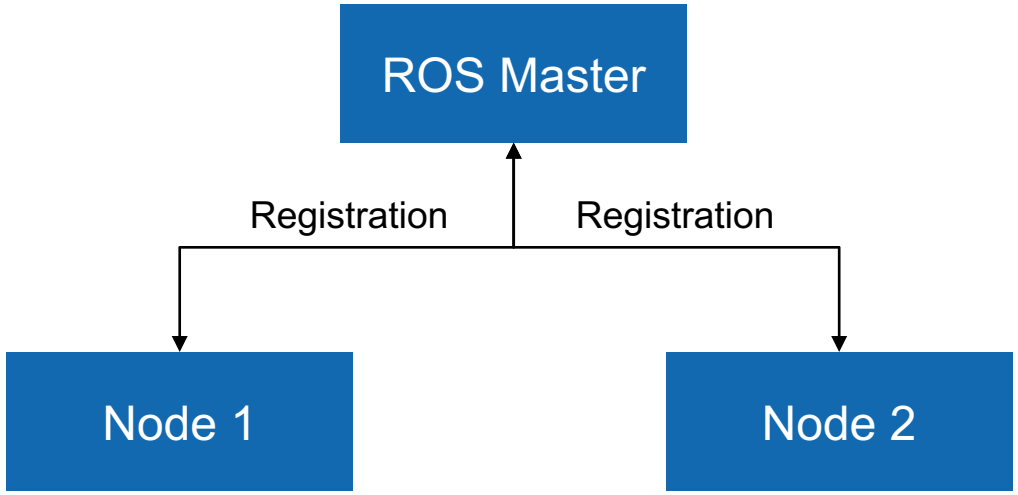
```
> rosrun package_name node_name
```

See active nodes with

```
> rosnode list
```

Retrieve information about a node with

```
> rosnode info node_name
```



More info
http://wiki.ros.org/rosnode

ROS Topics

- Nodes communicate over *topics*
  - Nodes can *publish* or *subscribe* to a topic
  - Typically, 1 publisher and *n* subscribers
- Topic is a name for a stream of *messages*

List active topics with

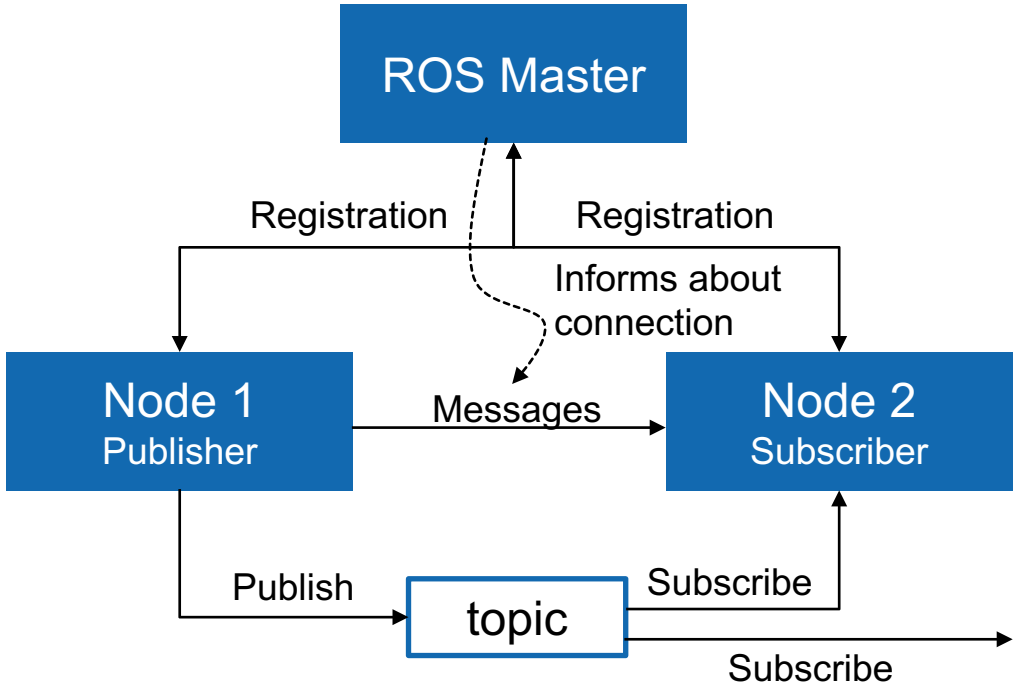
```
> rostopic list
```

Subscribe and print the contents of a topic with

```
> rostopic echo /topic
```

Show information about a topic with

```
> rostopic info /topic
```



More info
http://wiki.ros.org/rostopic

ROS Messages

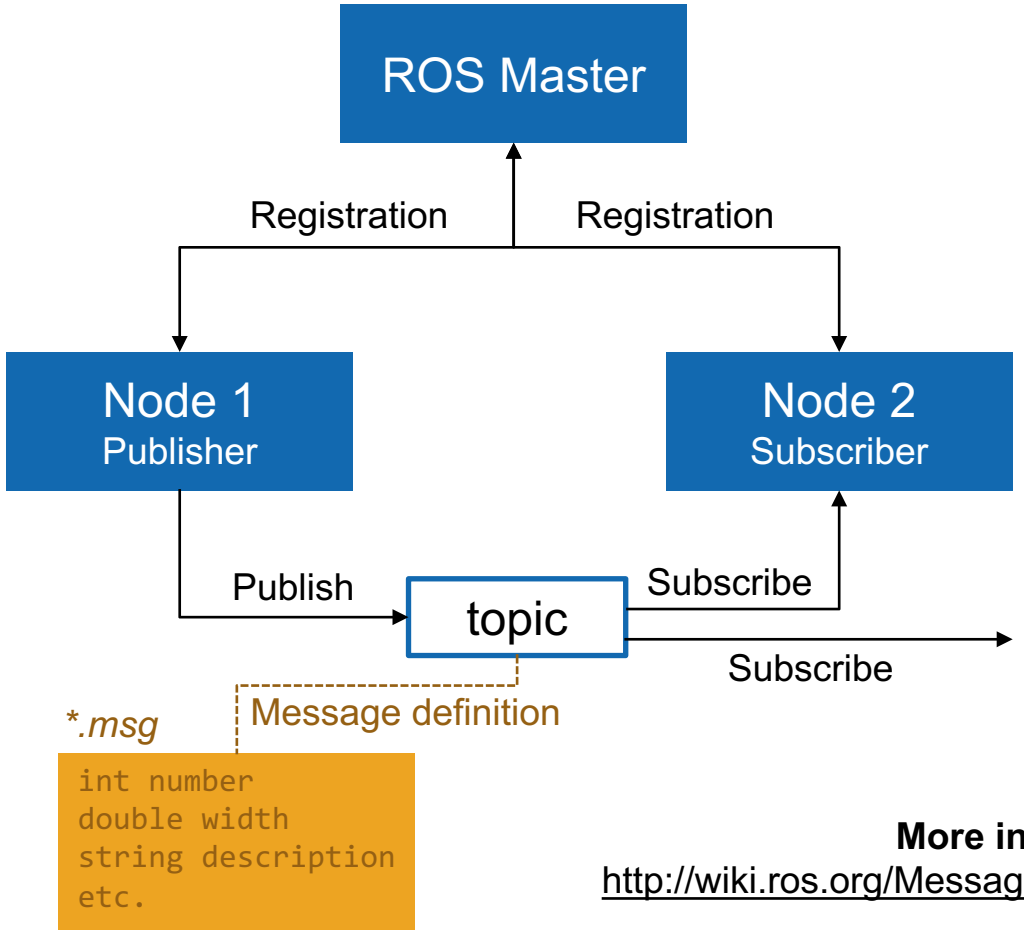
- Data structure defining the *type* of a topic
- Compromised of a nested structure of integers, floats, booleans, strings etc. and arrays of objects
- Defined in **.msg* files

See the type of a topic

```
> rostopic type /topic
```

Publish a message to a topic

```
> rostopic pub /topic type args
```



More info
http://wiki.ros.org/Messages

ROS Messages
Pose Stamped Example

geometry_msgs/Point.msg

```
float64 x
float64 y
float64 z
```

sensor_msgs/Image.msg

```
std_msgs/Header header
  uint32 seq
  time stamp
  string frame_id
uint32 height
uint32 width
string encoding
uint8 is_bigendian
uint32 step
uint8[] data
```

geometry_msgs/PoseStamped.msg

```
std_msgs/Header header
 uint32 seq
 time stamp
 string frame_id
geometry_msgs/Pose pose
  geometry_msgs/Point position
     float64 x
     float64 y
     float64 z
   geometry_msgs/Quaternion
orientation
     float64 x
     float64 y
     float64 z
     float64 w
```

Example
Console Tab Nr. 1 – Starting a *roscore*

Start a roscore with

```
> roscore
```

```
student@ubuntu:~/catkin_ws$ roscore
... logging to /home/student/.ros/log/6c1852aa-e961-11e6-8543-000c297bd368/ros
launch-ubuntu-6696.log
Checking log directory for disk usage. This may take awhile.
Press Ctrl-C to interrupt
Done checking log file disk usage. Usage is <1GB.

started roslaunch server http://ubuntu:34089/
ros_comm version 1.11.20


SUMMARY
========

PARAMETERS
 * /rosdistro: indigo
 * /rosversion: 1.11.20

NODES

auto-starting new master
process[master]: started with pid [6708]
ROS_MASTER_URI=http://ubuntu:11311/

setting /run_id to 6c1852aa-e961-11e6-8543-000c297bd368
process[rosout-1]: started with pid [6721]
started core service [/rosout]
```

Example

Console Tab Nr. 2 – Starting a *talker* node

Run a talker demo node with

```
> rosrun roscpp_tutorials talker
```

```
student@ubuntu:~/catkin_ws$ rosrun roscpp_tutorials talker
[ INFO] [1486051708.424661519]: hello world 0
[ INFO] [1486051708.525227845]: hello world 1
[ INFO] [1486051708.624747612]: hello world 2
[ INFO] [1486051708.724826782]: hello world 3
[ INFO] [1486051708.825928577]: hello world 4
[ INFO] [1486051708.925379775]: hello world 5
[ INFO] [1486051709.024971132]: hello world 6
[ INFO] [1486051709.125450960]: hello world 7
[ INFO] [1486051709.225272747]: hello world 8
[ INFO] [1486051709.325389210]: hello world 9
```

Example

Console Tab Nr. 3 – Analyze *talker* node

See the list of active nodes

```
> rosnode list
```

```
student@ubuntu:~/catkin_ws$ rosnode list
/rosout
/talker
```

Show information about the *talker* node

```
> rosnode info /talker
```

```
student@ubuntu:~/catkin_ws$ rosnode info /talker
--------------------------------------------------------------------------------
Node [/talker]
Publications:
 * /chatter [std_msgs/String]
 * /rosout [rosgraph_msgs/Log]

Subscriptions: None

Services:
 * /talker/get_loggers
 * /talker/set_logger_level
```

See information about the *chatter* topic

```
> rostopic info /chatter
```

```
student@ubuntu:~/catkin_ws$ rostopic info /chatter
Type: std_msgs/String

Publishers:
 * /talker (http://ubuntu:39173/)

Subscribers: None
```

Example

Console Tab Nr. 3 – Analyze *chatter* topic

Check the type of the *chatter* topic

```
> rostopic type /chatter
```

```
student@ubuntu:~/catkin_ws$ rostopic type /chatter
std_msgs/String
```

Show the message contents of the topic

```
> rostopic echo /chatter
```

```
student@ubuntu:~/catkin_ws$ rostopic echo /chatter
data: hello world 11874
---
data: hello world 11875
---
data: hello world 11876
```

Analyze the frequency

```
> rostopic hz /chatter
```

```
student@ubuntu:~/catkin_ws$ rostopic hz /chatter
subscribed to [/chatter]
average rate: 9.991
        min: 0.099s max: 0.101s std dev: 0.00076s window: 10
average rate: 9.996
        min: 0.099s max: 0.101s std dev: 0.00069s window: 20
```

Example
Console Tab Nr. 4 – Starting a *listener* node

Run a listener demo node with

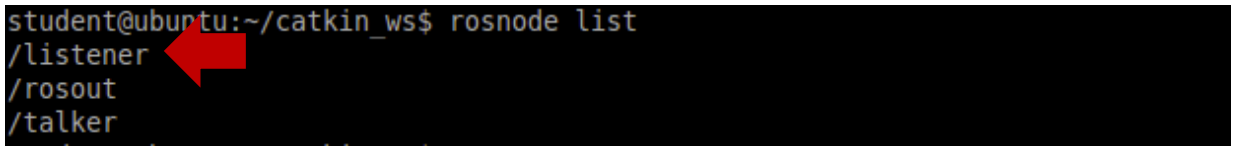
```
> rosrun roscpp_tutorials listener
```

```
student@ubuntu:~/catkin_ws$ rosrun roscpp_tutorials listener
[ INFO] [1486053802.204104598]: I heard: [hello world 19548]
[ INFO] [1486053802.304538827]: I heard: [hello world 19549]
[ INFO] [1486053802.403853395]: I heard: [hello world 19550]
[ INFO] [1486053802.504438133]: I heard: [hello world 19551]
[ INFO] [1486053802.604297608]: I heard: [hello world 19552]
```

Example
Console Tab Nr. 3 – Analyze

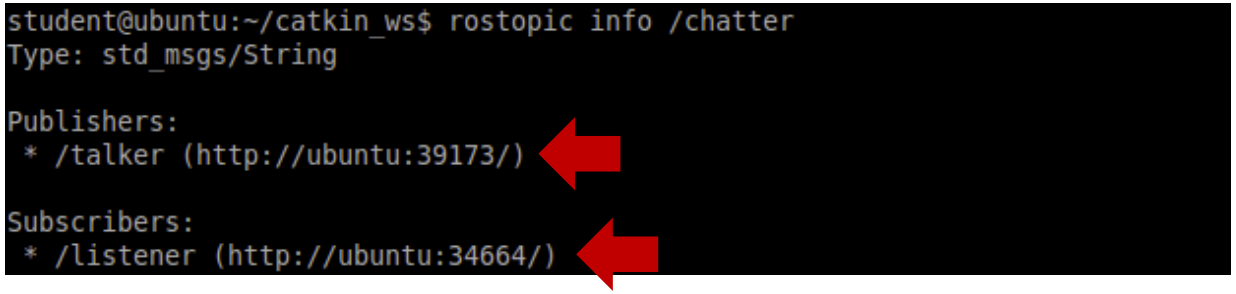
See the new *listener* node with

```
> rosnode list
```



Show the connection of the nodes over the chatter topic with

```
> rostopic info /chatter
```



Example
Console Tab Nr. 3 – Publish Message from Console

Close the *talker* node in console nr. 2 with `Ctrl + C`

Publish your own message with

```
> rostopic pub /chatter std_msgs/String
  "data: 'ETH Zurich ROS Course'"
```

```
student@ubuntu:~/catkin_ws$ rostopic pub /chatter std_msgs/String "data: 'ETH
Zurich ROS Course'"
publishing and latching message. Press ctrl-C to terminate
```

Check the output of the *listener* in console nr. 4

```
[ INFO] [1486054667.604322265]: I heard: [hello world 28202]
[ INFO] [1486054667.704264199]: I heard: [hello world 28203]
[ INFO] [1486054667.804389058]: I heard: [hello world 28204]
[ INFO] [1486054707.646404558]: I heard: [ETH Zurich ROS Course]
```

catkin Build System

- *catkin* is the ROS build system to generate executables, libraries, and interfaces
- We suggest to use the *Catkin Command Line Tools*

➔ Use **`catkin build`** instead of `catkin_make`

Navigate to your catkin workspace with

```
> cd ~/catkin_ws
```

Build a package with

```
> catkin build package_name
```

! Whenever you build a **new** package, update your environment

```
> source devel/setup.bash
```

The catkin command line tools are pre-installed in the provided installation.

More info
http://wiki.ros.org/catkin/Tutorials
https://catkin-tools.readthedocs.io/

catkin Build System

The catkin workspace contains the following spaces

Work here

The *source space* contains the source code. This is where you can clone, create, and edit source code for the packages you want to build.

Don't touch

The *build space* is where CMake is invoked to build the packages in the source space. Cache information and other intermediate files are kept here.

Don't touch

The *development (devel) space* is where built targets are placed (prior to being installed).

If necessary, clean the entire build and devel space with

```
> catkin clean
```

More info
http://wiki.ros.org/catkin/workspaces

catkin Build System

The catkin workspace setup can be checked with

```
> catkin config
```

For example, to set the *CMake build type* to Release (or Debug etc.), use

```
> catkin build --cmake-args
      -DCMAKE_BUILD_TYPE=Release
```

```
student@ubuntu:~/catkin_ws$ catkin config
--------------------------------------------------------------------------------
Profile:                     default
Extending:             [env] /opt/ros/indigo:/home/student/catkin_ws/devel
Workspace:                   /home/student/catkin_ws
--------------------------------------------------------------------------------
Source Space:       [exists] /home/student/catkin_ws/src
Log Space:          [exists] /home/student/catkin_ws/logs
Build Space:        [exists] /home/student/catkin_ws/build
Devel Space:        [exists] /home/student/catkin_ws/devel
Install Space:      [unused] /home/student/catkin_ws/install
DESTDIR:            [unused] None
--------------------------------------------------------------------------------
Devel Space Layout:          linked
Install Space Layout:        None
--------------------------------------------------------------------------------
Additional CMake Args:       -GEclipse CDT4 - Unix Makefiles -DCMAKE_CXX_COMP
ILER_ARG1=-std=c++11 -DCMAKE_BUILD_TYPE=Release
Additional Make Args:        None
Additional catkin Make Args: None
Internal Make Job Server:    True
Cache Job Environments:      False
--------------------------------------------------------------------------------
Whitelisted Packages:        None
Blacklisted Packages:        None
--------------------------------------------------------------------------------
Workspace configuration appears valid.
--------------------------------------------------------------------------------
```

Already setup in the provided installation.

More info
http://catkin-tools.readthedocs.io/en/latest/verbs/catkin_config.html
http://catkin-tools.readthedocs.io/en/latest/cheat_sheet.html

Example

Open a terminal and browse to your `git` folder

```
> cd ~/git
```

Clone the Git repository with

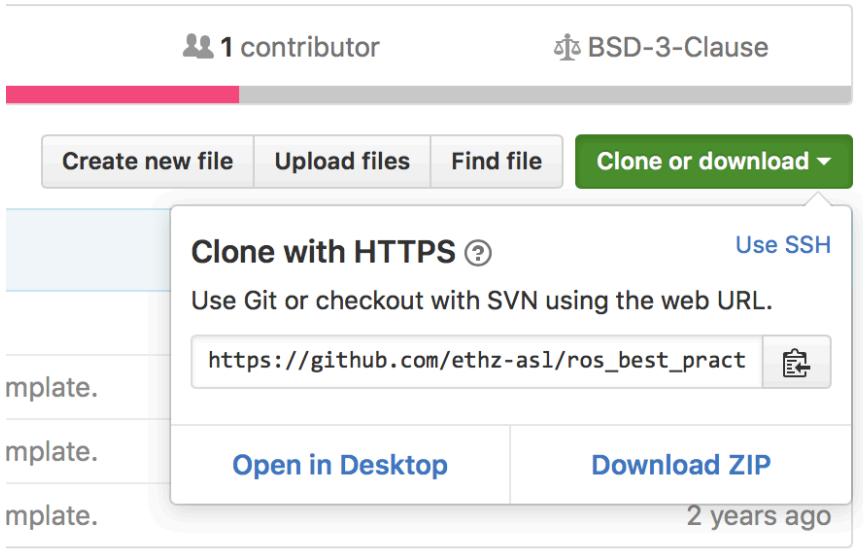
```
> git clone https://github.com/ethz-asl/ros_best_practices.git
```

Symlink the new package to your catkin workspace

```
> ln -s ~/git/ros_best_practices/ ~/catkin_ws/src/
```

Note: You could also directly clone to your catkin workspace, but using a common `git` folder is convenient if you have multiple catkin workspaces.

https://github.com/ethz-asl/ros_best_practices



Example

Go to your catkin workspace

```
> cd ~/catkin_ws
```

Build the package with

```
> catkin build ros_package_template
```

Re-source your workspace setup

```
> source devel/setup.bash
```

Launch the node with

```
> roslaunch ros_package_template
  ros_package_template.launch
```

```
NOTE: Forcing CMake to run for each package.
--------------------------------------------------------------------------------
[build] Found '1' packages in 0.0 seconds.
[build] Updating package table.
Starting  >>> catkin_tools_prebuild
Finished  <<< catkin_tools_prebuild                [ 1.0 seconds ]
Starting  >>> ros_package_template
Finished  <<< ros_package_template                 [ 4.1 seconds ]
[build] Summary: All 2 packages succeeded!
[build]   Ignored:   None.
[build]   Warnings:  None.
[build]   Abandoned: None.
[build]   Failed:    None.
[build] Runtime: 5.2 seconds total.
[build] Note: Workspace packages have changed, please re-source setup files to u
se them.
student@ubuntu:~/catkin_ws$
```

```
 * /rosdistro: indigo
 * /rosversion: 1.11.20

NODES
  /
    ros_package_template (ros_package_template/ros_package_template)

auto-starting new master
process[master]: started with pid [27185]
ROS_MASTER_URI=http://localhost:11311

setting /run_id to e43f937a-ed52-11e6-9789-000c297bd368
process[rosout-1]: started with pid [27198]
started core service [/rosout]
process[ros_package_template-2]: started with pid [27201]
[ INFO] [1486485095.843512614]: Successfully launched node.
```

ROS Launch

- *launch* is a tool for launching multiple nodes (as well as setting parameters)
- Are written in XML as **.launch* files
- If not yet running, launch automatically starts a roscore

Browse to the folder and start a launch file with

```
> roslaunch file_name.launch
```

Start a launch file from a package with

```
> roslaunch package_name file_name.launch
```

More info
http://wiki.ros.org/roslaunch

Example console output for
`roslaunch roscpp_tutorials talker_listener.launch`

```
student@ubuntu:~/catkin_ws$ roslaunch roscpp_tutorials talker_listener.launch
... logging to /home/student/.ros/log/794321aa-e950-11e6-95db-000c297bd368/rosl
Checking log directory for disk usage. This may take awhile.
Press Ctrl-C to interrupt
Done checking log file disk usage. Usage is <1GB.

started roslaunch server http://ubuntu:37592/

SUMMARY
========

PARAMETERS
 * /rosdistro: indigo
 * /rosversion: 1.11.20

NODES
  /
    listener (roscpp_tutorials/listener)
    talker (roscpp_tutorials/talker)

auto-starting new master
process[master]: started with pid [5772]
ROS_MASTER_URI=http://localhost:11311

setting /run_id to 794321aa-e950-11e6-95db-000c297bd368
process[rosout-1]: started with pid [5785]
started core service [/rosout]
process[listener-2]: started with pid [5788]
process[talker-3]: started with pid [5795]
[ INFO] [1486044252.537801350]: hello world 0
[ INFO] [1486044252.638886504]: hello world 1
[ INFO] [1486044252.738279674]: hello world 2
[ INFO] [1486044252.838357245]: hello world 3
```

ROS Launch
File Structure

talker_listener.launch

```
<launch>
    <node name="listener" pkg="roscpp_tutorials" type="listener" output="screen"/>
    <node name="talker" pkg="roscpp_tutorials" type="talker" output="screen"/>
</launch>
```

! Notice the syntax difference for self-closing tags: `<tag></tag>` and `<tag/>`

- **`launch`**: Root element of the launch file
- **`node`**: Each *<node>* tag specifies a node to be launched
- **`name`**: Name of the node (free to choose)
- **`pkg`**: Package containing the node
- **`type`**: Type of the node, there must be a corresponding executable with the same name
- **`output`**: Specifies where to output log messages (`screen`: console, `log`: log file)

More info
http://wiki.ros.org/roslaunch/XML
http://wiki.ros.org/roslaunch/Tutorials/Roslaunch%20tips%20for%20larger%20projects

ROS Launch
Arguments

- Create re-usable launch files with <arg> tag, which works like a parameter (default optional)

```
<arg name="arg_name" default="default_value"/>
```

- Use arguments in launch file with

```
$(arg arg_name)
```

- When launching, arguments can be set with

```
> roslaunch launch_file.launch arg_name:=value
```

range_world.launch (simplified)

```
<?xml version="1.0"?>
<launch>
  <arg name="use_sim_time" default="true"/>
  <arg name="world" default="gazebo_ros_range"/>
  <arg name="debug" default="false"/>
  <arg name="physics" default="ode"/>

  <group if="$(arg use_sim_time)">
    <param name="/use_sim_time" value="true" />
  </group>

  <include file="$(find gazebo_ros)
                                 /launch/empty_world.launch">
    <arg name="world_name" value="$(find gazebo_plugins)/
                      test/test_worlds/$(arg world).world"/>
    <arg name="debug" value="$(arg debug)"/>
    <arg name="physics" value="$(arg physics)"/>
  </include>
</launch>
```

More info
http://wiki.ros.org/roslaunch/XML/arg

ROS Launch
Including Other Launch Files

- Include other launch files with <include> tag to organize large projects

```
<include file="package_name"/>
```

- Find the system path to other packages with

```
$(find package_name)
```

- Pass arguments to the included file

```
<arg name="arg_name" value="value"/>
```

range_world.launch (simplified)

```
<?xml version="1.0"?>
<launch>
  <arg name="use_sim_time" default="true"/>
  <arg name="world" default="gazebo_ros_range"/>
  <arg name="debug" default="false"/>
  <arg name="physics" default="ode"/>

  <group if="$(arg use_sim_time)">
    <param name="/use_sim_time" value="true" />
  </group>

  <include file="$(find gazebo_ros)
                                 /launch/empty_world.launch">
    <arg name="world_name" value="$(find gazebo_plugins)/
                      test/test_worlds/$(arg world).world"/>
    <arg name="debug" value="$(arg debug)"/>
    <arg name="physics" value="$(arg physics)"/>
  </include>
</launch>
```

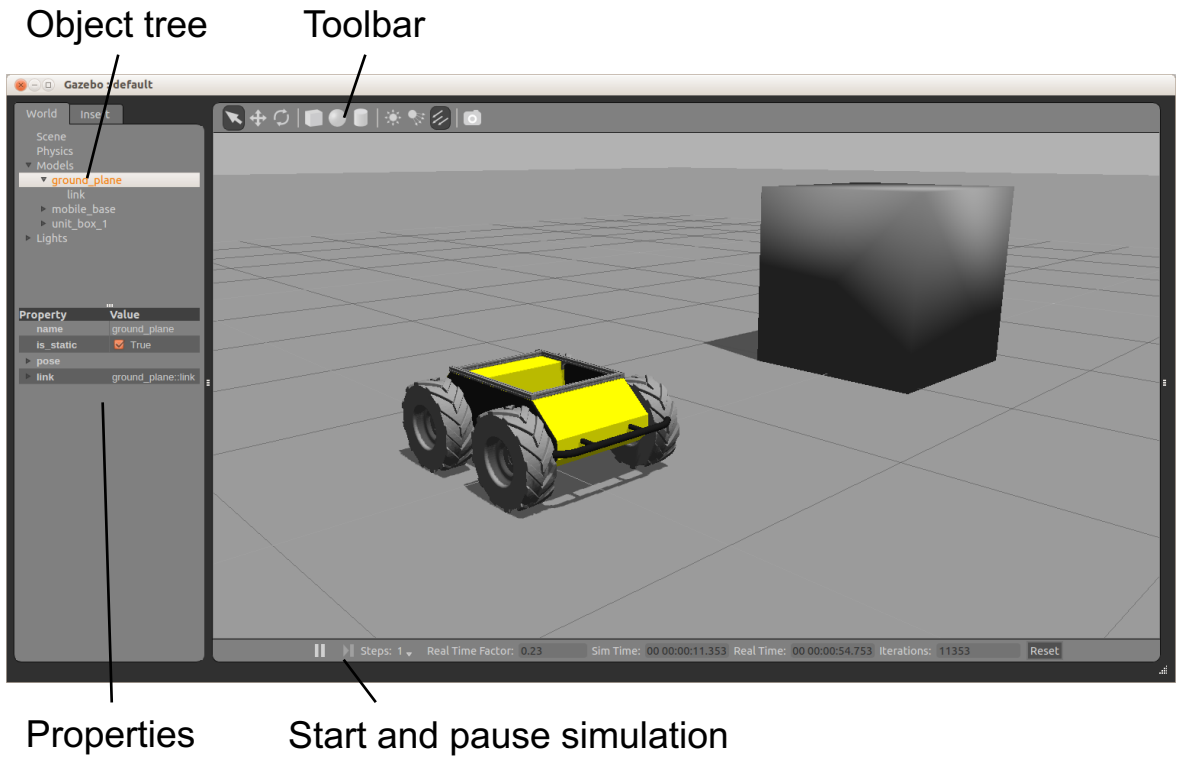
More info
http://wiki.ros.org/roslaunch/XML/include

Gazebo Simulator

- Simulate 3d rigid-body dynamics
- Simulate a variety of sensors including noise
- 3d visualization and user interaction
- Includes a database of many robots and environments (*Gazebo worlds*)
- Provides a ROS interface
- Extensible with plugins

Run Gazebo with

```
> rosrun gazebo_ros gazebo
```



More info
http://gazebosim.org/
http://gazebosim.org/tutorials

Overview Part 2

- ROS package structure
- Integration and programming with Eclipse
- ROS C++ client library (roscpp)
- ROS subscribers and publishers
- ROS parameter server
- RViz visualization

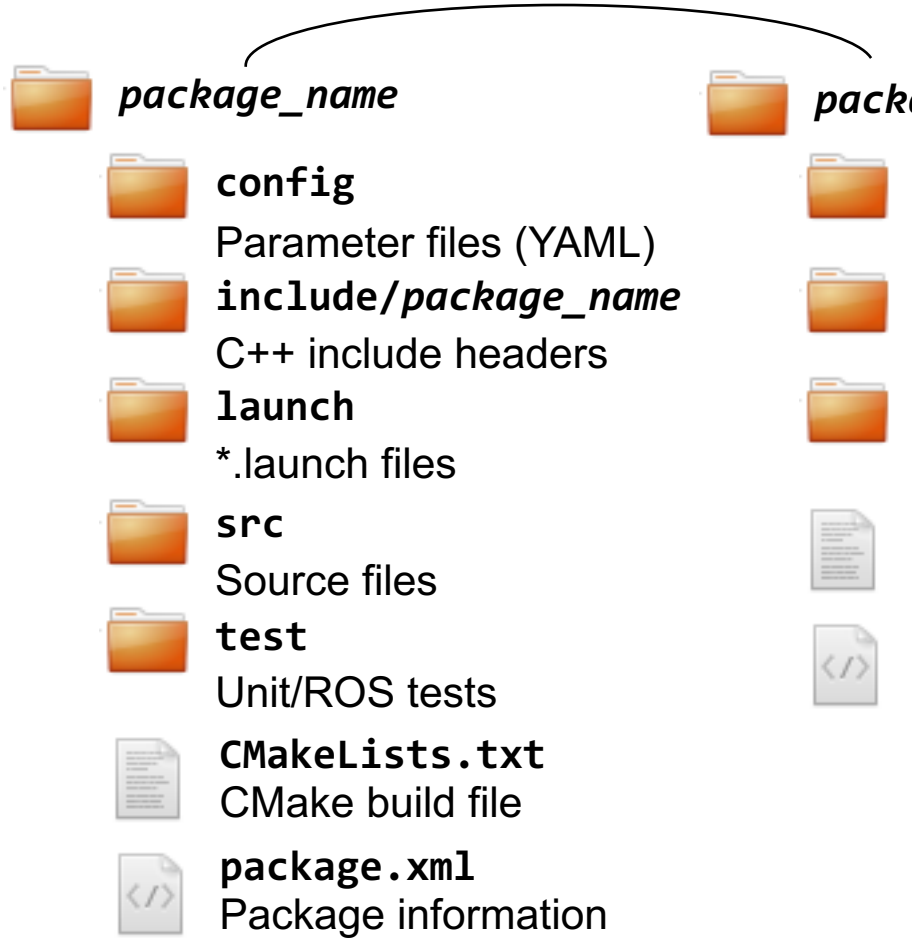
ROS Packages

- ROS software is organized into *packages*, which can contain source code, launch files, configuration files, message definitions, data, and documentation
- A package that builds up on/requires other packages (e.g. message definitions), declares these as *dependencies*

To create a new package, use

```
> catkin_create_pkg package_name
    {dependencies}
```

Separate message definition packages from other packages!



More info
http://wiki.ros.org/Packages

ROS Packages
package.xml

- The `package.xml` file defines the properties of the package
  - Package name
  - Version number
  - Authors
  - **Dependencies on other packages**
  - …

package.xml

```
<?xml version="1.0"?>
<package format="2">
  <name>ros_package_template</name>
  <version>0.1.0</version>
  <description>A template for ROS packages.</description>
  <maintainer email="pfankhauser@e…">Peter Fankhauser</maintainer>
  <license>BSD</license>
  <url type="website">https://github.com/ethz-asl/ros_best_pr…</url>
  <author email="pfankhauser@ethz.ch">Peter Fankhauser</author>

  <buildtool_depend>catkin</buildtool_depend>

  <depend>roscpp</depend>
  <depend>sensor_msgs</depend>
</package>
```

More info
http://wiki.ros.org/catkin/package.xml

ROS Packages
CMakeLists.xml

The `CMakeLists.txt` is the input to the CMakebuild system

1. Required CMake Version (`cmake_minimum_required`)
2. Package Name (`project()`)
3. Find other CMake/Catkin packages needed for build (`find_package()`)
4. Message/Service/Action Generators (`add_message_files()`, `add_service_files()`, `add_action_files()`)
5. Invoke message/service/action generation (`generate_messages()`)
6. Specify package build info export (`catkin_package()`)
7. Libraries/Executables to build (`add_library()`/`add_executable()`/`target_link_libraries()`)
8. Tests to build (`catkin_add_gtest()`)
9. Install rules (`install()`)

CMakeLists.txt

```
cmake_minimum_required(VERSION 2.8.3)
project(ros_package_template)

## Use C++11
add_definitions(--std=c++11)

## Find catkin macros and libraries
find_package(catkin REQUIRED
  COMPONENTS
    roscpp
    sensor_msgs
)

…
```

More info
http://wiki.ros.org/catkin/CMakeLists.txt

ROS Packages
CMakeLists.xml Example

```
cmake_minimum_required(VERSION 2.8.3)
project(husky_highlevel_controller)
add_definitions(--std=c++11)

find_package(catkin REQUIRED
  COMPONENTS roscpp sensor_msgs
)

catkin_package(
  INCLUDE_DIRS include
  # LIBRARIES
  CATKIN_DEPENDS roscpp sensor_msgs
  # DEPENDS
)

include_directories(include ${catkin_INCLUDE_DIRS})

add_executable(${PROJECT_NAME} src/${PROJECT_NAME}_node.cpp
src/HuskyHighlevelController.cpp)

target_link_libraries(${PROJECT_NAME} ${catkin_LIBRARIES})
```

Use the same name as in the `package.xml`

We use C++11 by default

List the packages that your package requires to build (have to be listed in `package.xml`)

Specify build export information
- `INCLUDE_DIRS`: Directories with header files
- `LIBRARIES`: Libraries created in this project
- `CATKIN_DEPENDS`: Packages dependent projects also need
- `DEPENDS`: System dependencies dependent projects also need (have to be listed in `package.xml`)

Specify locations of of header files

Declare a C++ executable

Specify libraries to link the executable against

Setup a Project in Eclipse

- Build the Eclipse project files with additional build flag

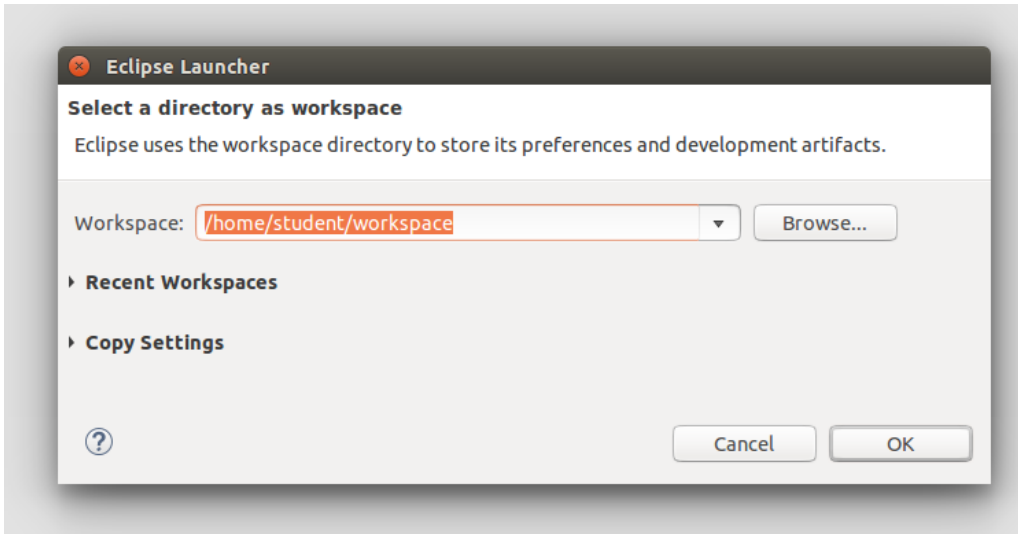
```
> catkin build package_name -G"Eclipse CDT4 - Unix Makefiles"
  -DCMAKE_CXX_COMPILER_ARG1=-std=c++11
```

- The project files will be generated in `~/catkin_ws/build`

The build flags are already setup in the provided installation.

Setup a Project in Eclipse

- Start Eclipse and set the workspace folder

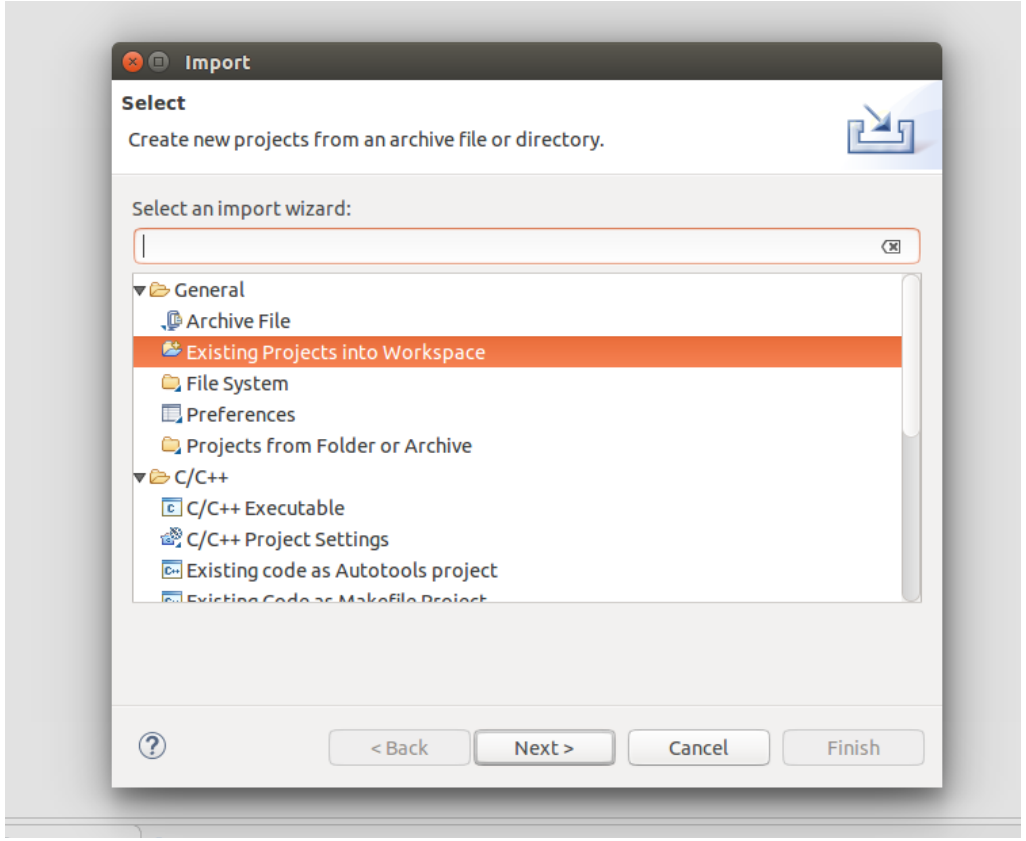


The Eclipse workspace is already set in the provided installation.

Setup a Project in Eclipse

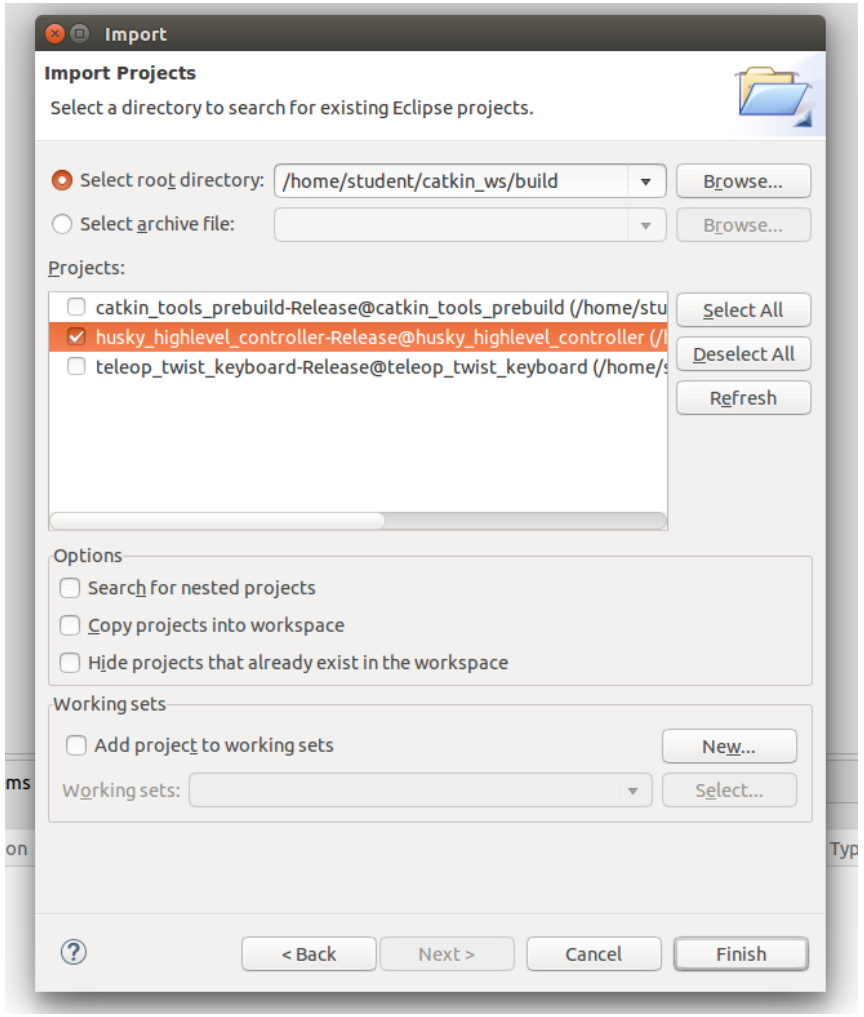
- Import your project to Eclipse

  File → Import → General
  → Existing Projects into Workspace



Setup a Project in Eclipse

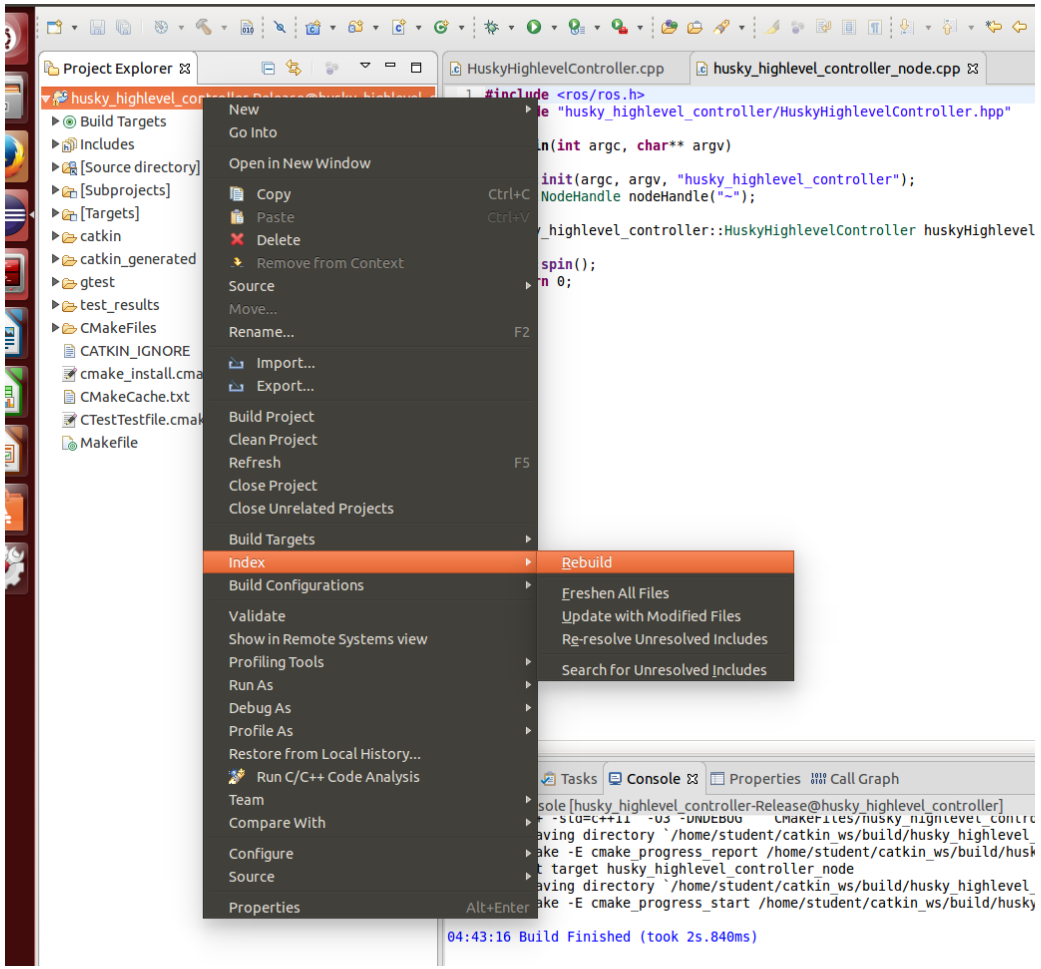
- The project files can be imported from the `~/catkin_ws/build` folder



Setup a Project in Eclipse

- Rebuild the C/C++ index of your project by Right click on Project → Index → Rebuild

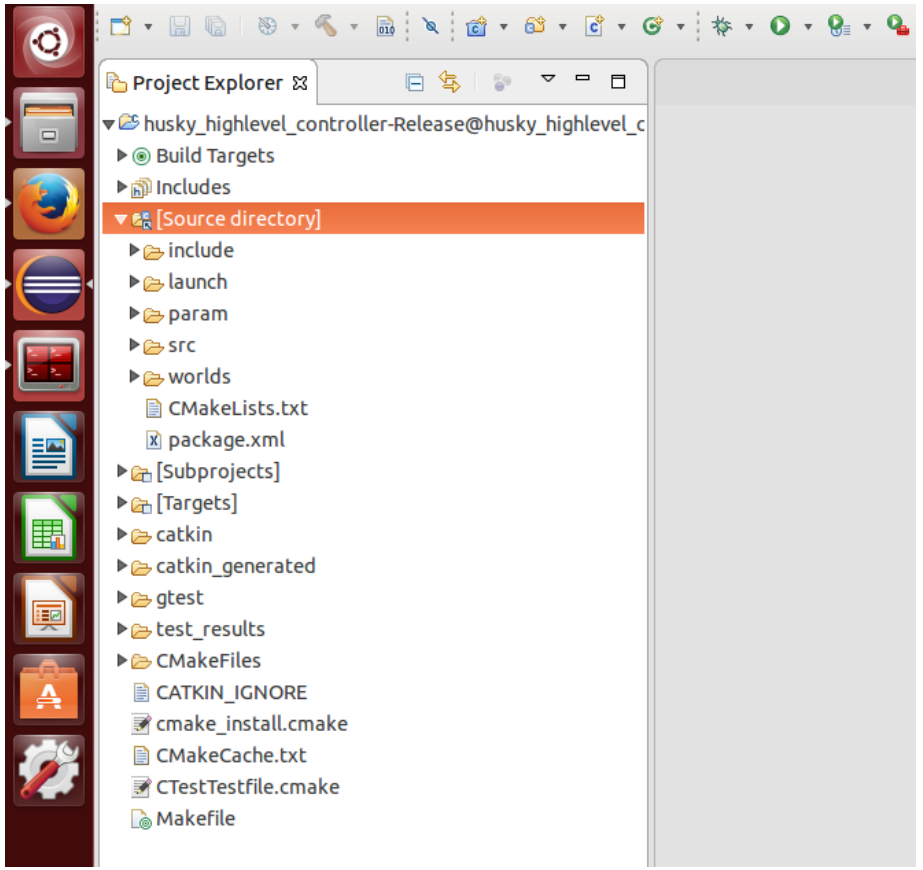
- Resolving the includes enables
  - Fast navigation through links (`Ctrl` + click)
  - Auto-completion (`Ctrl` + `Space`)
  - Building (`Ctrl` + `B`) and debugging your code in Eclipse



Setup a Project in Eclipse

- Within the project a link `[Source directory]` is provided such that you can edit your project

- Useful Eclipse shortcuts
  - `Ctrl` + `Space`: Auto-complete
  - `Ctrl` + `/`: Comment / uncomment line or section
  - `Ctrl` + `Shift` + `F`: Auto-format code using code formatter
  - `Alt` + `Arrow Up / Arrow Down`: Move line or selection up or down
  - `Ctrl` + `D`: Delete line



ROS C++ Client Library (*roscpp*)

hello_world.cpp

```
#include <ros/ros.h>

int main(int argc, char** argv)
{
  ros::init(argc, argv, "hello_world");
  ros::NodeHandle nodeHandle;
  ros::Rate loopRate(10);

  unsigned int count = 0;
  while (ros::ok()) {
    ROS_INFO_STREAM("Hello World " << count);
    ros::spinOnce();
    loopRate.sleep();
    count++;
  }

  return 0;
}
```

ROS main header file include

`ros::init(…)` has to be called before calling other ROS functions

The node handle is the access point for communications with the ROS system (topics, services, parameters)

`ros::Rate` is a helper class to run loops at a desired frequency

`ros::ok()` checks if a node should continue running
Returns `false` if `SIGINT` is received (`Ctrl` + `C`) or `ros::shutdown()` has been called

`ROS_INFO()` logs messages to the filesystem

`ros::spinOnce()` processes incoming messages via callbacks

More info
http://wiki.ros.org/roscpp
http://wiki.ros.org/roscpp/Overview

ROS C++ Client Library (*roscpp*)
Node Handle

- There are four main types of node handles

1. Default (public) node handle:
   `nh_ = ros::NodeHandle();`
2. Private node handle:
   `nh_private_ = ros::NodeHandle("~");`
3. Namespaced node handle:
   `nh_eth_ = ros::NodeHandle("eth");`
4. Global node handle:
   `nh_global_ = ros::NodeHandle("/");`

Recommended

Not recommended

For a ***node*** in ***namespace*** looking up ***topic***, these will resolve to:

```
/namespace/topic

/namespace/node/topic

/namespace/eth/topic

/topic
```

More info
http://wiki.ros.org/roscpp/Overview/NodeHandles

ROS C++ Client Library (*roscpp*)
Logging

- Mechanism for logging human readable text from nodes in the console and to log files
- Instead of `std::cout`, use e.g. `ROS_INFO`
- Automatic logging to console, log file, and `/rosout` topic
- Different severity levels (Info, Warn, Error etc.)
- Supports both printf- and stream-style formatting

```
ROS_INFO("Result: %d", result);
ROS_INFO_STREAM("Result: " << result);
```

- Further features such as conditional, throttled, delayed logging etc.

	Debug	Info	Warn	Error	Fatal
stdout	x	x			
stderr			x	x	x
Log file	x	x	x	x	x
/rosout	x	x	x	x	x

! To see the output in the console, set the output configuration to `screen` in the launch file

```
<launch>
    <node name="listener" ... output="screen"/>
</launch>
```

More info
http://wiki.ros.org/rosconsole
http://wiki.ros.org/roscpp/Overview/Logging

ROS C++ Client Library (*roscpp*)
Subscriber

- Start listening to a topic by calling the method `subscribe()` of the node handle

```
ros::Subscriber subscriber =
nodeHandle.subscribe(topic, queue_size,
                     callback_function);
```

- When a message is received, callback function is called with the contents of the message as argument
- Hold on to the subscriber object until you want to unsubscribe

`ros::spin()` processes callbacks and will not return until the node has been shutdown

listener.cpp

```
#include "ros/ros.h"
#include "std_msgs/String.h"

void chatterCallback(const std_msgs::String& msg)
{
  ROS_INFO("I heard: [%s]", msg.data.c_str());
}

int main(int argc, char **argv)
{
  ros::init(argc, argv, "listener");
  ros::NodeHandle nodeHandle;

  ros::Subscriber subscriber =
       nodeHandle.subscribe("chatter",10, chatterCallback);
  ros::spin();
  return 0;
}
```

More info
http://wiki.ros.org/roscpp/Overview/Publishers%20and%20Subscribers

ROS C++ Client Library (*roscpp*)
Publisher

- Create a publisher with help of the node handle

```
ros::Publisher publisher =
nodeHandle.advertise<message_type>(topic,
queue_size);
```

- Create the message contents
- Publish the contents with

```
publisher.publish(message);
```

talker.cpp

```
#include <ros/ros.h>
#include <std_msgs/String.h>

int main(int argc, char **argv) {
  ros::init(argc, argv, "talker");
  ros::NodeHandle nh;
  ros::Publisher chatterPublisher =
    nh.advertise<std_msgs::String>("chatter", 1);
  ros::Rate loopRate(10);

  unsigned int count = 0;
  while (ros::ok()) {
    std_msgs::String message;
    message.data = "hello world " + std::to_string(count);
    ROS_INFO_STREAM(message.data);
    chatterPublisher.publish(message);
    ros::spinOnce();
    loopRate.sleep();
    count++;
  }
  return 0;
}
```

More info
http://wiki.ros.org/roscpp/Overview/Publishers%20and%20Subscribers

ROS C++ Client Library (*roscpp*)

Object Oriented Programming

my_package_node.cpp

```
#include <ros/ros.h>
#include "my_package/MyPackage.hpp"
int main(int argc, char** argv)
{
  ros::init(argc, argv, "my_package");
  ros::NodeHandle nodeHandle("~");

  my_package::MyPackage myPackage(nodeHandle);

  ros::spin();
  return 0;
}
```

MyPackage.hpp

MyPackage.cpp

`class MyPackage`

Main node class providing ROS interface (subscribers, parameters, timers etc.)

Algorithm.hpp

Algorithm.cpp

`class Algorithm`

Class implementing the algorithmic part of the node

Note: The algorithmic part of the code could be separated in a (ROS-independent) library

! Specify a function handler to a method from within the class as

```
subscriber_ = nodeHandle_.subscribe(topic, queue_size,
&ClassName::methodName, this);
```

More info
http://wiki.ros.org/roscpp_tutorials/Tutorials/UsingClassMethodsAsCallbacks

ROS Parameter Server

- Nodes use the *parameter server* to store and retrieve parameters at runtime
- Best used for static data such as configuration parameters
- Parameters can be defined in launch files or separate *YAML* files

List all parameters with

```
> rosparam list
```

Get the value of a parameter with

```
> rosparam get parameter_name
```

Set the value of a parameter with

```
> rosparam set parameter_name value
```

config.yaml

```
camera:
  left:
    name: left_camera
    exposure: 1
  right:
    name: right_camera
    exposure: 1.1
```

package.launch

```
<launch>
  <node name="name" pkg="package" type="node_type">
      <rosparam command="load"
                file="$(find package)/config/config.yaml" />
  </node>
</launch>
```

More info
http://wiki.ros.org/rosparam

ROS Parameter Server
C++ API

- Get a parameter in C++ with

```
nodeHandle.getParam(parameter_name, variable)
```

- Method returns `true` if parameter was found, `false` otherwise
- Global and relative parameter access:
  - Global parameter name with preceding `/`

```
nodeHandle.getParam("/package/camera/left/exposure", variable)
```

  - Relative parameter name (relative to the node handle)

```
nodeHandle.getParam("camera/left/exposure", variable)
```

- For parameters, typically use the private node handle `ros::NodeHandle("~")`

```
ros::NodeHandle nodeHandle("~");
std::string topic;
if (!nodeHandle.getParam("topic", topic)) {
  ROS_ERROR("Could not find topic
             parameter!");
}
```

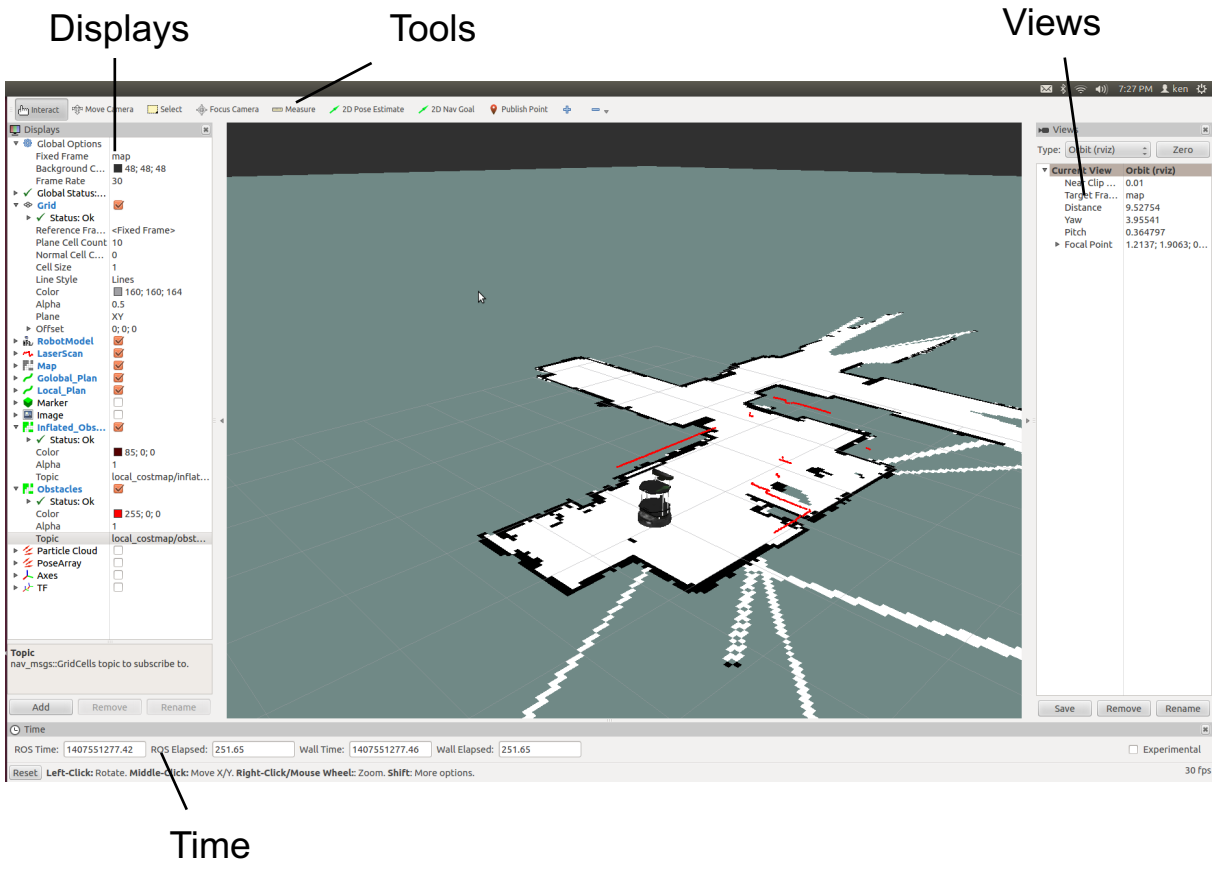
More info
http://wiki.ros.org/roscpp/Overview/Parameter%20Server

RViz

- 3D visualization tool for ROS
- Subscribes to topics and visualizes the message contents
- Different camera views (orthographic, top-down, etc.)
- Interactive tools to publish user information
- Save and load setup as RViz configuration
- Extensible with plugins

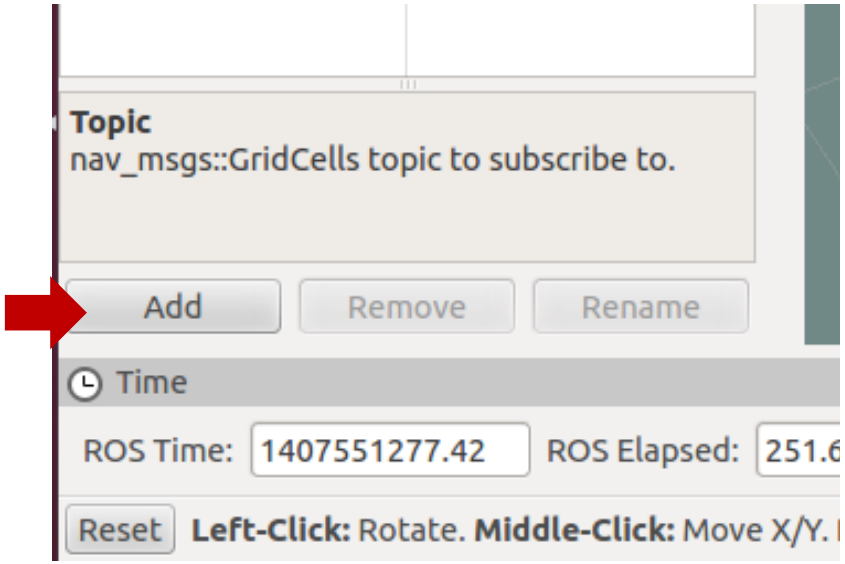
Run RViz with

```
> rosrun rviz rviz
```



More info
http://wiki.ros.org/rviz

RViz
Display Plugins



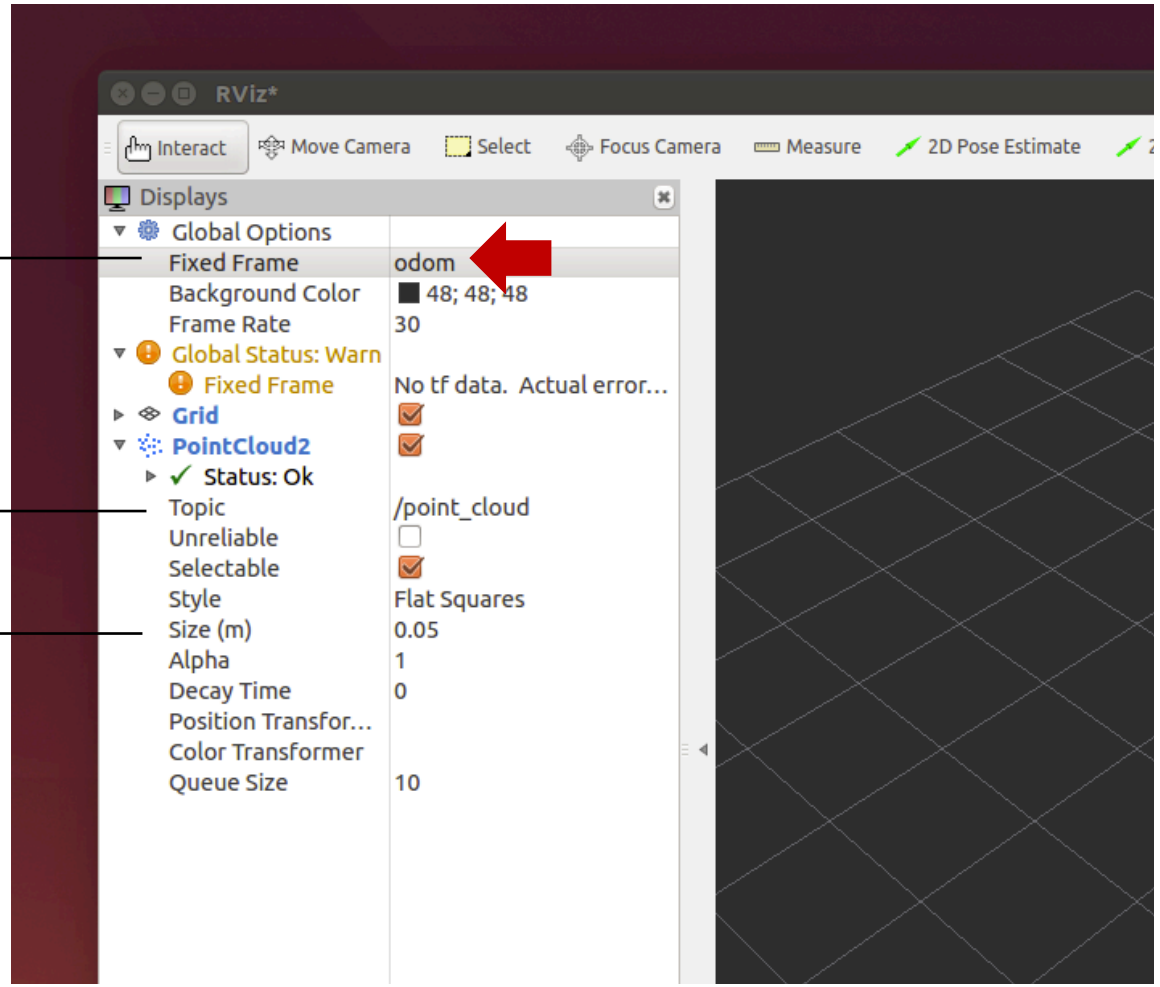
- Axes
- Camera
- DepthCloud
- Effort
- FluidPressure
- Grid
- GridCells
- Group
- Illuminance
- Image
- InteractiveMarkers
- LaserScan
- Map
- Marker
- MarkerArray
- Odometry
- Path
- PointCloud
- PointCloud2
- PointStamped
- Polygon
- Pose
- PoseArray
- Range
- RelativeHumidity
- RobotModel
- TF
- Temperature
- WrenchStamped

RViz
Visualizing Point Clouds Example

! Frame in which the data is displayed (has to exist!)

Choose the topic for the display

Change the display options (e.g. size)

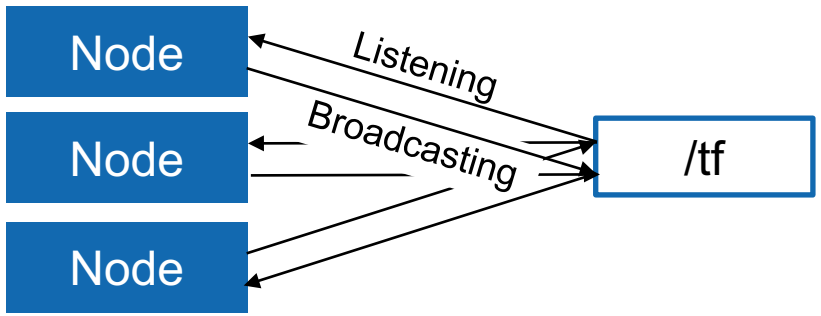


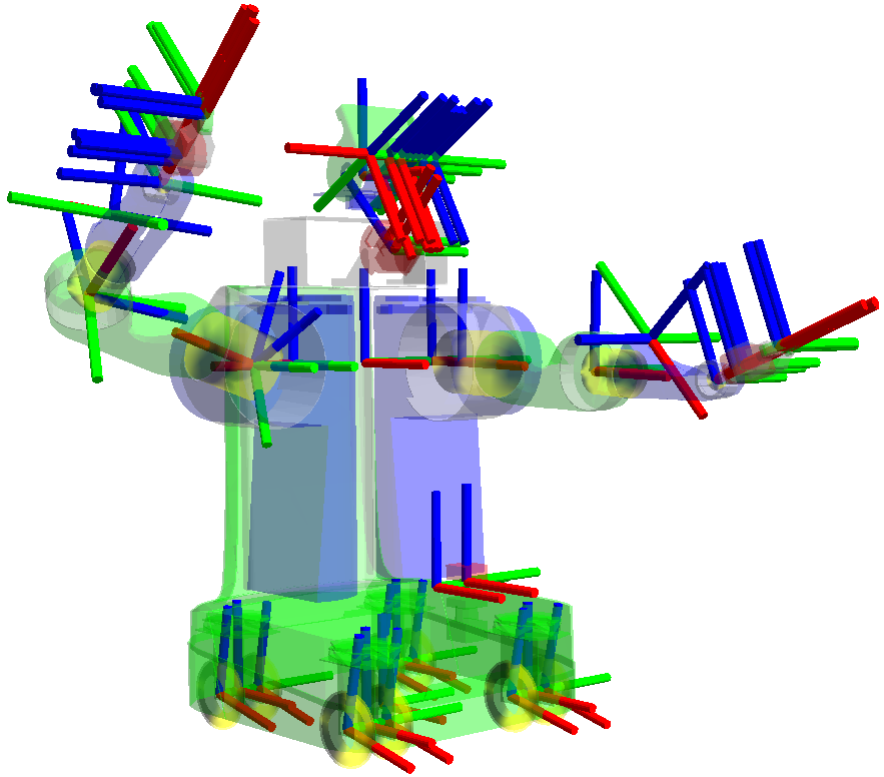
Overview Part 3

- TF Transformation System
- rqt User Interface
- Robot models (URDF)
- Simulation descriptions (SDF)

TF Transformation System

- Tool for keeping track of coordinate frames over time
- Maintains relationship between coordinate frames in a tree structure buffered in time
- Lets the user transform points, vectors, etc. between coordinate frames at desired time
- Implemented as publisher/subscriber model on the topics `/tf` and `/tf_static`





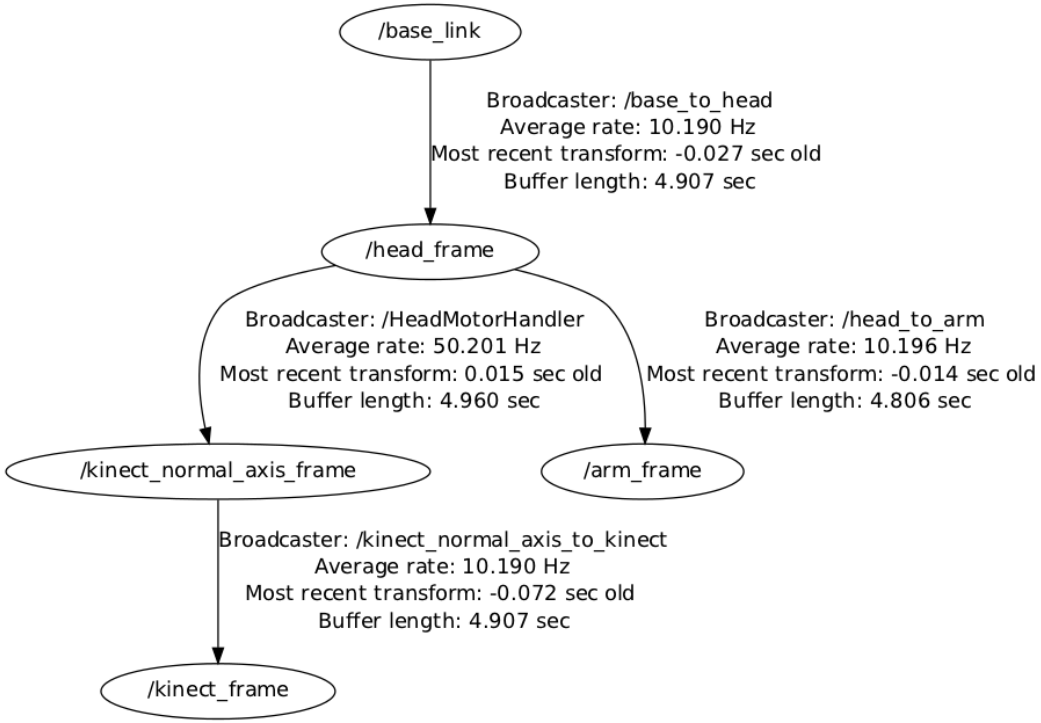
More info
http://wiki.ros.org/tf2

TF Transformation System
Transform Tree

- TF listeners use a buffer to listen to all broadcasted transforms
- Query for specific transforms from the transform tree

tf2_msgs/TFMessage.msg

```
geometry_msgs/TransformStamped[] transforms
  std_msgs/Header header
    uint32 seqtime stamp
    string frame_id
  string child_frame_id
  geometry_msgs/Transform transform
    geometry_msgs/Vector3 translation
    geometry_msgs/Quaternion rotation
```



TF Transformation System

Tools

Command line

Print information about the current tranform tree

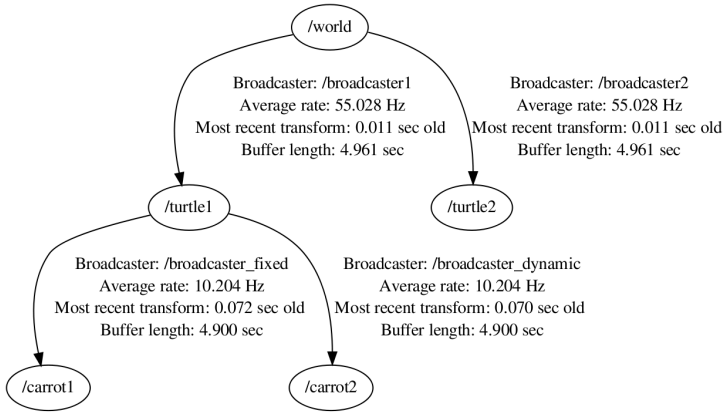
```
> rosrun tf tf_monitor
```

Print information about the transform between two frames

```
> rosrun tf tf_echo
    source_frame target_frame
```

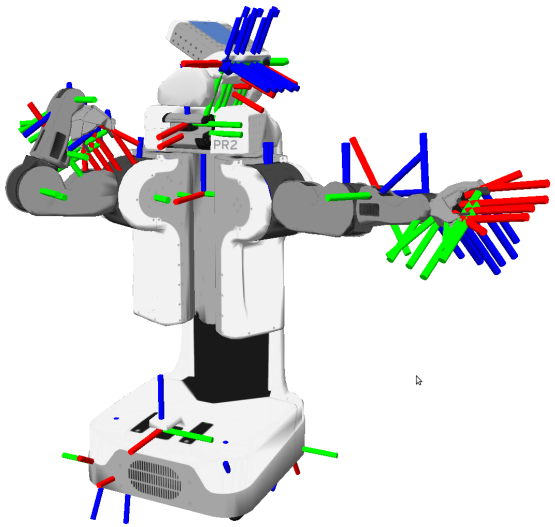
View Frames

```
> rosrun tf view_frames
```



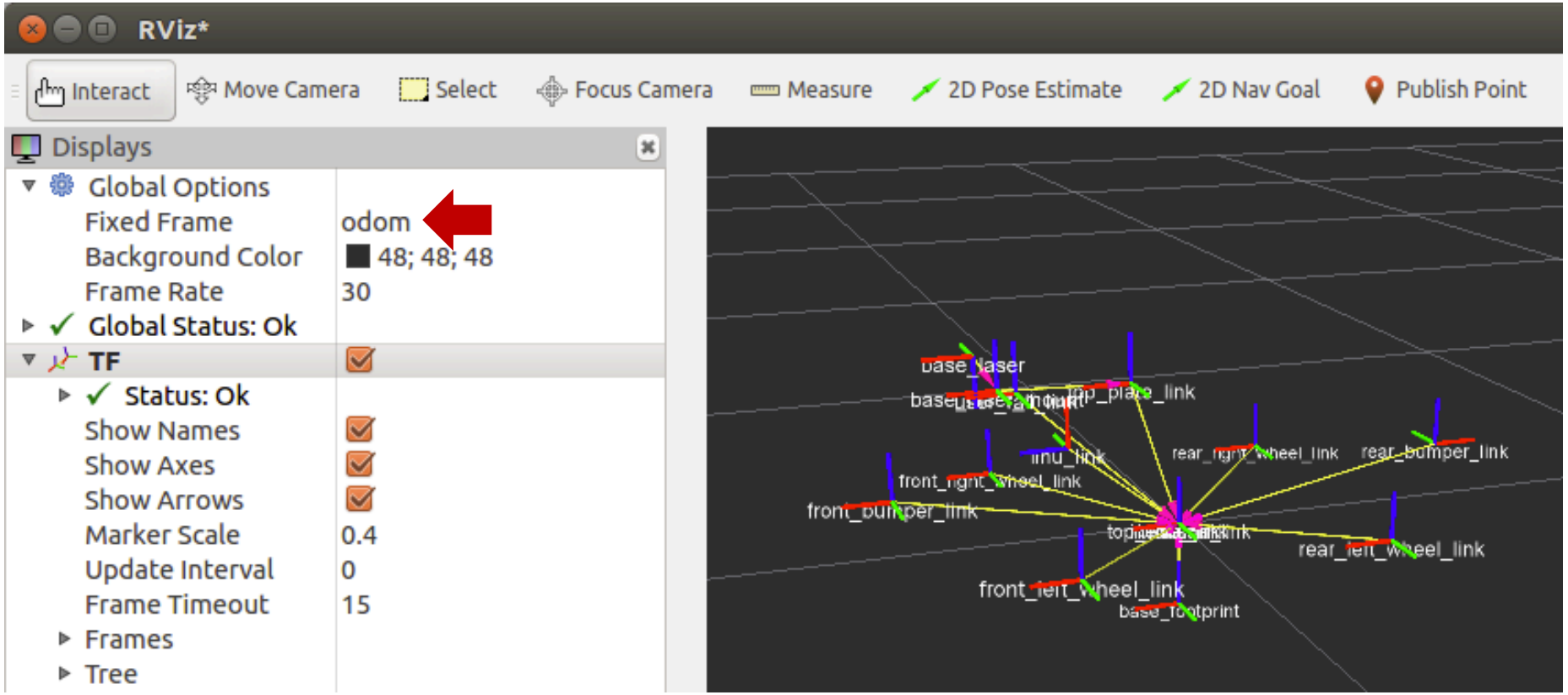
RViz

3D visualization of the transforms



TF Transformation System

RViz Plugin



TF Transformation System
Transform Listener C++ API

- Create a TF listener to fill up a buffer

```
tf2_ros::Buffer tfBuffer;
tf2_ros::TransformListener tfListener(tfBuffer);
```

- Make sure, that the `listener` does not run out of scope!
- To lookup transformations, use

```
geometry_msgs::TransformStamped transformStamped =
tfBuffer.lookupTransform(target_frame_id,
                         source_frame_id, time);
```

- For `time`, use `ros::Time(0)` to get the latest available transform

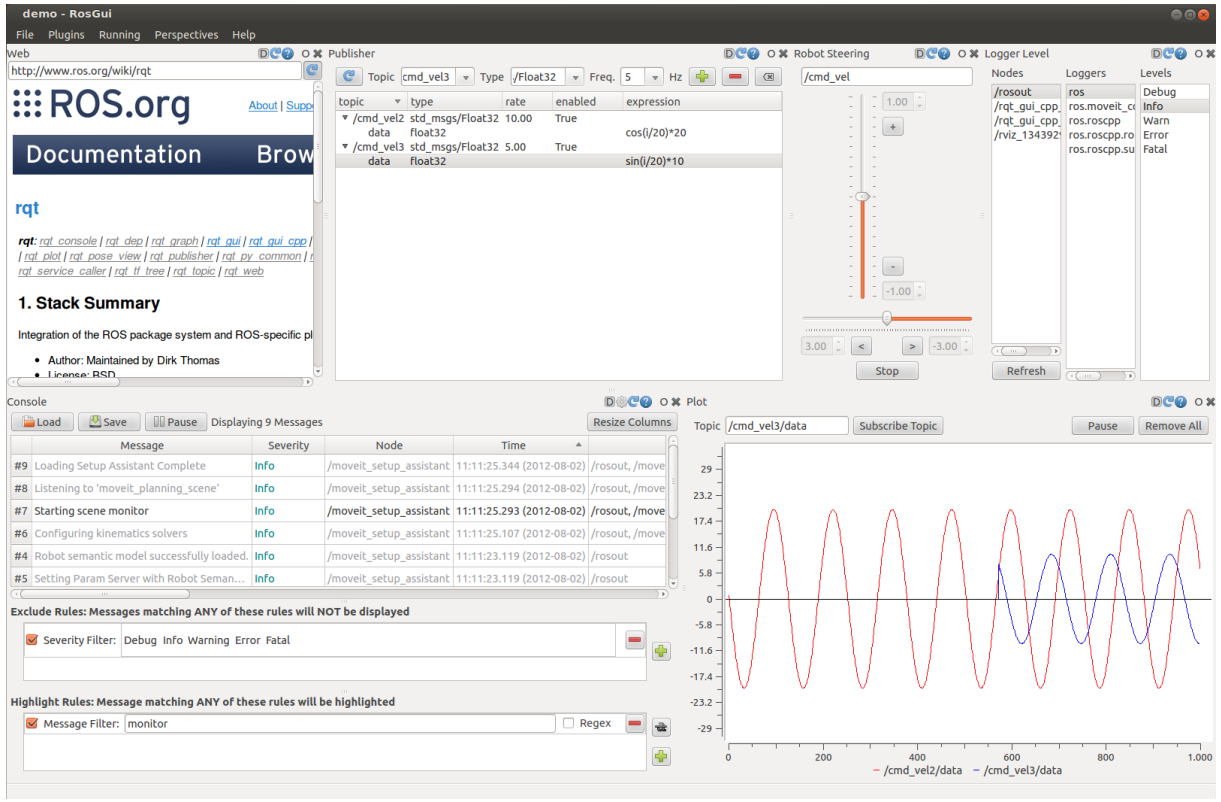
```
#include <ros/ros.h>
#include <tf2_ros/transform_listener.h>
#include <geometry_msgs/TransformStamped.h>

int main(int argc, char** argv) {
  ros::init(argc, argv, "tf2_listener");
  ros::NodeHandle nodeHandle;
  tf2_ros::Buffer tfBuffer;
  tf2_ros::TransformListener tfListener(tfBuffer);

  ros::Rate rate(10.0);
  while (nodeHandle.ok()) {
    geometry_msgs::TransformStamped transformStamped;
    try {
      transformStamped = tfBuffer.lookupTransform("base",
                                                  "odom", ros::Time(0));
    } catch (tf2::TransformException &exception) {
      ROS_WARN("%s", exception.what());
      ros::Duration(1.0).sleep();
      continue;
    }
    rate.sleep();
  }
  return 0;
};
```

More info

http://wiki.ros.org/tf2/Tutorials/Writing%20a%20tf2%20listener%20%28C%2B%2B%29

rqt User Interface

- User interface base on Qt
- Custom interfaces can be setup
- Lots of existing plugins exist
- Simple to write own plugins



Run RQT with

```
> rosrun rqt_gui rqt_gui
```

or

```
> rqt
```

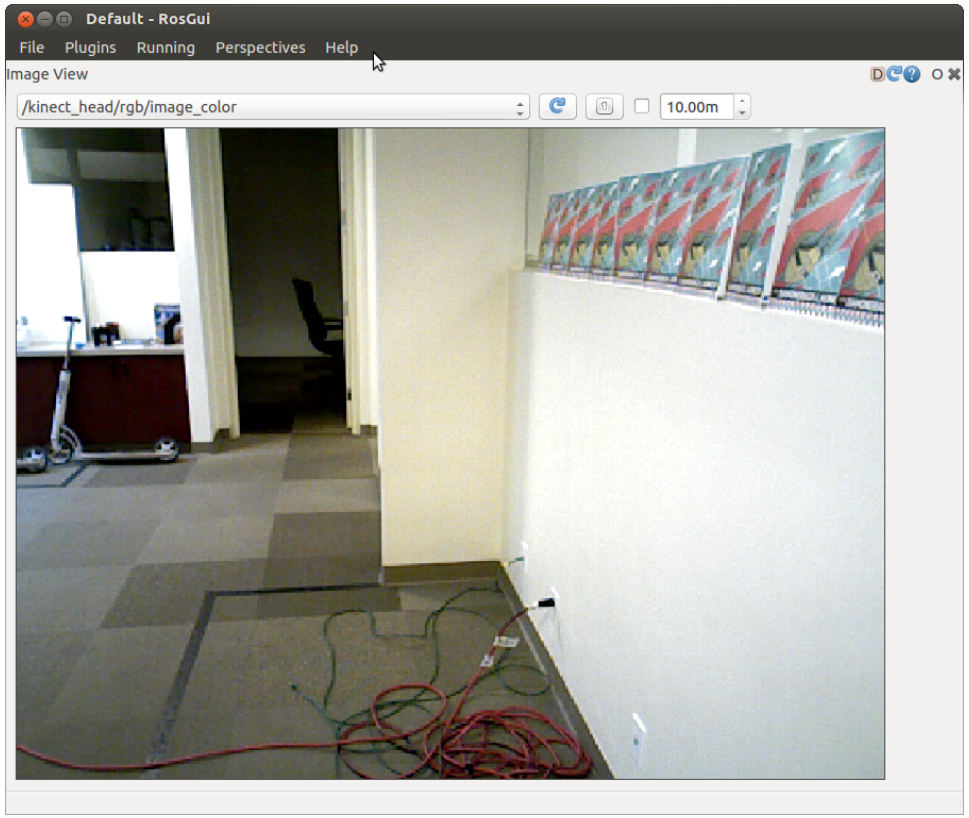
More info
http://wiki.ros.org/rqt/Plugins

rqt User Interface
rqt_image_view

- Visualizing images

Run *rqt_graph* with

```
> rosrun rqt_image_view rqt_image_view
```



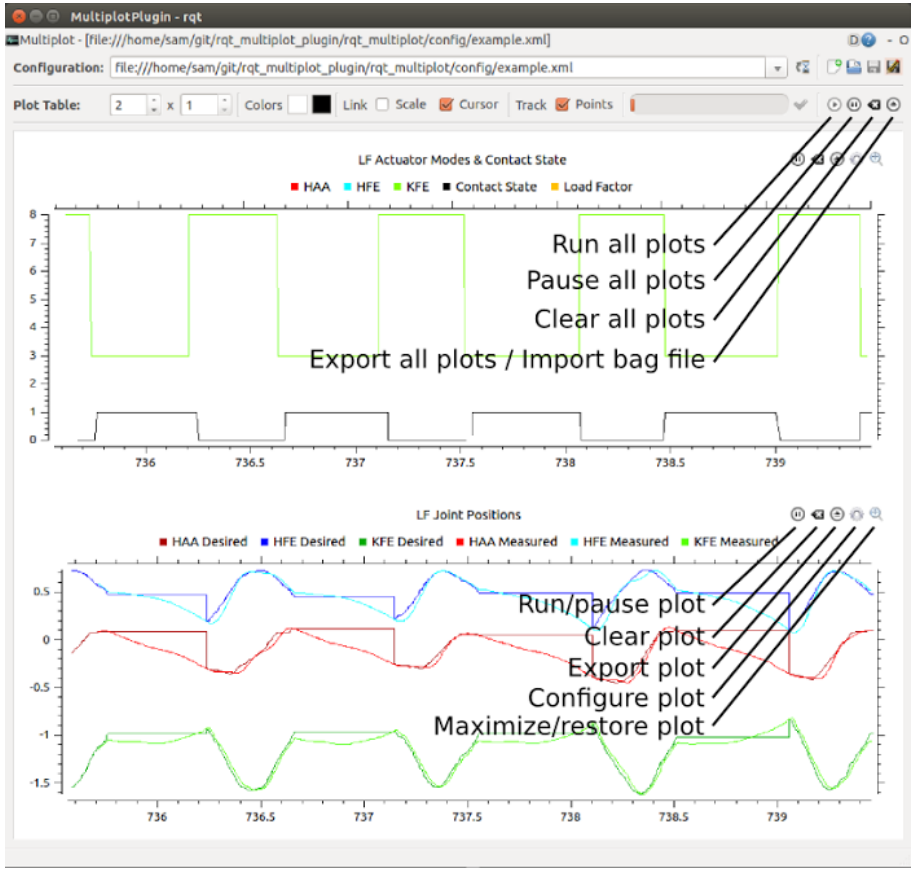
More info
http://wiki.ros.org/rqt_image_view

rqt User Interface
rqt_multiplot

- Visualizing numeric values in 2D plots

Run *rqt_multiplot* with

```
> rosrun rqt_multiplot rqt_multiplot
```



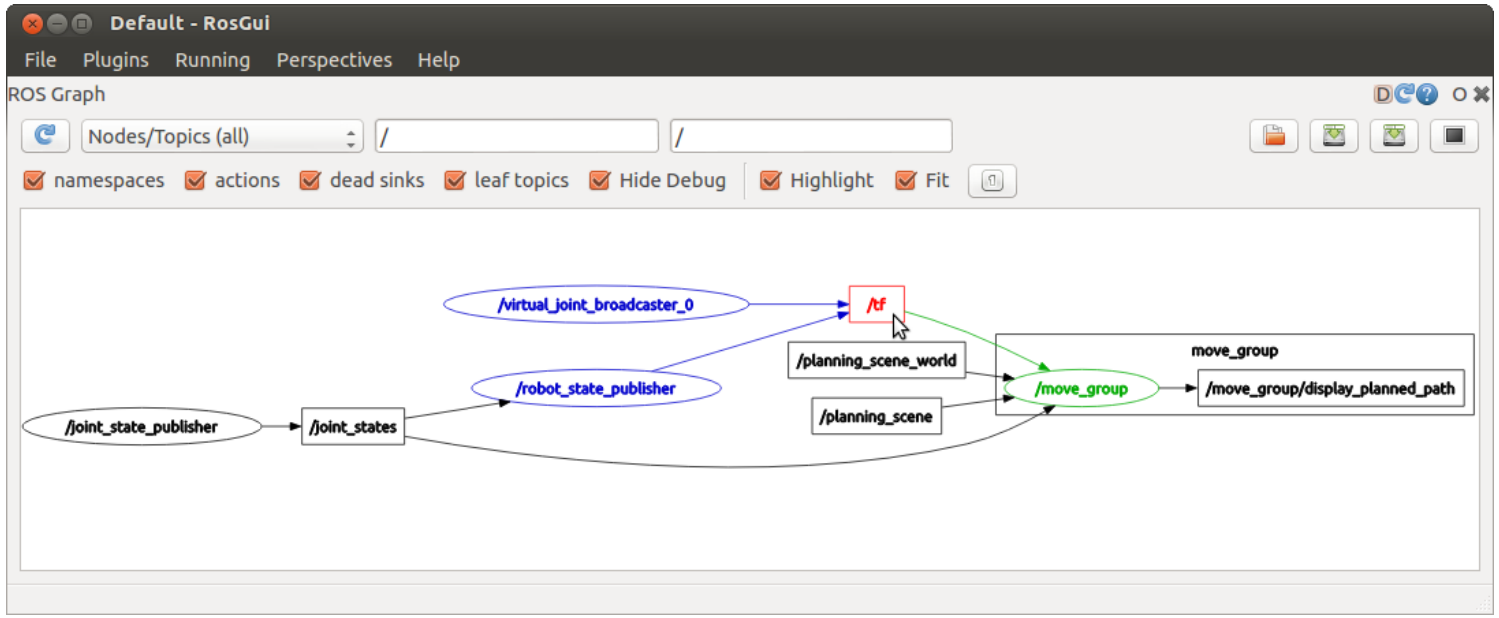
More info
http://wiki.ros.org/rqt_multiplot

rqt User Interface
rqt_graph

- Visualizing the ROS computation graph

Run *rqt_graph* with

```
> rosrun rqt_graph rqt_graph
```



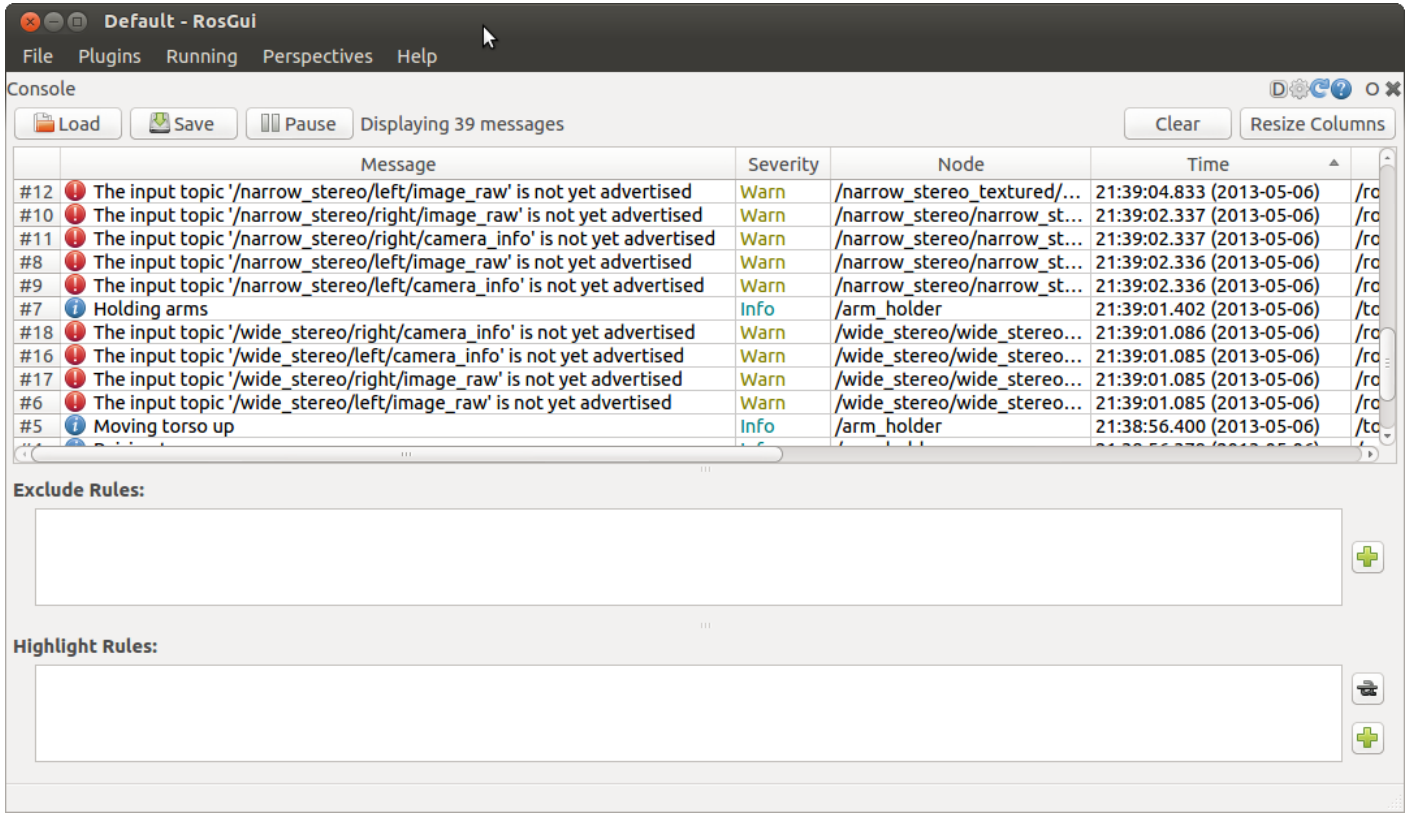
More info
http://wiki.ros.org/rqt_graph

rqt User Interface
rqt_console

- Displaying and filtering ROS messages

Run *rqt_console* with

```
> rosrun rqt_console rqt_console
```



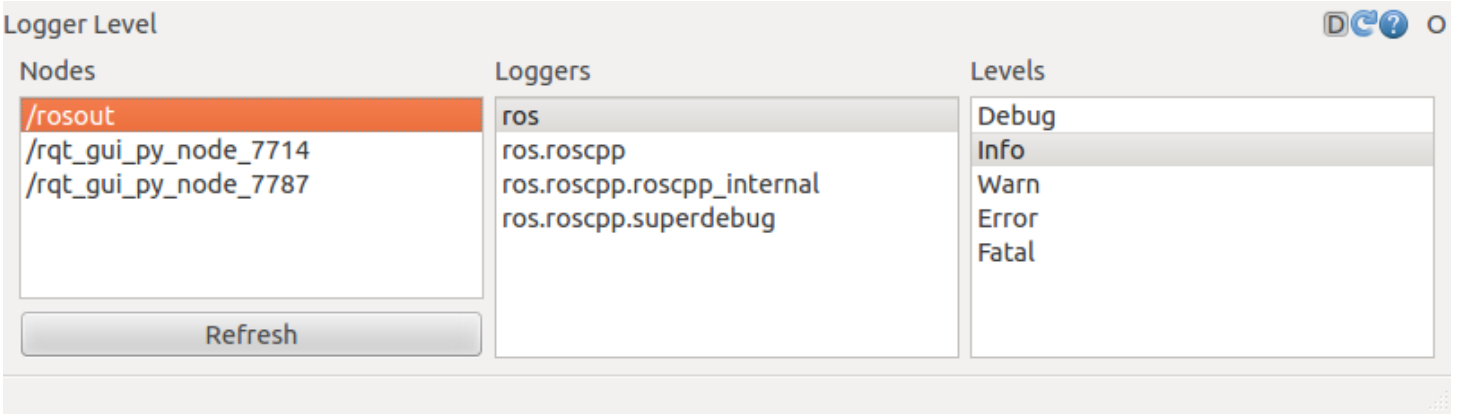
More info
http://wiki.ros.org/rqt_console

rqt User Interface
rqt_logger_level

- Configuring the logger level of ROS nodes

Run *rqt_logger_level* with

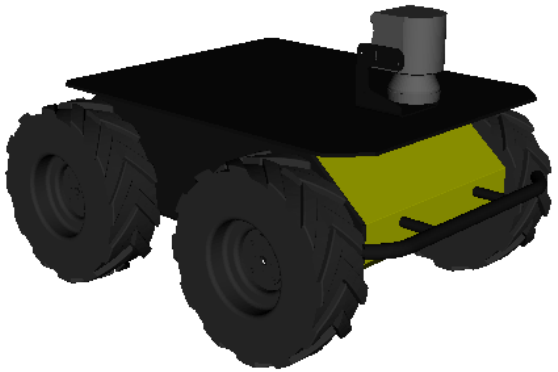
```
> rosrun rqt_logger_level
  rqt_logger_level
```



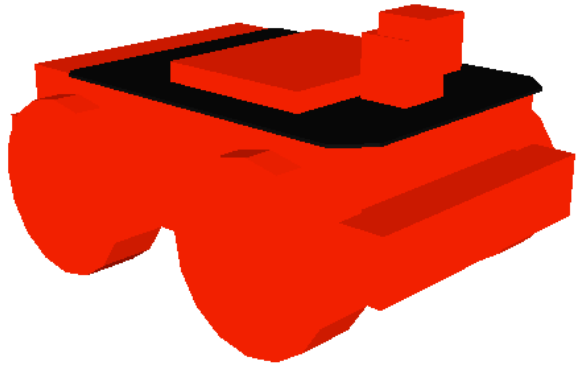
More info
http://wiki.ros.org/rqt_logger_level

Robot Models
Unified Robot Description Format (URDF)

- Defines an XML format for representing a robot model
  - Kinematic and dynamic description
  - Visual representation
  - Collision model
- URDF generation can be be scripted with *XACRO*



Mesh for visuals

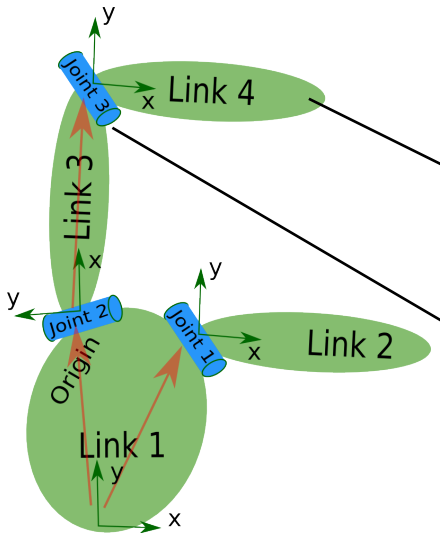


Primitives for collision

More info
http://wiki.ros.org/urdf
http://wiki.ros.org/xacro

Robot Models
Unified Robot Description Format (URDF)

- Description consists of a set of *link* elements and a set of *joint* elements
- Joints connect the links together



robot.urdf

```
<robot name="robot">
  <link> ... </link>
  <link> ... </link>
  <link> ... </link>

  <joint> .... </joint>
  <joint> .... </joint>
  <joint> .... </joint>
</robot>
```

```
<link name="link_name">
  <visual>
    <geometry>
      <mesh filename="mesh.dae"/>
    </geometry>
  </visual>
  <collision>
    <geometry>
      <cylinder length="0.6" radius="0.2"/>
    </geometry>
  </collision>
  <inertial>
    <mass value="10"/>
    <inertia ixx="0.4" ixy="0.0" …/>
  </inertial>
</link>
```

```
<joint name="joint_name" type="revolute">
  <axis xyz="0 0 1"/>
  <limit effort="1000.0" upper="0.548" … />
  <origin rpy="0 0 0" xyz="0.2 0.01 0"/>
  <parent link="parent_link_name"/>
  <child link="child_link_name"/>
</joint>
```

More info
http://wiki.ros.org/urdf/XML/model

Robot Models
Usage in ROS

- The robot description (URDF) is stored on the parameter server (typically) under `/robot_description`
- You can visualize the robot model in Rviz with the  *RobotModel* plugin

husky_empty_world.launch

```
…
<include file="$(find husky_gazebo)/launch/spawn_husky.launch">
  <arg name="laser_enabled" value="$(arg laser_enabled)"/>
  <arg name="ur5_enabled" value="$(arg ur5_enabled)"/>
  <arg name="kinect_enabled" value="$(arg kinect_enabled)"/>
</include>
…
```

spawn_husky.launch

```
…
<param name="robot_description" command="$(find xacro)/xacro.py
'$(arg husky_gazebo_description)'
   laser_enabled:=$(arg laser_enabled)
   ur5_enabled:=$(arg ur5_enabled)
   kinect_enabled:=$(arg kinect_enabled)" />
…
```

Simulation Descriptions
Simulation Description Format (SDF)

- Defines an XML format to describe
  - Environments (lighting, gravity etc.)
  - Objects (static and dynamic)
  - Sensors
  - Robots
- SDF is the standard format for Gazebo
- Gazebo converts a URDF to SDF automatically

More info
http://sdformat.org

Overview Part 4

- ROS services
- ROS actions (actionlib)
- ROS time
- ROS bags
- Debugging strategies

ROS Services

- Request/response communication between nodes is realized with *services*
  - The *service server* advertises the service
  - The *service client* accesses this service
- Similar in structure to messages, services are defined in **.srv* files

List available services with

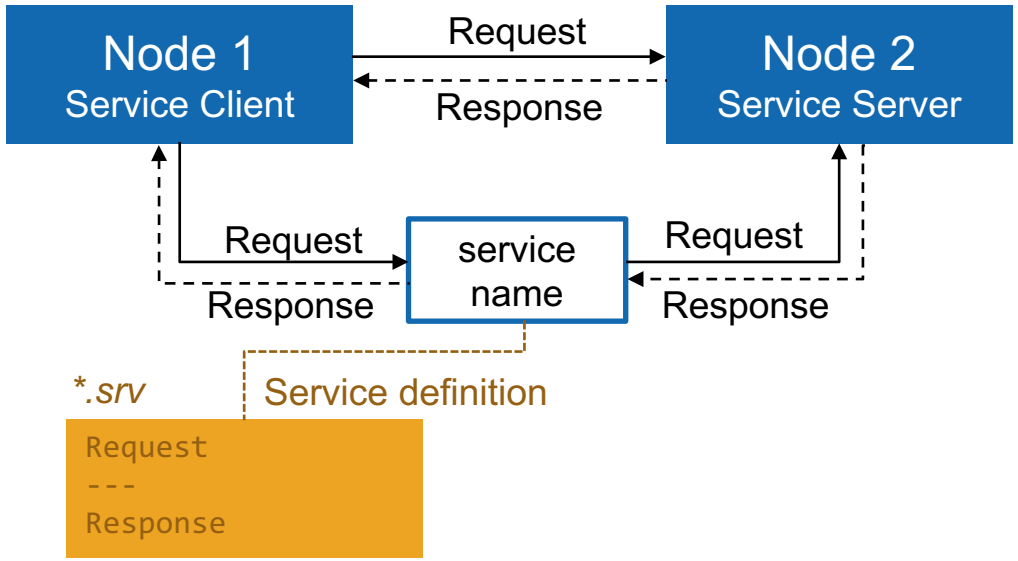
```
> rosservice list
```

Show the type of a service

```
> rosservice type /service_name
```

Call a service with the request contents

```
> rosservice call /service_name args
```



More info
http://wiki.ros.org/Services

ROS Services
Examples

std_srvs/Trigger.srv

```
---
bool success
string message
```

Request

Response

nav_msgs/GetPlan.srv

```
geometry_msgs/PoseStamped start
geometry_msgs/PoseStamped goal
float32 tolerance
---
nav_msgs/Path plan
```

ROS Service Example

Starting a *roscore* and a *add_two_ints_server* node

In console nr. 1:
Start a roscore with

```
> roscore
```

```
PARAMETERS
 * /rosdistro: indigo
 * /rosversion: 1.11.20

NODES

auto-starting new master
process[master]: started with pid [6708]
ROS_MASTER_URI=http://ubuntu:11311/

setting /run_id to 6c1852aa-e961-11e6-8543-000c297bd368
process[rosout-1]: started with pid [6721]
started core service [/rosout]
```

In console nr. 2:
Run a service demo node with

```
> rosrun roscpp_tutorials add_two_ints_server
```

```
student@ubuntu:~$ rosrun roscpp_tutorials add_two_ints_server
```

ROS Service Example

Console Nr. 3 – Analyze and call service

See the available services with

```
> rosservice list
```

```
student@ubuntu:~$ rosservice list
/add_two_ints
/add_two_ints_server/get_loggers
/add_two_ints_server/set_logger_level
/rosout/get_loggers
/rosout/set_logger_level
```

See the type of the service with

```
> rosservice type /add_two_ints
```

```
student@ubuntu:~$ rosservice type /add_two_ints
roscpp_tutorials/TwoInts
```

Show the service definition with

```
> rossrv show roscpp_tutorials/TwoInts
```

```
student@ubuntu:~$ rossrv show roscpp_tutorials/TwoInts
int64 a
int64 b
---
int64 sum
```

Call the service (use `Tab` for auto-complete)

```
> rosservice call /add_two_ints "a: 10
  b: 5"
```

```
student@ubuntu:~$ rosservice call /add_two_ints "a: 10
b: 5"
sum: 15
```

ROS C++ Client Library (*roscpp*)
Service Server

- Create a service server with

```
ros::ServiceServer service =
 nodeHandle.advertiseService(service_name,
                             callback_function);
```

- When a service request is received, callback function is called with the request as argument
- Fill in the response to the response argument
- Return to function with true to indicate that it has been executed properly

More info
http://wiki.ros.org/roscpp/Overview/Services

add_two_ints_server.cpp

```
#include <ros/ros.h>
#include <roscpp_tutorials/TwoInts.h>

bool add(roscpp_tutorials::TwoInts::Request &request,
         roscpp_tutorials::TwoInts::Response &response)
{
  response.sum = request.a + request.b;
  ROS_INFO("request: x=%ld, y=%ld", (long int)request.a,
                                    (long int)request.b);
  ROS_INFO("  sending back response: [%ld]",
           (long int)response.sum);
  return true;
}

int main(int argc, char **argv)
{
  ros::init(argc, argv, "add_two_ints_server");
  ros::NodeHandle nh;
  ros::ServiceServer service =
          nh.advertiseService("add_two_ints", add);
  ros::spin();
  return 0;
}
```

ROS C++ Client Library (*roscpp*)
Service Client

- Create a service client with

```
ros::ServiceClient client =
    nodeHandle.serviceClient<service_type>
                              (service_name);
```

- Create service request contents `service.request`
- Call service with

```
client.call(service);
```

- Response is stored in `service.response`

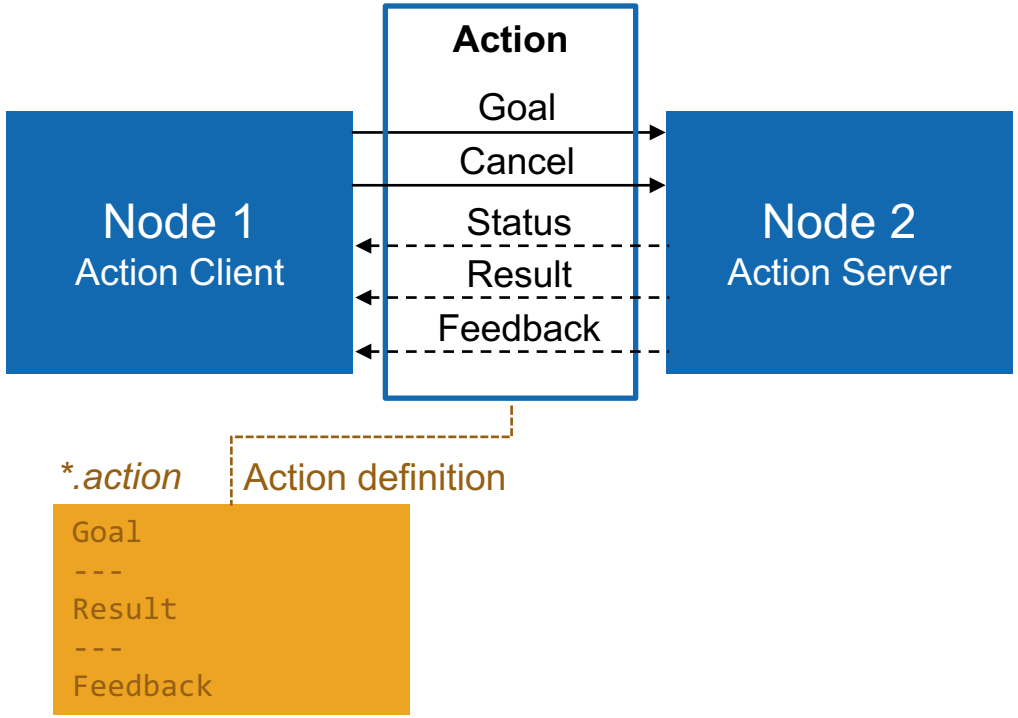
More info
http://wiki.ros.org/roscpp/Overview/Services

add_two_ints_client.cpp

```
#include <ros/ros.h>
#include <roscpp_tutorials/TwoInts.h>
#include <cstdlib>

int main(int argc, char **argv) {
  ros::init(argc, argv, "add_two_ints_client");
  if (argc != 3) {
    ROS_INFO("usage: add_two_ints_client X Y");
    return 1;
  }

  ros::NodeHandle nh;
  ros::ServiceClient client =
  nh.serviceClient<roscpp_tutorials::TwoInts>("add_two_ints");
  roscpp_tutorials::TwoInts service;
  service.request.a = atoi(argv[1]);
  service.request.b = atoi(argv[2]);
  if (client.call(service)) {
    ROS_INFO("Sum: %ld", (long int)service.response.sum);
  } else {
    ROS_ERROR("Failed to call service add_two_ints");
    return 1;
  }
  return 0;
}
```

ROS Actions (actionlib)

- Similar to service calls, but provide possibility to
  - Cancel the task (preempt)
  - Receive feedback on the progress
- Best way to implement interfaces to time-extended, goal-oriented behaviors
- Similar in structure to services, action are defined in **.action* files
- Internally, actions are implemented with a set of topics



More info
http://wiki.ros.org/actionlib
http://wiki.ros.org/actionlib/DetailedDescription

ROS Actions (actionlib)

Averaging.action

```
int32 samples
---
float32 mean
float32 std_dev
---
int32 sample
float32 data
float32 mean
float32 std_dev
```

Goal

Result

Feedback

FollowPath.action

```
navigation_msgs/Path path
---
bool success
---
float32 remaining_distance
float32 initial_distance
```

ROS Parameters, Dynamic Reconfigure, Topics, Services, and Actions Comparison

	Parameters	Dynamic Reconfigure	Topics	Services	Actions
Description	Global constant parameters	Local, changeable parameters	Continuous data streams	Blocking call for processing a request	Non-blocking, preemptable goal oriented tasks
Application	Constant settings	Tuning parameters	One-way continuous data flow	Short triggers or calculations	Task executions and robot actions
Examples	Topic names, camera settings, calibration data, robot setup	Controller parameters	Sensor data, robot state	Trigger change, request state, compute quantity	Navigation, grasping, motion execution

ROS Time

- Normally, ROS uses the PC's system clock as time source (*wall time*)
- For simulations or playback of logged data, it is convenient to work with a simulated time (pause, slow-down etc.)
- To work with a simulated clock:
  - Set the `/use_sim_time` parameter

```
> rosparam set use_sim_time true
```

  - Publish the time on the topic `/clock` from
    - Gazebo (enabled by default)
    - ROS bag (use option `--clock`)

- To take advantage of the simulated time, you should always use the ROS Time APIs:
  - **`ros::Time`**

```
ros::Time begin = ros::Time::now();
double secs = begin.toSec();
```

  - **`ros::Duration`**

```
ros::Duration duration(0.5); // 0.5s
```

  - **`ros::Rate`**

```
ros::Rate rate(10); // 10Hz
```

- If wall time is required, use `ros::WallTime`, `ros::WallDuration`, and `ros::WallRate`

More info
http://wiki.ros.org/Clock
http://wiki.ros.org/roscpp/Overview/Time

ROS Bags

- A *bag* is a format for storing message data
- Binary format with file extension *.bag
- Suited for logging and recording datasets for later visualization and analysis

Record all topics in a bag

```
> rosbag record --all
```

Record given topics

```
> rosbag record topic_1 topic_2 topic_3
```

Stop recording with `Ctrl` + `C`
Bags are saved with start date and time as file name in the current folder (e.g. `2017-02-07-01-27-13.bag`)

Show information about a bag

```
> rosbag info bag_name.bag
```

Read a bag and publish its contents

```
> rosbag play bag_name.bag
```

Playback options can be defined e.g.

```
> rosbag play --rate=0.5 bag_name.bag
```

`--rate=`*`factor`*	Publish rate factor
`--clock`	Publish the clock time (set param `use_sim_time` to `true`)
`--loop`	Loop playback
	etc.

More info
http://wiki.ros.org/rosbag/Commandline

Debugging Strategies

Debug with the tools you have learned

- Compile and run code often to catch bugs early
- Understand compilation and runtime error messages
- Use analysis tools to check data flow (`rosnode info`, `rostopic echo`, `roswtf`, `rqt_graph` etc.)
- Visualize and plot data (RViz, RQT Multiplot etc.)
- Divide program into smaller steps and check intermediate results (`ROS_INFO`, `ROS_DEBUG` etc.)
- Make your code robust with argument and return value checks and catch exceptions
- If things don't make sense, clean your workspace

```
> catkin clean --all
```

Learn new tools

- Build in *debug* mode and use GDB or Valgrind

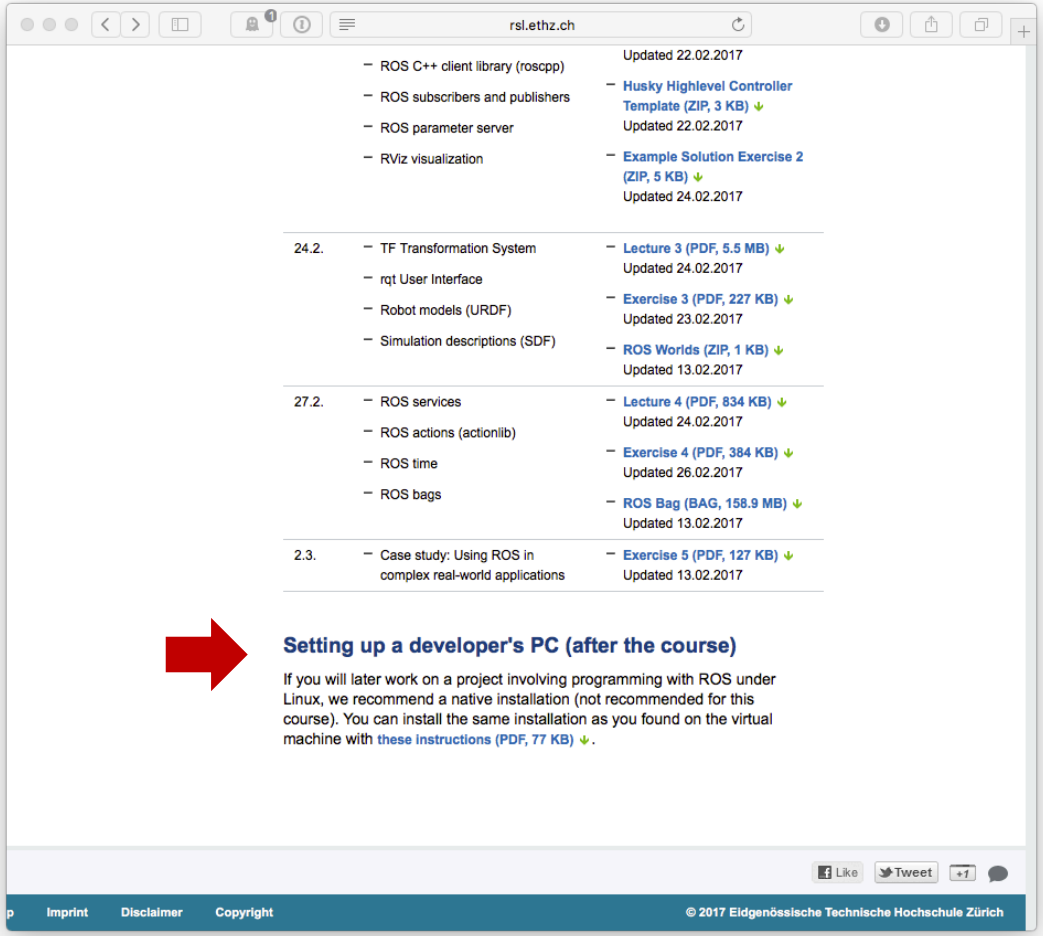
```
> catkin config --cmake-args
                -DCMAKE_BUILD_TYPE=Debug
```

- Use Eclipse breakpoints
- Maintain code with unit tests and integration tests

More info

http://wiki.ros.org/UnitTesting
http://wiki.ros.org/gtest
http://wiki.ros.org/rostest
http://wiki.ros.org/roslaunch/Tutorials/Roslaunch%20Nodes%20in%20Valgrind%20or%20GDB

Setting Up up a Developer's PC



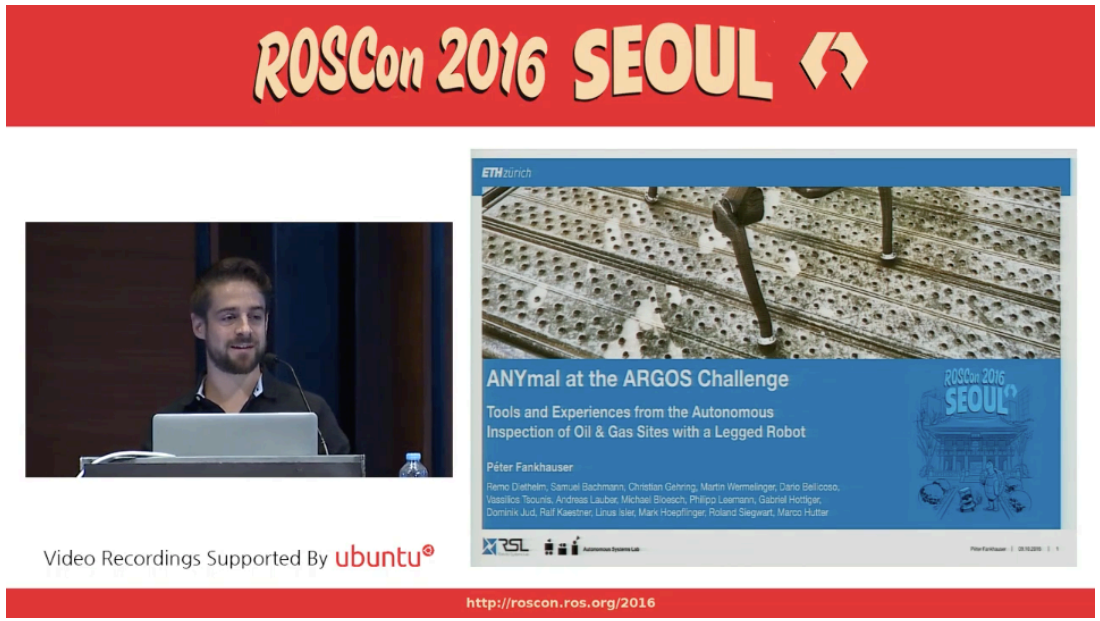
Further References

- **ROS Wiki**
  - http://wiki.ros.org/
- **Installation**
  - http://wiki.ros.org/ROS/Installation
- **Tutorials**
  - http://wiki.ros.org/ROS/Tutorials
- **Available packages**
  - http://www.ros.org/browse/
- **ROS Cheat Sheet**
  - https://github.com/ros/cheatsheet/releases/download/0.0.1/ROScheatsheet_catkin.pdf
- **ROS Best Practices**
  - https://github.com/ethz-asl/ros_best_practices/wiki
- **ROS Package Template**
  - https://github.com/ethz-asl/ros_best_practices/tree/master/ros_package_template

Part 5 – Case Study
Using ROS in Complex Real-World Applications

P. Fankhauser, R. Diethelm, S. Bachmann, C. Gehring, M. Wermelinger, D. Bellicoso, V. Tsounis, A. Lauber, M. Bloesch, P. Leemann, G. Hottiger, D. Jud, R. Kaestner, L. Isler, M. Hoepflinger, R. Siegwart, and M. Hutter, "**ANYmal at the ARGOS Challenge – Tools and Experiences from the Autonomous Inspection of Oil & Gas Sites with a Legged Robot**," in *ROSCon*, 2016.

Presentation



https://vimeo.com/187696096

Slides

https://www.researchgate.net/publication/308953021

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Course website:
http://www.rsl.ethz.ch/education-students/lectures/ros.html