Industrial Training

Oct 18, 2018

Contents

CHAPTER 1

Setup PC

1.1 PC Setup

There are two options for utilizing the ROS-Industrial training materials. The first **recommended** option is to utilize a pre-configured virtual machine. The second option is to install a native Ubuntu machine with the required software. The virtual machine approach is by far the easiest option and ensures the fewest build errors during training but is limited in its ability to connect to certain hardware, particularly over USB (i.e. kinect-like devices). For the perception training a .bag file is provided so that USB connection is not required for this training course.

1.1.1 Virtual Machine Configuration (Recommended)

The VM method is the most convenient method of utilizing the training materials:

1. Download virtual box
2. Download ROS Kinetic training VM
3. Import image into virtual box
4. Start virtual machine
5. Log into virtual machine, user: `ros-industrial`, pass: `rosindustrial` (no spaces or hyphens)
6. Get the latest changes (Open Terminal).

```
cd ~/industrial_training
git checkout kinetic
git pull
./.check_training_config.bash
```

Limitations of Virtual Box

The Virtual Box is limited both in hardware capability(due to VM limitations) and package installs (to save space). Kinect-based demos aren't possible due to USB limitations.

Common VM Issues

On most new systems, Virtual Box and VMs work out of the box. The following is a list of issues others have encountered and solutions:

- Virtualization must be enabled - Older systems do not have virtualization enabled (by default). Virtualization must be enabled in the BIOS. See http://www.sysprobs.com/disable-enable-virtualization-technology-bios for more information.

1.1.2 Direct Linux PC Configuration (NOT Recommended)

An installation shell script is provided to run in Ubuntu Linux 16.04 (Xenial Xerus) LTS. This script installs ROS and any other packages needed for the environment used for this training.

After this step (or if you already have a working ROS environment), clone the training material repository into your home directory:

```
git clone -b kinetic https://github.com/ros-industrial/industrial_training.git
~/industrial_training
```

1.1.3 Configuration Check

The following is a quick check to ensure that the appropriate packages have been installed and the the `industrial_training` git repository is current. Enter the following into the terminal:

```
~/industrial_training/.check_training_config.bash
```

CHAPTER 2

Prerequisites

2.1 C++

2.2 Linux Fundamentals

`Slides`

2.2.1 Navigating the Ubuntu GUI

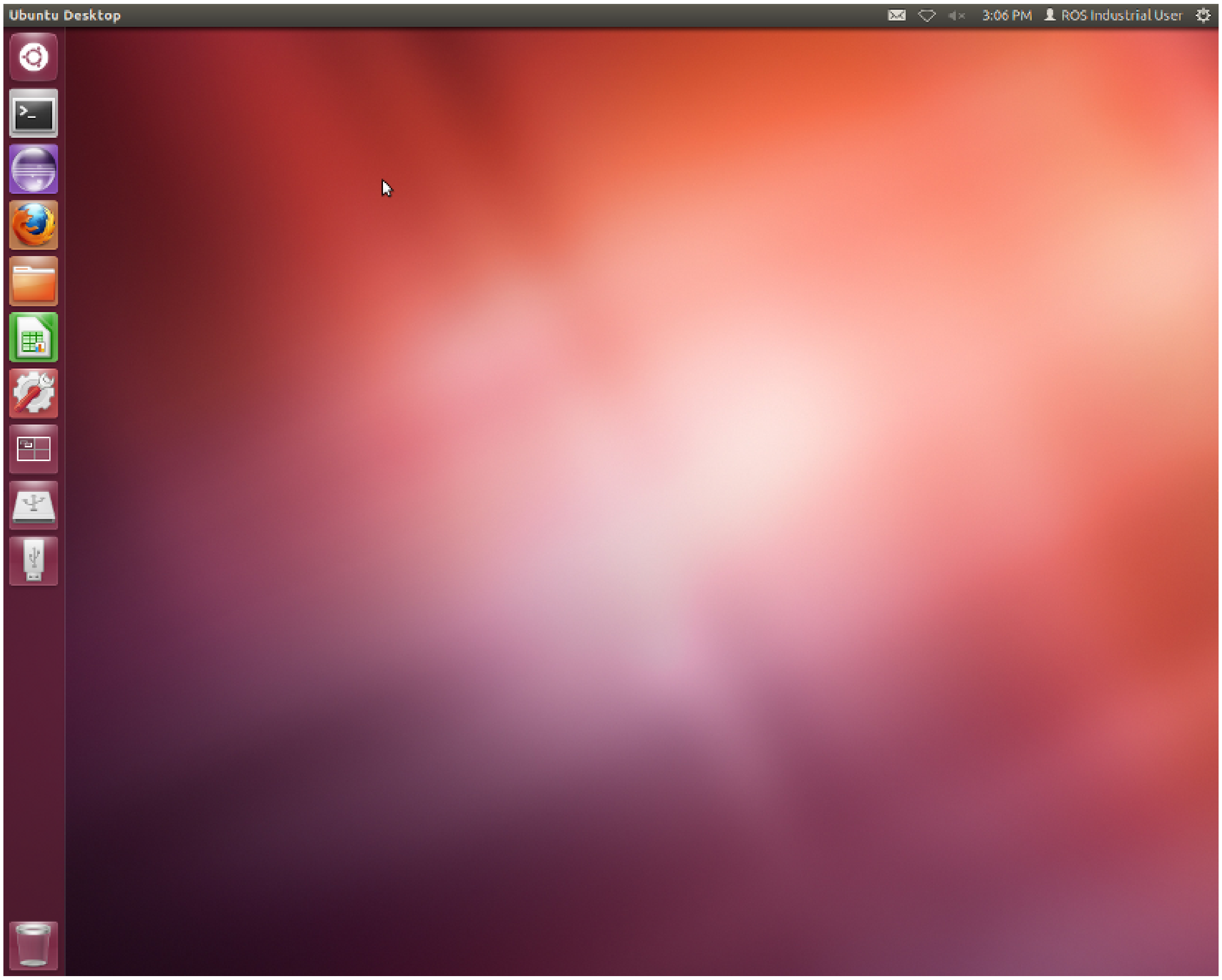
> In this exercise, we will familiarize ourselves with the graphical user interface (GUI) of the Ubuntu operating system.

Task 0: Presentation Slides

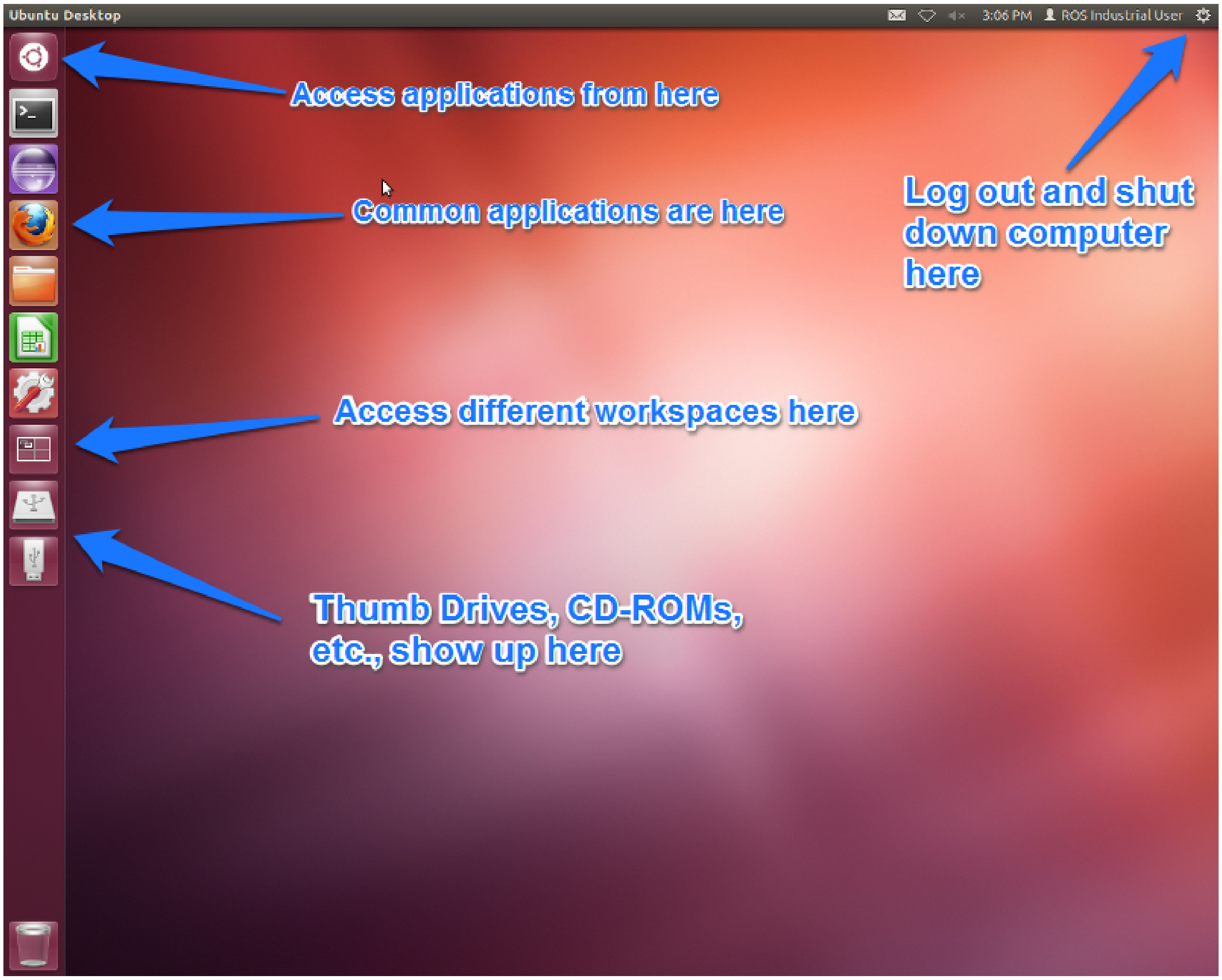
Don't forget about the presentation slides that accompany this Lesson!

Task 1: Familiarize Yourself with the Ubuntu Desktop

At the log-in screen, click in the password input box, enter `rosindustrial` for the password, and hit enter. The screen should look like the image below when you log in:



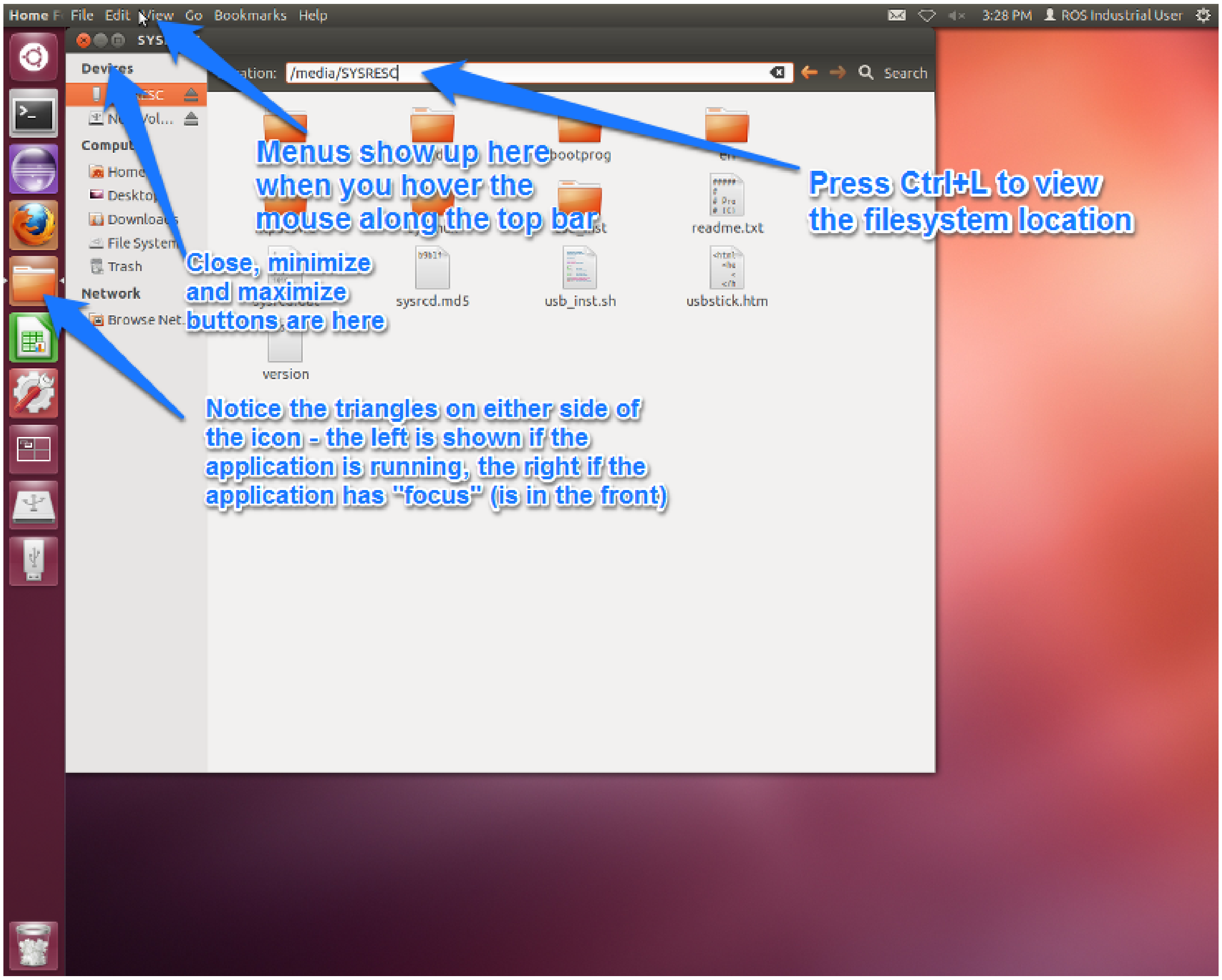
There are several things you will notice on the desktop:


Ubuntu Desktop
3:06 PM
ROS Industrial User
Access applications from here
Common applications are here
Log out and shut down computer here
Access different workspaces here
Thumb Drives, CD-ROMs, etc., show up here

1. The gear icon on the top right of the screen brings up a menu which allows the user to log out, shut down the computer, access system settings, etc…
2. The bar on the left side shows running and “favorite” applications, connected thumb drives, etc.
3. The top icon is used to access all applications and files. We will look at this in more detail later.
4. The next icons are either applications which are currently running or have been “pinned” (again, more on pinning later)
5. Any removable drives, like thumb drives, are found after the application icons.
6. If the launcher bar gets “too full”, clicking and dragging up/down allows you to see the applications that are hidden.
7. To reorganize the icons on the launcher, click and hold the icon until it “pops out”, then move it to the desired location.

Task 2: Open and Inspect an Application

Click on the filing-cabinet icon in the launcher. A window should show up, and your desktop should look like something below:



Menus show up here when you hover the mouse along the top bar

Press Ctrl+L to view the filesystem location

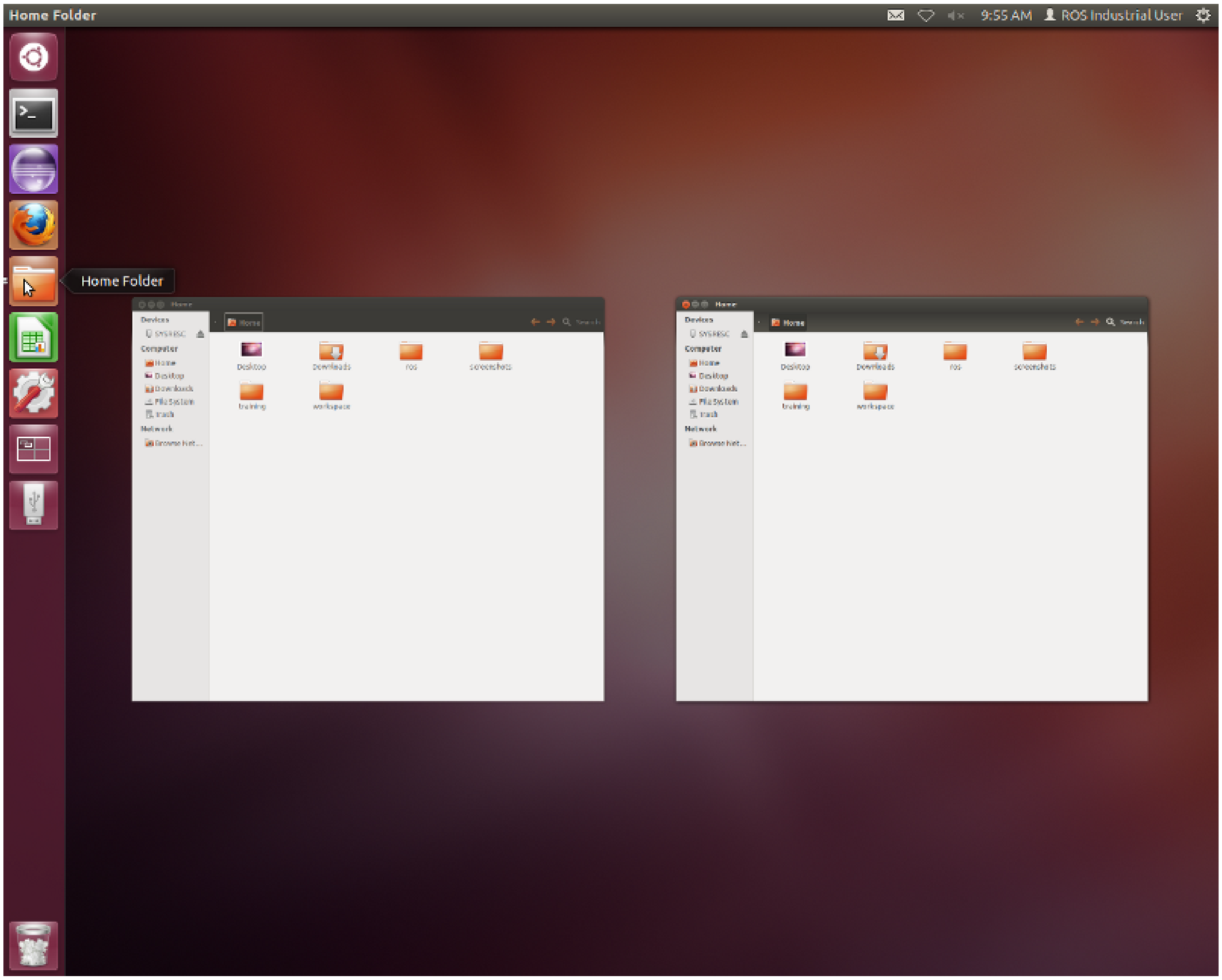
Close, minimize and maximize buttons are here

Notice the triangles on either side of the icon - the left is shown if the application is running, the right if the application has "focus" (is in the front)

Things to notice:

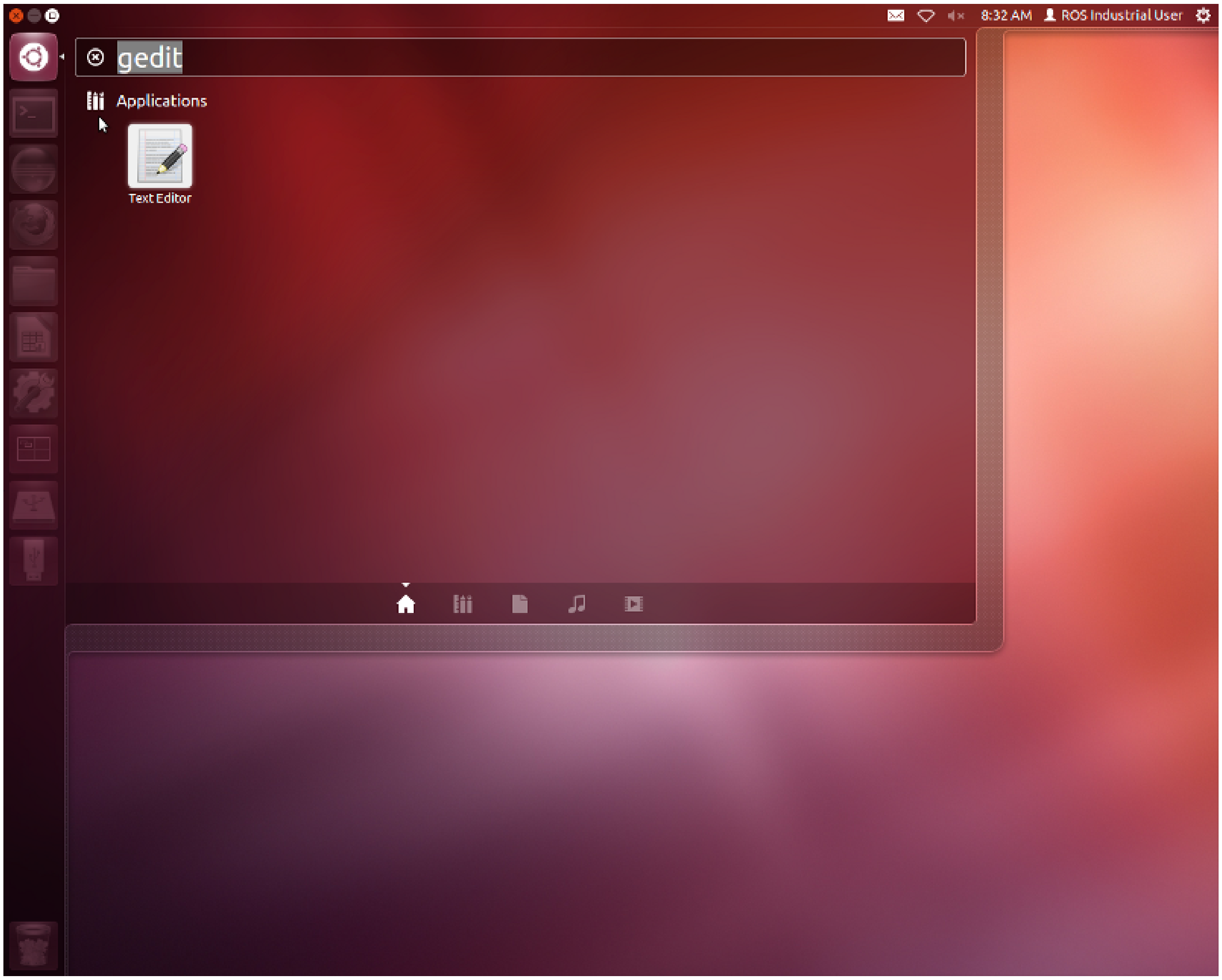
1. The close, minimize, and maximize buttons typically found on the right-hand side of the window title bar are found on the left-hand side.
2. The menu for windows are found on the menu bar at the top of the screen, much in the same way Macs do. The menus, however, only show up when you hover the mouse over the menu bar.
3. Notice that there are triangles on the left and right of the folder icon. The triangles on the left show how many windows of this application are open, and the right shows which application is currently in the foreground, or “has focus”. Clicking on these icons when the applications are open does one of two things:

- If there is only one window open, this window gets focus.
- If more than one are open, clicking a second time causes all of the windows to show up in the foreground, so that you can choose which window to go to (see below):



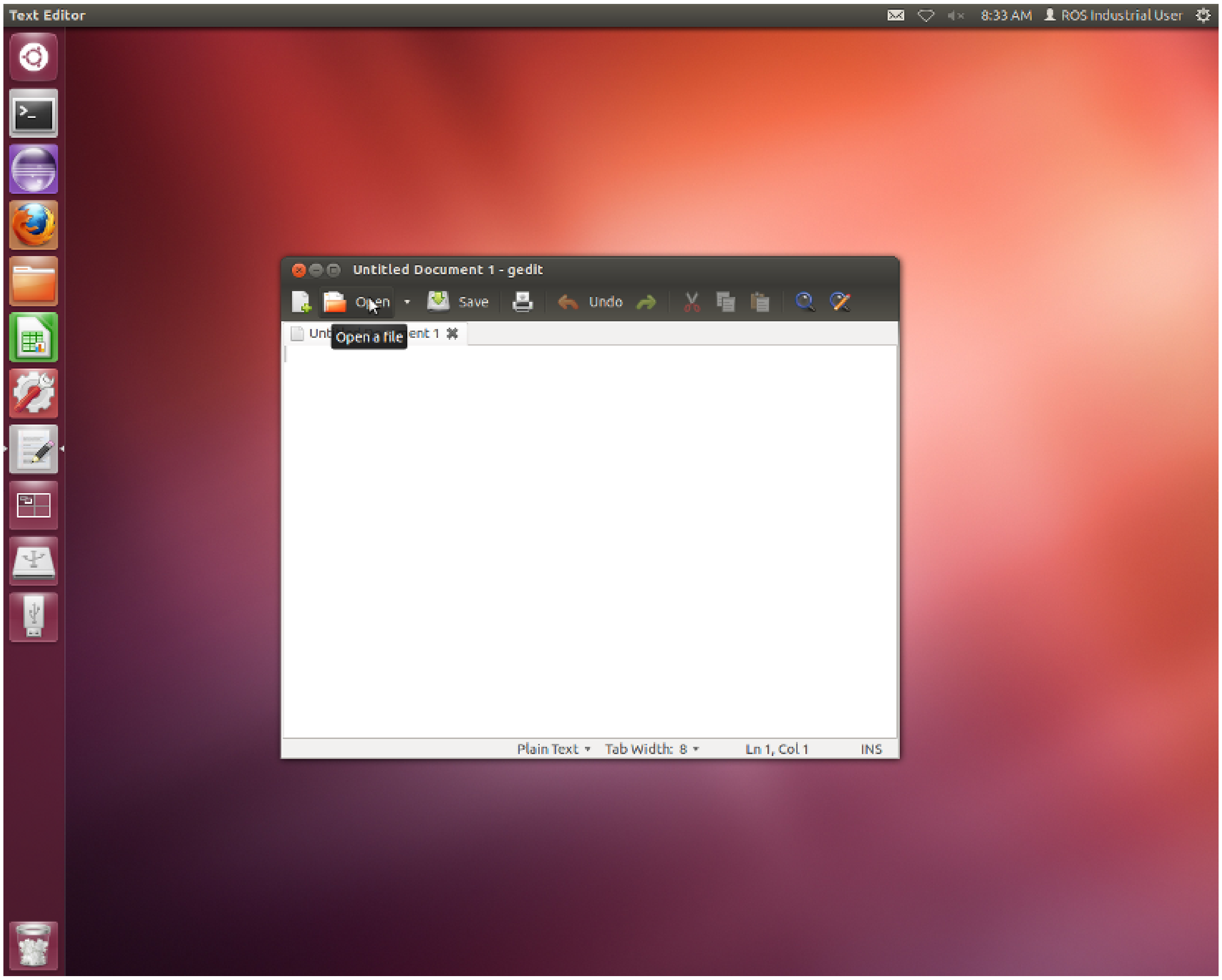
Task 3: Start an Application & Pin it to the Launcher Bar

Click on the launcher button (top left) and type gedit in the search box. The “Text Editor” application (this is actually gedit) should show up (see below):



gedit

Click on the application. The text editor window should show up on the screen, and the text editor icon should show up on the launcher bar on the left-hand side (see below):



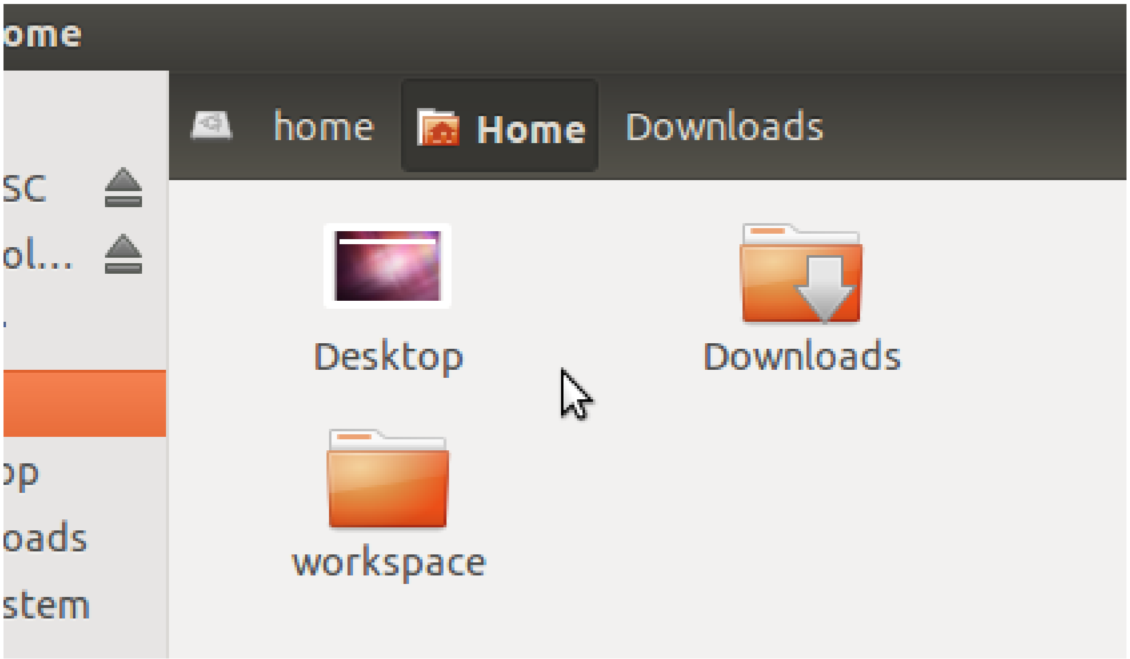
1. Right-click on the text editor launch icon, and select "Lock to Launcher".
2. Close the gedit window. The launcher icon should remain after the window closes.
3. Click on the gedit launcher icon. You should see a new gedit window appear.

2.2.2 Exploring the Linux File System

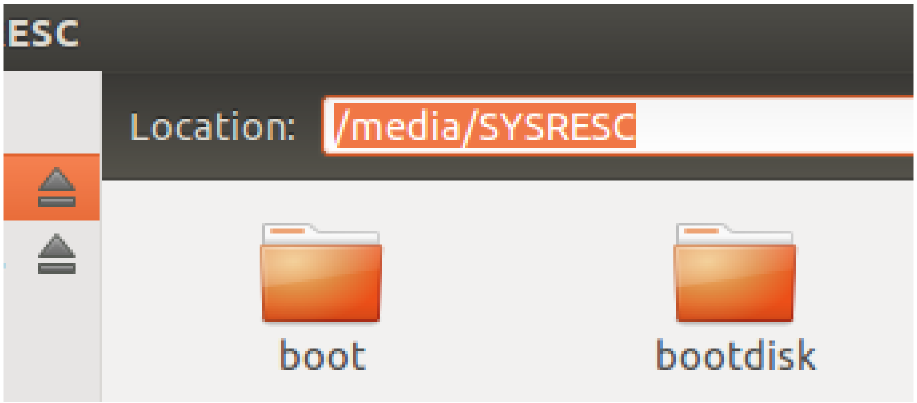
In this exercise, we will look at how to navigate and move files in the Linux file system using the Ubuntu GUI, and learn some of the basics of Linux file attributes.

Using the File Browser to Navigate

1. Open the folder browser application we opened in the previous exercise. You should see an window like the one below. The icons and text above the main window show the current location of the window in the file system.



1. The icons at the top constitute the "location bar" of the file browser. While the location bar is very useful for navigating in the GUI, it hides the exact location of the window. You can show the location by pressing *Ctrl+L*. You should see the location bar turn into something like the image below:



Location: /media/SYSRESC

1. The folder browser opens up in the user's home folder by default. This folder is typically */home/*, which in the ROS-Industrial training computer is */home/ros-industrial*. This folder is the only one which the user has full access to. This is by design for security's sake.

2. By default, the file browser doesn't show hidden files (files which begin with a . character) or "backup" files (which end with a ~ character). To show these files, click on the "View" menu, and select "Show Hidden Files" (or press Ctrl+H). This will show all of the hidden files. Uncheck the option to re-hide those files.

3. Two hidden directories are *never* shown: The . folder, which is a special folder that represents the current folder, and .., which represents the folder which contains the current folder. These will become important in the next exercise.

4. On the left hand side of the window are some quick links to removable devices, other hard drives, bookmarks, etc. Click on the "Computer" shortcut link. This will take you to the "root" of the file system, the / folder. All of the files on the computer are in sub-folders under this folder.

5. Double click on the *opt* folder, then the *ros* folder. This is where all of the ROS software resides. Each version is stored in its own folder; we should see a kinetic folder there. Double-click on that folder. The *setup.bash* file

will be used in the terminal exercise to configure the terminal for ROS. The programs, data, etc. are in the *bin* and *share* folders. You generally do not need to modify any of these files directly, but it is good to know where they reside.

Making Changes

Copying, Moving, and Removing Files

1. Create a directory and file
   (a) Make a directory *<Home>/ex0.3*. We will be working within this folder.
      - Inside the file browser, click on the “Home” shortcut in the left sidebar.
      - Right click in the file browser’s main panel and select “New Folder”.
      - Name the folder “ex0.3” and press “return”.

   (b) Make a file *test.txt* inside the newly-created *ex0.3* folder.
      - Double-click on the *ex0.3* folder. Note how the File Browser header changes to show the current folder.
      - Right click in the file browser’s main panel and select “New Document”, then “Empty Document”.
      - Name the file “test.txt” and press “return”.
2. Copying Files
   (a) Copy the file using one of the following methods:
      - Click and hold on the *test.txt* file, hold down on the control key, drag somewhere else on the folder, and release.
      - Click on the file, go to the “Copy” from the “Edit” menu, and then “Paste” from the “Edit” menu. *Remember: to see the Menu, hover your mouse above the bar at the top of the screen*

   (b) Rename the copied file to *copy.txt* using one of the following methods:
      - Right-click on the copied file, select “Rename…” and enter *copy.txt*.
      - Click on the file, press the F2 key, and enter *copy.txt*.

   (c) Create a folder *new* using one of the following methods:
      - Right-click on an open area of the file browser window, select “New Folder”, and naming it *new*
      - Select “New Folder” from the “File” menu, and naming it *new*

   (d) Move the file *copy.txt* into the *new* folder by dragging the file into the *new* folder.

   (e) Copy the file *test.txt* by holding down the Control key while dragging the file into the new folder.

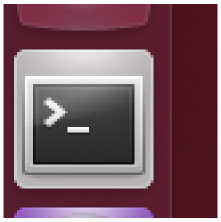
   (f) Navigate into the *new* folder, and delete the *test.txt* folder by clicking on the file, and pressing the delete key.

/# The Linux Terminal

In this exercise, we will familiarize ourselves with the Linux terminal.

2.2.3 Starting the Terminal

1. To open the terminal, click on the terminal icon:

2. Create a second terminal window, either by:
   - Right-clicking on the terminal and selecting the "Open Terminal" or
   - Selecting "Open Terminal" from the "File" menu
3. Create a second terminal within the same window by pressing "Ctrl+Shift+T" while the terminal window is selected.
4. Close the 2nd terminal tab, either by:
   - clicking the small 'x' in the terminal tab (not the main terminal window)
   - typing `exit` and hitting enter.
5. The window will have a single line, which looks like this:

   ```
   ros-industrial@ros-i-kinetic-vm:~$
   ```

6. This is called the prompt, where you enter commands. The prompt, by default, provides three pieces of information:

   (a) *ros-industrial* is the login name of the user you are running as.

   (b) *ros-i-kinetic-vm* is the host name of the computer.

   (c) ~ is the directory in which the terminal is currently in. (More on this later).

7. Close the terminal window by typing `exit` or clicking on the red 'x' in the window's titlebar.

2.2.4 Navigating Directories and Listing Files

Prepare your environment

1. Open your home folder in the file browser.
2. Double-click on the `ex0.3` folder we created in the previous step.
   - *We'll use this to illustrate various file operations in the terminal.*
3. Right click in the main file-browser window and select "Open in Terminal" to create a terminal window at that location.
4. In the terminal window, type the following command to create some sample files that we can study later:
   - `cp -a ~/industrial_training/exercises/0.3/. .`

ls Command

1. Enter `ls` into the terminal.
   - You should see `test.txt`, and `new` listed. (If you don't see 'new', go back and complete the previous exercise).
   - Directories, like `new`, are colored in blue.
   - The file `sample_job` is in green; this indicates it has its "execute" bit set, which means it can be executed as a command.
2. Type `ls *.txt`. Only the file `test.txt` will be displayed.
3. Enter `ls -l` into the terminal.
   - Adding the `-l` option shows one entry per line, with additional information about each entry in the directory.
   - The first 10 characters indicate the file type and permissions
   - The first character is `d` if the entry is a directory.
   - The next 9 characters are the permissions bits for the file
   - The third and fourth fields are the owning user and group, respectively.
   - The second-to-last field is the time the file was last modified.
   - If the file is a symbolic link, the link's target file is listed after the link's file name.
4. Enter `ls -a` in the terminal.
   - You will now see one additional file, which is hidden.
5. Enter `ls -a -l` (or `ls -al`) in the command.
   - You'll now see that the file `hidden_link.txt` points to `.hidden_text_file.txt`.

`pwd` and `cd` Commands

1. Enter `pwd` into the terminal.
   - This will show you the full path of the directory you are working in.
2. Enter `cd new` into the terminal.
   - The prompt should change to `ros-industrial@ros-i-kinetic-vm:~/ex0.3/new$`.
   - Typing `pwd` will show you now in the directory `/home/ros-industrial/ex0.3/new`.
3. Enter `cd ..` into the terminal. * In the previous exercise, we noted that `..` is the parent folder. * The prompt should therefore indicate that the current working directory is `/home/ros-industrial/ex0.3`.
4. Enter `cd /bin`, followed by `ls`.
   - This folder contains a list of the most basic Linux commands. *Note that `pwd` and `ls` are both in this folder.*
5. Enter `cd ~/ex0.3` to return to our working directory.
   - Linux uses the ~ character as a shorthand representation for your home directory.
   - It's a convenient way to reference files and paths in command-line commands.
   - You'll be typing it a lot in this class… remember it!

If you want a full list of options available for any of the commands given in this section, type `man <command>` (where `<command>` is the command you want information on) in the command line. This will provide you with built-in documentation for the command. Use the arrow and page up/down keys to scroll, and `q` to exit.

2.2.5 Altering Files

mv Command

1. Type `mv test.txt test2.txt`, followed by `ls`.
   - You will notice that the file has been renamed to `test2.txt`. *This step shows how `mv` can rename files.*
2. Type `mv test2.txt new`, then `ls`.
   - The file will no longer be present in the folder.
3. Type `cd new`, then `ls`.
   - You will see `test2.txt` in the folder. *These steps show how `mv` can move files.*
4. Type `mv test2.txt ../test.txt`, then `ls`.
   - `test2.txt` will no longer be there.
5. Type `cd ..`, then `ls`.
   - You will notice that `test.txt` is present again. *This shows how `mv` can move and rename files in one step.*

cp Command

1. Type `cp test.txt new/test2.txt`, then `ls new`.
   - You will see `test2.txt` is now in the `new` folder.
2. Type `cp test.txt "test copy.txt"`, then `ls -l`.
   - You will see that `test.txt` has been copied to `test copy.txt`. *Note that the quotation marks are necessary when spaces or other special characters are included in the file name.*

rm Command

1. Type `rm "test copy.txt"`, then `ls -l`.
   - You will notice that `test copy.txt` is no longer there.

mkdir Command

1. Type `mkdir new2`, then `ls`.
   - You will see there is a new folder `new2`.

You can use the `-i` flag with `cp`, `mv`, and `rm` commands to prompt you when a file will be overwritten or removed.

2.2.6 Job management

Stopping Jobs

1. Type `./sample_job`.
    - The program will start running.
2. Press Control+C.
    - The program should exit.
3. Type `./sample_job sigterm`.
    - The program will start running.
4. Press Control+C.
    - This time the program will not die.

Stopping "Out of Control" Jobs

1. Open a new terminal window.
2. Type `ps ax`.
3. Scroll up until you find `python ./sample_job sigterm`.
    - This is the job that is running in the first window.
    - The first field in the table is the ID of the process (use `man ps` to learn more about the other fields).
4. Type `ps ax | grep sample`.
    - You will notice that only a few lines are returned.
    - This is useful if you want to find a particular process
    - *Note: this is an advanced technique called "piping", where the output of one program is passed into the input of the next. This is beyond the scope of this class, but is useful to learn if you intend to use the terminal extensively.*
5. Type `kill <id>`, where `<id>` is the job number you found with the `ps ax`.
6. In the first window, type `./sample_job sigterm sigkill`.
    - The program will start running.
7. In the second window, type `ps ax | grep sample` to get the id of the process.
8. Type `kill <id>`.
    - This time, the process will not die.
9. Type `kill -SIGKILL <id>`.
    - This time the process will exit.

Showing Process and Memory usage

1. In a terminal, type `top`.
    - A table will be shown, updated once per second, showing all of the processes on the system, as well as the overall CPU and memory usage.

2. Press the Shift+P key.
   - This will sort processes by CPU utilization. *This can be used to determine which processes are using too much CPU time.*
3. Press the Shift+M key.
   - This will sort processes by memory utilization *This can be used to determine which processes are using too much memory.*
4. Press q or Ctrl+C to exit the program.

Editing Text (and Other GUI Commands)

1. Type `gedit test.txt`.
   - You will notice that a new text editor window will open, and `test.txt` will be loaded.
   - The terminal will not come back with a prompt until the window is closed.
2. There are two ways around this limitation. Try both. . .
3. **Starting the program and immediately returning a prompt:**
   (a) Type `gedit test.txt &`.
      - The `&` character tells the terminal to run this command in "the background", meaning the prompt will return immediately.

   (b) Close the window, then type `ls`.
      - In addition to showing the files, the terminal will notify you that `gedit` has finished.
4. **Moving an already running program into the background:**
   (a) Type `gedit test.txt`.
      - The window should open, and the terminal should not have a prompt waiting.

   (b) In the terminal window, press Ctrl+Z.
      - The terminal will indicate that `gedit` has stopped, and a prompt will appear.

   (c) Try to use the `gedit` window.
      - Because it is paused, the window will not run.

   (d) Type `bg` in the terminal.
      - The `gedit` window can now run.

   (e) Close the `gedit` window, and type `ls` in the terminal window.
      - As before, the terminal window will indicate that `gedit` is finished.

Running Commands as Root

1. In a terminal, type `ls -a /root`.
   - The terminal will indicate that you cannot read the folder `/root`.
   - Many times you will need to run a command that cannot be done as an ordinary user, and must be done as the "super user"
2. To run the previous command as root, add `sudo` to the beginning of the command.

- In this instance, type `sudo ls -a /root` instead.
- The terminal will request your password (in this case, `rosindustrial`) in order to proceed.
- Once you enter the password, you should see the contents of the `/root` directory.

***Warning**: `sudo` is a powerful tool which doesn't provide any sanity checks on what you ask it to do, so be **VERY** careful in using it.*

CHAPTER 3

Basic Topics

3.1 Session 1 - ROS Concepts and Fundamentals

`Slides`

3.1.1 ROS-Setup

> In this exercise, we will setup ROS to be used from the terminal, and start roscore

Motivation

In order to start programming in ROS, you should know how to install ROS on a new machine as well and check that the installation worked properly. This module will walk you through a few simple checks of your installed ROS system. Assuming you are working from the VM, you can skip any installation instructions as ROS is already installed.

Reference Example

Configuring ROS

Further Information and Resources

Installation Instructions

Navigating ROS

Scan-N-Plan Application: Problem Statement

We believe we have a good installation of ROS but let's test it to make sure.

Scan-N-Plan Application: Guidance

Setup ~/.bashrc

1. If you are ever having problems finding or using your ROS packages make sure that you have your environment properly setup. A good way to check is to ensure that environment variables like ROS_ROOT and ROS_PACKAGE_PATH are set:

   ```
   printenv | grep ROS
   ```

2. If they are not then you might need to 'source' some setup.*sh files.

   ```
   source /opt/ros/kinetic/setup.bash
   ```

3. In a "bare" ROS install, you will need to run this command on every new shell you open to have access to the ROS commands. One of the setup steps in a *typical* ROS install is to add that command to the end of your `~/.bashrc` file, which is run automatically in every new terminal window. Check that your `.bashrc` file has already been configured to source the ROS-kinetic `setup.bash` script:

   ```
   tail ~/.bashrc
   ```

This process allows you to install several ROS distributions (e.g. indigo and kinetic) on the same computer and switch between them by sourcing the distribution-specific `setup.bash` file.

Starting roscore

1. *roscore* is a collection of nodes and programs that are pre-requisites of a ROS-based system. You must have a roscore running in order for ROS nodes to communicate. It is launched using the *roscore* command.

   ```
   roscore
   ```

   roscore will start up:

   - a ROS Master
   - a ROS Parameter Server
   - a rosout logging node

   You will see ending with `started core service [/rosout]`. If you see `roscore: command not found` then you have not sourced your environment, please refer to section 5.1. .bashrc Setup.

2. To view the logging node, open a new terminal and enter:

   ```
   rosnode list
   ```

   The logging node is named */rosout*

3. Press *Ctrl+C* in the first terminal window to stop roscore. Ctrl-C is the typical method used to stop most ROS commands.

3.1.2 Create Catkin Workspace

In this exercise, we will create a ROS catkin workspace.

Motivation

Any ROS project begins with making a workspace. In this workspace, you will put all the things related to this particular project. In this module we will create the workspace where we will build the components of our Scan-N-Plan application.

Reference Example

Steps to creating a workspace: Creating a Catkin Workspace

Note: Many current examples on ros.org use the older-style `catkin_init_workspace` commands. These are similar, but not directly interchangeable with the `catkin_tools` commands used in this course.

Further Information and Resources

Using a Catkin Workspace: Using a Workspace

Scan-N-Plan Application: Problem Statement

We have a good installation of ROS, and we need to take the first step to setting up our particular application. Your goal is to create a workspace - a catkin workspace - for your application and its supplements.

Scan-N-Plan Application: Guidance

Create a Catkin Workspace

1. Create the root workspace directory (we'll use `catkin_ws`)

   ```
   cd ~/
   mkdir --parents catkin_ws/src
   cd catkin_ws
   ```

2. Initialize the catkin workspace

   ```
   catkin init
   ```

   - *Look for the statement "Workspace configuration appears valid", showing that your catkin workspace was created successfully. If you forgot to create the `src` directory, or did not run `catkin init` from the workspace root (both common mistakes), you'll get an error message like "WARNING: Source space does not yet exist".*

3. Build the workspace. This command may be issued anywhere under the workspace root-directory (i.e. `catkin_ws`).

   ```
   catkin build
   ls
   ```

   - *See that the `catkin_ws` directory now contains additional directories (build, devel, logs).*

4. These new directories can be safely deleted at any time (either manually, or using `catkin clean`). Note that catkin never changes any files in the `src` directory. Re-run `catkin build` to re-create the build/devel/logs directories.

```
catkin clean
ls
catkin build
ls
```

5. Make the workspace visible to ROS. Source the setup file in the devel directory.

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

   - *This file MUST be sourced for every new terminal.*
   - To save typing, add this to your `~/.bashrc` file, so it is automatically sourced for each new terminal:
     (a) `gedit ~/.bashrc`
     (b) add to the end: `source ~/catkin_ws/devel/setup.bash`
     (c) save and close the editor

3.1.3 Installing Packages

Motivation

Many of the coolest and most useful capabilities of ROS already exist somewhere in its community. Often, stable resources exist as easily downloadable debian packages. Alternately, some resources are less tested or more "cutting edge" and have not reached a stable release state; you can still access many of these resources by downloading them from their repository (usually housed on Github). Getting these git packages takes a few more steps than the debian packages. In this module we will access both types of packages and install them on our system.

Reference Example

apt-get usage

Further Information and Resources

Ubuntu apt-get How To

Git Get Repo

Git Clone Documentation

Scan-N-Plan Application: Problem Statement

We have a good installation of ROS, and we have an idea of some packages that exist in ROS that we would like to use within our program. We have found a package which is stable and has a debian package we can download. We've also found a less stable git package that we are interested in. Go out into the ROS world and download these packages!

1. A certain message type exists which you want to use. The stable ROS package is called: calibration_msgs
2. You are using an AR tag, but for testing purposes you would like a node to publish similar info : fake_ar_publisher

Your goal is to have access to both of these packages' resources within your package/workspace:

1. calibration_msgs (using apt-get)

2. fake_ar_publisher (from git)

Scan-N-Plan Application: Guidance

Install Package from apt Repository

1. Open a terminal window. Type roscd calibration_msgs.

   ```
   roscd calibration_msgs
   ```

   - This command changes the working directory to the directory of the ROS *calibration_msgs* package.
   - You should see an error message ‘**No such package/stack ‘calibration_msgs**’ .
   - *This package is not installed on the system, so we will install it.*

2. Type *apt install ros-kinetic-calibration-msgs*.

   ```
   apt install ros-kinetic-calibration-msgs
   ```

   - The program will say it cannot install the package, and suggests that we must run the program as root.
   - Try pressing the *TAB* key while typing the package name.
     - The system will try to automatically complete the package name, if possible.
     - Frequent use of the TAB key will help speed up entry of many typed commands.

3. Type *sudo apt install ros-kinetic-calibration-msgs*.

   ```
   sudo apt install ros-kinetic-calibration-msgs
   ```

   - Note the use of the *sudo* command to run a command with “root” (administrator) privileges.
   - Enter your password, and (if asked) confirm you wish to install the program.

4. Type *roscd calibration_msgs* again.

   ```
   roscd calibration_msgs
   ```

   - This time, you will see the working directory change to */opt/ros/kinetic/share/calibration_msgs*.

5. Type *sudo apt remove ros-kinetic-calibration-msgs* to remove the package.

   ```
   sudo apt remove ros-kinetic-calibration-msgs
   ```

   - *Don’t worry. We won’t be needing this package for any future exercises, so it’s safe to remove.*

6. Type *cd ~* to return to your home directory.

   ```
   cd ~
   ```

Download and Build a Package from Source

1. Identify the source repository for the desired package:

   (a) Go to github.

   (b) Search for fake_ar_publisher.

   (c) Click on this repository, and look to the right for the *Clone or Download*, then copy to clipboard.

2. Clone the *fake_ar_publisher* repository into the catkin workspace's *src* directory.

```
cd ~/catkin_ws/src
git clone https://github.com/jmeyer1292/fake_ar_publisher.git
```

   - *Use Ctrl-Shift-V to paste within the terminal, or use your mouse to right-click and select paste*
   - *Git commands are outside of the scope of this class, but there are good tutorials available here*

3. Build the new package using `catkin build` *The build command can be issued from anywhere inside the catkin workspace*

4. Once the build completes, notice the instruction to *"re-source setup files to use them"*.

   - In the previous exercise, we added a line to our `~/.bashrc` file to automatically re-source the catkin setup files in each new terminal.
   - This is sufficient for most development activities, but you may sometimes need to re-execute the `source` command in your current terminal (e.g. when adding new packages):

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

5. Once the build completes, explore the *build* and *devel* directories to see what files were created.

6. Run *rospack find fake_ar_publisher* to verify the new packages are visible to ROS.

```
rospack find fake_ar_publisher
```

   - This is a helpful command to troubleshoot problems with a ROS workspace.
   - If ROS can't find your package, try re-building the workspace and then re-sourcing the workspace's `setup.bash` file.

3.1.4 Creating Packages and Nodes

In this exercise, we will create our own ROS package and node.

Motivation

The basis of ROS communication is that multiple executables called nodes are running in an environment and communicating with each other in various ways. These nodes exist within a structure called a package. In this module we will create a node inside a newly created package.

Reference Example

Create a Package

Further Information and Resources

Building Packages

Understanding Nodes

Scan-N-Plan Application: Problem Statement

We've installed ROS, created a workspace, and even built a few times. Now we want to create our own package and our own node to do what we want to do.

Your goal is to create your first ROS node:

1. First you need to create a package inside your catkin workspace.
2. Then you can write your own node

Scan-N-Plan Application: Guidance

Create a Package

1. cd into the catkin workspace src directory *Note: Remember that all packages should be created inside a workspace src directory.*

   ```
   cd ~/catkin_ws/src
   ```

2. Use the ROS command to create a package called *myworkcell_core* with a dependency on *roscpp*

   ```
   catkin create pkg myworkcell_core --catkin-deps roscpp
   ```

   See the catkin_tools documentation for more details on this command.

   - *This command creates a directory and required files for a new ROS package.*
   - *The first argument is the name of the new ROS package.*
   - *Use* `--catkin-deps` *to specify packages which the newly created package depends on.*

3. There will now be a folder named *myworkcell_core*. Change into that folder and edit the *package.xml* file. Edit the file and change the description, author, etc., as desired.

   ```
   cd myworkcell_core
   gedit package.xml
   ```

   If you forget to add a dependency when creating a package, you can add additional dependencies in the package.xml *file.*

STOP! We'll go through a few more lecture slides before continuing this exercise.

Create a Node

1. In the package folder, edit the *CMakeLists.txt* file using *gedit*. Browse through the example rules, and add an executable(*add_executable*), node named vision_node, source file named vision_node.cpp. Also within the *CMakeLists.txt*, make sure your new vision_node gets linked ('target_link_libraries') to the catkin libraries.

   ```
   add_compile_options(-std=c++11)
   add_executable(vision_node src/vision_node.cpp)
   target_link_libraries(vision_node ${catkin_LIBRARIES})
   ```

   These lines can be placed anywhere in `CMakeLists.txt`, but I typically:

   - Uncomment existing template examples for `add_compile_options` near the top (just below `project()`)

- Uncomment and edit existing template examples for `add_executable` and `target_link_libraries` near the bottom
- This helps make sure these rules are defined in the correct order, and makes it easy to remember the proper syntax.

Note: You're also allowed to spread most of the CMakeLists rules across multiple lines, as shown in the `target_link_libraries` *template code*

2. In the package folder, create the file *src/vision_node.cpp* (using *gedit*).
3. Add the ros header (include ros.h).

```
/**
**  Simple ROS Node
**/
#include <ros/ros.h>
```

4. Add a main function (typical in c++ programs).

```
/**
**  Simple ROS Node
**/
#include <ros/ros.h>

int main(int argc, char* argv[])
{

}
```

5. Initialize your ROS node (within the main).

```
/**
**  Simple ROS Node
**/
#include <ros/ros.h>

int main(int argc, char* argv[])
{
  // This must be called before anything else ROS-related
  ros::init(argc, argv, "vision_node");
}
```

6. Create a ROS node handle.

```
/**
**  Simple ROS Node
**/
#include <ros/ros.h>

int main(int argc, char* argv[])
{
  // This must be called before anything else ROS-related
  ros::init(argc, argv, "vision_node");

  // Create a ROS node handle
  ros::NodeHandle nh;
}
```

7. Print a "Hello World" message using ROS print tools.

```
/**
**  Simple ROS Node
**/
#include <ros/ros.h>

int main(int argc, char* argv[])
{
  // This must be called before anything else ROS-related
  ros::init(argc, argv, "vision_node");

  // Create a ROS node handle
  ros::NodeHandle nh;

  ROS_INFO("Hello, World!");
}
```

8. Do not exit the program automatically - keep the node alive.

```
/**
**  Simple ROS Node
**/
#include <ros/ros.h>

int main(int argc, char* argv[])
{
  // This must be called before anything else ROS-related
  ros::init(argc, argv, "vision_node");

  // Create a ROS node handle
  ros::NodeHandle nh;

  ROS_INFO("Hello, World!");

  // Don't exit the program.
  ros::spin();
}
```

ROS_INFO is one of the many logging methods.

- It will print the message to the terminal output, and send it to the */rosout* topic for other nodes to monitor.
- There are 5 levels of logging: *DEBUG, INFO, WARNING, ERROR, & FATAL.*
- To use a different logging level, replace INFO in *ROS_INFO* or *ROS_INFO_STREAM* with the appropriate level.
- Use *ROS_INFO* for printf-style logging, and *ROS_INFO_STREAM* for cout-style logging.

9. Build your program (node), by running `catkin build` in a terminal window

- *Remember that you must run* `catkin build` *from within your* `catkin_ws` *(or any subdirectory)*
- This will build all of the programs, libraries, etc. in *myworkcell_core*
- In this case, it's just a single ROS node *vision_node*

Run a Node

1. Open a terminal and start the ROS master.

```
roscore
```

The ROS Master must be running before any ROS nodes can function.

2. Open a second terminal to run your node.

   - In a previous exercise, we added a line to our `.bashrc` to automatically source `devel/setup.bash` in new terminal windows
   - This will automatically export the results of the build into your new terminal session.
   - If you're reusing an existing terminal, you'll need to manually source the setup files (since we added a new node):

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

3. Run your node.

   ```
   rosrun myworkcell_core vision_node
   ```

   This runs the program we just created. Remember to use TAB to help speed-up typing and reduce errors.

4. In a third terminal, check what nodes are running.

   ```
   rosnode list
   ```

   In addition to the /rosout node, you should now see a new /vision_node listed.

5. Enter *rosnode kill /vision_node*. This will stop the node.

   Note: It is more common to use Ctrl+C to stop a running node in the current terminal window.

Challenge

Goal: Modify the node so that it prints your name. This will require you to run through the build process again.

3.1.5 Topics and Messages

In this exercise, we will explore the concept of ROS messages and topics.

Motivation

The first type of ROS communication that we will explore is a one-way communication called messages which are sent over channels called topics. Typically one node publishes messages on a topic and another node subscribes to messages on that same topic. In this module we will create a subscriber node which subscribes to an existing publisher (topic/message).

Reference Example

Create a Subscriber

Further Information and Resources

Understanding Topics

Examining Publisher & Subscriber

Creating Messages and Services

Scan-N-Plan Application: Problem Statement

We now have a base ROS node and we want to build on this node. Now we want to create a subscriber within our node.

Your goal is to create your first ROS subscriber:

1. First you will want to find out the message structure.
2. You also want to determine the topic name.
3. Last you can write the c++ code which serves as the subscriber.

Scan-N-Plan Application: Guidance

Add the fake_ar_publisher Package as a Dependency

1. Locate the `fake_ar_publisher` package you downloaded earlier.

   ```
   rospack find fake_ar_publisher
   ```

2. Edit your package's `CMakeLists.txt` file (`~/catkin_ws/src/myworkcell_core/CMakeLists.txt`). Make the following changes in the matching sections of the existing template file, by uncommenting and/or editing existing rules.

   (a) Tell cmake to find the fake_ar_publisher package:

   ```
   ## Find catkin macros and libraries
   ## if COMPONENTS list like find_package(catkin REQUIRED COMPONENTS xyz)
   ## is used, also find other catkin packages
   find_package(catkin REQUIRED COMPONENTS
     roscpp
     fake_ar_publisher
   )
   ```

   (b) Add The catkin runtime dependency for publisher.

   ```
   ## The catkin_package macro generates cmake config files for your package
   ## Declare things to be passed to dependent projects
   ## LIBRARIES: libraries you create in this project that dependent projects␣
   ↪also need
   ## CATKIN_DEPENDS: catkin_packages dependent projects also need
   ## DEPENDS: system dependencies of this project that dependent projects also␣
   ↪need
   catkin_package(
    #  INCLUDE_DIRS include
    #  LIBRARIES myworkcell_core
      CATKIN_DEPENDS
        roscpp
   ```

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```
    fake_ar_publisher
#  DEPENDS system_lib
)
```

   (c) Uncomment/edit the `add_dependencies` line **below** your `add_executable` rule:

   ```
   add_dependencies(vision_node ${${PROJECT_NAME}_EXPORTED_TARGETS} ${catkin_
   ↪EXPORTED_TARGETS})
   ```

3. add dependencies into your package's `package.xml`:

   ```
   <depend>fake_ar_publisher</depend>
   ```

4. `cd` into your catkin workspace

   ```
   cd ~/catkin_ws
   ```

5. Build your package and source the setup file to activate the changes in the current terminal.

   ```
   catkin build
   source ~/catkin_ws/devel/setup.bash
   ```

6. In a terminal, enter `rosmsg list`. You will notice that, included in the list, is `fake_ar_publisher/ARMarker`. If you want to see only the messages in a package, type `rosmsg package <package_name>`

7. Type `rosmsg show fake_ar_publisher/ARMarker`. The terminal will return the types and names of the fields in the message.

   Note that three fields under the `header` *field are indented, indicating that these are members of the* `std_msgs/Header` *message type*

Run a Publisher Node

1. In a terminal, type `rosrun fake_ar_publisher fake_ar_publisher_node`. You should see the program start up and begin publishing messages.

2. In another terminal, enter `rostopic list`. You should see `/ar_pose_marker` among the topics listed. Entering `rostopic type /ar_pose_marker` will return the type of the message.

3. Enter `rostopic echo /ar_pose_marker`. The terminal will show the fields for each message as they come in, separated by a `---` line. Press Ctrl+C to exit.

4. Enter `rqt_plot`.

   (a) Once the window opens, type `/ar_pose_marker/pose/pose/position/x` in the "Topic:" field and click the "+" button. You should see the X value be plotted.

   (b) Type `/ar_pose_marker/pose/pose/position/y` in the topic field, and click on the add button. You will now see both the x and y values being graphed.

   (c) Close the window

5. Leave the publisher node running for the next task.

Create a Subscriber Node

1. Edit the `vision_node.cpp` file.

2. Include the message type as a header

```
#include <fake_ar_publisher/ARMarker.h>
```

3. Add the code that will be run when a message is received from the topic (the callback).

```
class Localizer
{
public:
  Localizer(ros::NodeHandle& nh)
  {
      ar_sub_ = nh.subscribe<fake_ar_publisher::ARMarker>("ar_pose_marker", 1,
      &Localizer::visionCallback, this);
  }

  void visionCallback(const fake_ar_publisher::ARMarkerConstPtr& msg)
  {
      last_msg_ = msg;
      ROS_INFO_STREAM(last_msg_->pose.pose);
  }

  ros::Subscriber ar_sub_;
  fake_ar_publisher::ARMarkerConstPtr last_msg_;
};
```

4. Add the code that will connect the callback to the topic (within `main()`)

```
int main(int argc, char** argv)
{
  ...
  // The Localizer class provides this node's ROS interfaces
  Localizer localizer(nh);

  ROS_INFO("Vision node starting");
  ...
}
```

   - You can replace or leave the “Hello World” print… your choice!
   - These new lines must go below the `NodeHandle` declaration, so `nh` is actually defined.
   - Make sure to retain the `ros::spin()` call. It will typically be the last line in your `main` routine. Code after `ros::spin()` won't run until the node is shutting down.

5. Run `catkin build`, then `rosrun myworkcell_core vision_node`.
6. You should see the positions display from the publisher.
7. Press Ctrl+C on the publisher node. The subscriber will stop displaying information.
8. Start the publisher node again. The subscriber will continue to print messages as the new program runs.
   - This is a key capability of ROS, to be able to restart individual nodes without affecting the overall system.
9. In a new terminal, type `rqt_graph`. You should see a window similar to the one below:

- The rectangles in the the window show the topics currently available on the system.
- The ovals are ROS nodes.
- Arrows leaving the node indicate the topics the node publishes, and arrows entering the node indicate the topics the node subscribes to.

3.2 Session 2 - Basic ROS Applications

`Slides`

3.2.1 Services

In this exercise, we will create a custom service by defining a .srv file. Then we will write server and client nodes to utilize this service.

Motivation

The first type of ROS communication that we explored was a one-way interaction called messages which are sent over channels called topics. Now we are going to explore a different communication type, which is a two-way interaction via a request from one node to another and a response from that node to the first. In this module we will create a service server (waits for request and comes up with response) and client (makes request for info then waits for response).

Reference Example

Create a Service Server/Client

Further Information and Resources

- Creating Messages & Services
- Understanding Services & Params
- Examining Service Client

Scan-N-Plan Application: Problem Statement

We now have a base ROS node which is subscribing to some information and we want to build on this node. In addition we want this node to serve as a sub-function to another "main" node. The original vision node will now be responsible for subscribing to the AR information and responding to requests from the main workcell node.

Your goal is to create a more intricate system of nodes:

1. Update the vision node to include a service server
2. Create a new node which will eventually run the Scan-N-Plan App
   - First, we'll create the new node (myworkcell_core) as a service client. Later, we will expand from there

Scan-N-Plan Application: Guidance

Create Service Definition

1. Similar to the message file located in the fake_ar_publisher package, we need to create a service file. The following is a generic structure of a service file:

```
#request
---
#response
```

2. Create a folder called srv inside your myworkcell_core package (at same level as the package's src folder)

   ```
   cd ~/catkin_ws/src/myworkcell_core
   mkdir srv
   ```

3. Create a file (gedit or QT) called LocalizePart.srv inside the srv folder.

4. Inside the file, define the service as outlined above with a request of type string named base_frame and a response of type geometry_msgs/Pose named pose:

   ```
   #request
   string base_frame
   ---
   #response
   geometry_msgs/Pose pose
   ```

5. Edit the package's CMakeLists.txt and package.xml to add dependencies on key packages:

   - message_generation is required to build C++ code from the .srv file created in the previous step
   - message_runtime provides runtime dependencies for new messages
   - geometry_msgs provides the Pose message type used in our service definition

   (a) Edit the package's CMakeLists.txt file to add the new **build-time** dependencies to the existing find_package rule:

   ```
   find_package(catkin REQUIRED COMPONENTS
     roscpp
     fake_ar_publisher
     geometry_msgs
     message_generation
   )
   ```

   (b) Also in CMakeLists.txt, add the new **run-time** dependencies to the existing catkin_package rule:

   ```
   catkin_package(
   #  INCLUDE_DIRS include
   #  LIBRARIES myworkcell_node
     CATKIN_DEPENDS
       roscpp
       fake_ar_publisher
       message_runtime
       geometry_msgs
   #  DEPENDS system_lib
   )
   ```

   (c) Edit the package.xml file to add the appropriate build/run dependencies:

   ```
   <build_depend>message_generation</build_depend>
   <exec_depend>message_runtime</exec_depend>
   <depend>geometry_msgs</depend>
   ```

6. Edit the package's CMakeLists.txt to add rules to generate the new service files:

   (a) Uncomment/edit the following CMakeLists.txt rule to reference the LocalizePart service we defined earlier:

```
## Generate services in the 'srv' folder
add_service_files(
   FILES
   LocalizePart.srv
)
```

(b) Uncomment/edit the following `CMakeLists.txt` rule to enable generation of messages and services:

```
## Generate added messages and services with any dependencies listed here
generate_messages(
   DEPENDENCIES
   geometry_msgs
)
```

7. NOW! you have a service defined in you package and you can attempt to *Build* the code to generate the service:

```
catkin build
```

Note: (or use Qt!)

Service Server

1. Edit `vision_node.cpp`; remember that the ros wiki is a resource.
2. Add the header for the service we just created

```
 #include <myworkcell_core/LocalizePart.h>
```

3. Add a member variable (type: `ServiceServer`, name: `server_`), near the other `Localizer` class member variables:

```
ros::ServiceServer server_;
```

4. In the `Localizer` class constructor, advertise your service to the ROS master:

```
server_ = nh.advertiseService("localize_part", &Localizer::localizePart, this);
```

5. The `advertiseService` command above referenced a service callback named `localizePart`. Create an empty boolean function with this name in the `Localizer` class. Remember that your request and response types were defined in the `LocalizePart.srv` file. The arguments to the boolean function are the request and response type, with the general structure of `Package::ServiceName::Request` or `Package::ServiceName::Response`.

```
bool localizePart(myworkcell_core::LocalizePart::Request& req,
                  myworkcell_core::LocalizePart::Response& res)
{

}
```

6. Now add code to the `localizePart` callback function to fill in the Service Response. Eventually, this callback will transform the pose received from the `fake_ar_publisher` (in `visionCallback`) into the frame specifed in the Service Request. For now, we will skip the frame-transform, and just pass through the data received from `fake_ar_publisher`. Copy the pose measurement received from `fake_ar_publisher` (saved to `last_msg_`) directly to the Service Response.

```
bool localizePart(myworkcell_core::LocalizePart::Request& req,
                  myworkcell_core::LocalizePart::Response& res)
{
  // Read last message
  fake_ar_publisher::ARMarkerConstPtr p = last_msg_;
  if (!p) return false;

  res.pose = p->pose.pose;
  return true;
}
```

7. You should comment out the `ROS_INFO_STREAM` call in your `visionCallback` function, to avoid cluttering the screen with useless info.

8. Build the updated `vision_node`, to make sure there are no compile errors.

Service Client

1. Create a new node (inside the same `myworkcell_core` package), named `myworkcell_node.cpp`. This will eventually be our main "application node", that controls the sequence of actions in our Scan & Plan task. The first action we'll implement is to request the position of the AR target from the Vision Node's `LocalizePart` service we created above.

2. Be sure to include the standard ros header as well as the header for the `LocalizePart` service:

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

3. Create a standard C++ main function, with typical ROS node initialization:

```
int main(int argc, char **argv)
{
  ros::init(argc, argv, "myworkcell_node");
  ros::NodeHandle nh;

  ROS_INFO("ScanNPlan node has been initialized");

  ros::spin();
}
```

4. We will be using a cpp class "ScanNPlan" to contain most functionality of the myworkcell_node. Create a skeleton structure of this class, with an empty constructor and a private area for some internal/private variables.

```
class ScanNPlan
{
public:
  ScanNPlan(ros::NodeHandle& nh)
  {

  }

private:
  // Planning components

};
```

5. Within your new ScanNPlan class, define a ROS ServiceClient as a private member variable of the class. Initialize the ServiceClient in the ScanNPlan constructor, using the same service name as defined earlier ("localize_part"). Create a void function within the ScanNPlan class named `start`, with no arguments. This will contain most of our application workflow. For now, this function will call the `LocalizePart` service and print the response.

```
class ScanNPlan
{
public:
  ScanNPlan(ros::NodeHandle& nh)
  {
    vision_client_ = nh.serviceClient<myworkcell_core::LocalizePart>("localize_
↪part");
  }

  void start()
  {
    ROS_INFO("Attempting to localize part");
    // Localize the part
    myworkcell_core::LocalizePart srv;
    if (!vision_client_.call(srv))
    {
      ROS_ERROR("Could not localize part");
      return;
    }
    ROS_INFO_STREAM("part localized: " << srv.response);
  }

private:
  // Planning components
  ros::ServiceClient vision_client_;
};
```

6. Now back in `myworkcell_node`'s `main` function, instantiate an object of the `ScanNPlan` class and call the object's `start` function.

```
ScanNPlan app(nh);

ros::Duration(.5).sleep();  // wait for the class to initialize
app.start();
```

7. Edit the package's `CMakeLists.txt` to build the new node (executable), with its associated dependencies. Add the following rules to the appropriate sections, directly under the matching rules for `vision_node`:

```
add_executable(myworkcell_node src/myworkcell_node.cpp)

add_dependencies(myworkcell_node ${${PROJECT_NAME}_EXPORTED_TARGETS} ${catkin_
↪EXPORTED_TARGETS})

target_link_libraries(myworkcell_node ${catkin_LIBRARIES})
```

8. Build the nodes to check for any compile-time errors:

```
catkin build
```

Note: (or use Qt!)

Use New Service

1. Enter each of these commands in their own terminal:

```
roscore
rosrun fake_ar_publisher fake_ar_publisher_node
rosrun myworkcell_core vision_node
rosrun myworkcell_core myworkcell_node
```

3.2.2 Actions

This Exercise is not part of the standard ROS-I Training Class workflow. Follow the standard ROS tutorials (linked below), for practice using ROS **Actions**.

ROS Tutorials for C++ Action Client/Server usage

- SimpleActionServer
- SimpleActionClient

3.2.3 Launch Files

In this exercise, we will explore starting groups of nodes at once with launch files.

Motivation

The ROS architecture encourages engineers to use ‘‘nodes” as a fundamental unit of organization in their systems, and applications can quickly grow to require many nodes to operate. Opening a new terminal and running each node individually quickly becomes unfeasible. It’d be nice to have a tool to bring up groups of nodes at once. ROS ‘‘launch” files are one such tool. It even handles bringing `roscore` up and down for you.

Reference Example

Roslaunch Examples

Further Information and Resources

Roslaunch XML Specification

Debugging and Launch Files

Scan-N-Plan Application: Problem Statement

In this exercise, you will:

1. Create a new package, `myworkcell_support`.
2. Create a directory in this package called `launch`.

3. Create a file inside this directory called `workcell.launch` that:
   (a) Launches `fake_ar_publisher`
   (b) Launches `vision_node`

You may also choose to launch `myworkcell_core` node with the others or keep it separate. We often configure systems with two main launch files. In this example, `fake_ar_publisher` and `vision_node` are "environment nodes", while `myworkcell_node` is an "application" node.

1. "Environment" Launch File - driver/planning nodes, config data, etc.
2. "Application" Launch File - executes a sequence of actions for a particular application.

Scan-N-Plan Application: Guidance

1. In your workspace, create the new package `myworkcell_support` with a dependency on `myworkcell_core`. Rebuild and source the workspace so that ROS can find the new package:

```
cd ~/catkin_ws/src
catkin create pkg myworkcell_support --catkin-deps myworkcell_core
catkin build
source ~/catkin_ws/devel/setup.bash
```

2. Create a directory for launch files (inside the new `myworkcell_support` package):

```
roscd myworkcell_support
mkdir launch
```

3. Create a new file, `workcell.launch` (inside the `launch` directory) with the following XML skeleton:

```
<launch>

</launch>
```

4. Insert lines to bring up the nodes outlined in the problem statement. See the reference documentation for more information:

```
<node name="fake_ar_publisher" pkg="fake_ar_publisher" type="fake_ar_publisher_node" />
<node name="vision_node" pkg="myworkcell_core" type="vision_node" />
```

   - *Remember: All launch-file content must be **between** the `<launch> ... </launch>` tag pair.*

5. Test the launch file:

```
roslaunch myworkcell_support workcell.launch
```

   Note: roscore and both nodes were automatically started. Press Ctrl+C *to close all nodes started by the launch file. If no nodes are left running, roscore is also stopped.*

6. Notice that none of the usual messages were printed to the console window. Launch files will suppress console output below the **ERROR** severity level by default. To restore normal text output, add the `output="screen"` attribute to each of the nodes in your launch files:

```
<node name="fake_ar_publisher" pkg="fake_ar_publisher" type="fake_ar_publisher_node" output="screen"/>
<node name="vision_node" pkg="myworkcell_core" type="vision_node" output="screen" />
```

3.2.4 Parameters

In this exercise, we will look at ROS Parameters for configuring nodes‖

Motivation

By this point in these tutorials (or your career), you've probably typed the words `int main(int argc, char** argv)` more times than you can count. The arguments to `main` are the means by which a system outside scope and understanding of your program can configure your program to do a particular task. These are *command line parameters*.

The ROS ecosystem has an analogous system for configuring entire groups of nodes. It's a fancy key-value storage program that gets brought up as part of `roscore`. It's best used to pass configuration parameters to nodes individually (e.g. to identify which camera a node should subscribe to), but it can be used for much more complicated items.

Reference Example

Understanding Parameters

Further Information and Resource

Roscpp tutorial

Private Parameters

Parameter Server

Scan-N-Plan Application: Problem Statement

In previous exercises, we added a service with the following definition:

```
# request
string base_frame
---
# response
geometry_msgs/Pose pose
```

So far we haven't used the request field, `base_frame`, for anything. In this exercise we'll use ROS parameters to set this field. You will need to:

1. Add a private node handle to the main method of the `myworkcell_node` in addition to the normal one.
2. Use the private node handle to load the parameter `base_frame` and store it in a local string object.
   - If no parameter is provided, default to the parameter to `"world"`.
3. When making the service call to the `vision_node`, use this parameter to fill out the `request::base_frame` field.
4. Add a `<param>` tag to your launch file to initialize the new value.

Scan-N-Plan Application: Guidance

1. Open up `myworkcell_node.cpp` for editing.
2. Add a new `ros::NodeHandle` object to the `main` function, and make it private through its parameters. For more guidance, see the ros wiki on this subject.

```
ros::NodeHandle private_node_handle ("~");
```

3. Create a temporary string object, `std::string base_frame;`, and then use the private node handle's API to load the parameter `"base_frame"`.

```
private_node_handle.param<std::string>("base_frame", base_frame, "world"); //␣
↪parameter name, string object reference, default value
```

   - *`base_frame` parameter should be read after the `private_node_handle` is declared, but before `app.start()` is called*

4. Add a parameter to your `myworkcell_node` "start" function that accepts the base_frame argument, and assign the value from the parameter into the service request. Make sure to update the `app.start` call in your `main()` routine to pass through the `base_frame` value you read from the parameter server:

```
void start(const std::string& base_frame)
{
  ...
  srv.request.base_frame = base_frame;
  ROS_INFO_STREAM("Requesting pose in base frame: " << base_frame);
  ...
}

int main(...)
{
  ...
  app.start(base_frame);
  ...
}
```

   - *`srv.request` should be set **before** passing it into the service call (`vision_client.call(srv)`)*

5. Now we'll add `myworkcell_node` to the existing `workcell.launch` file, so we can set the `base_frame` parameter from a launch file. We'd like the `vision_node` to return the position of the target relative to the world frame, for motion-planning purposes. Even though that's the default value, we'll specify it in the launch-file anyway:

```
<node name="myworkcell_node" pkg="myworkcell_core" type="myworkcell_node" output=
↪"screen">
  <param name="base_frame" value="world"/>
</node>
```

6. Try it out by running the system.

```
catkin build
roslaunch myworkcell_support workcell.launch
```

   - Press *Ctrl+C* to kill the running nodes
   - Edit the launch file to change the base_frame parameter value (e.g. to "test2")
   - Re-launch workcell.launch, and observe that the "request frame" has changed

  - The response frame doesn't change, because we haven't updated vision_node (yet) to handle the request frame. Vision_node always returns the same frame (for now).

- Set the base_frame back to "world"

3.3 Session 3 - Motion Control of Manipulators

`Slides`

3.3.1 Introduction to URDF

In this exercise, we will explore how to describe a robot in the URDF format.

Motivation

Many of the coolest and most useful capabilities of ROS and its community involve things like collision checking and dynamic path planning. It's frequently useful to have a code-independent, human-readable way to describe the geometry of robots and their cells. Think of it like a textual CAD description: "part-one is 1 meter left of part-two and has the following triangle-mesh for display purposes." The Unified Robot Description Format (URDF) is the most popular of these formats today. This module will walk you through creating a simple robot cell that we'll expand upon and use for practical purposes later.

Reference Example

Building a Visual Robot Model with URDF from Scratch

Further Information and Resources

- XML Specification
- ROS Tutorials
- XACRO Extensions
- SolidWorks to URDF Exporter

Scan-N-Plan Application: Problem Statement

We have the software skeleton of our Scan-N-Plan application, so let's take the next step and add some physical context. The geometry we describe in this exercise will be used to:

1. Perform collision checking
2. Understand robot kinematics
3. Perform transformation math Your goal is to describe a workcell that features:
4. An origin frame called `world`
5. A separate frame with "table" geometry (a flat rectangular prism)
6. A frame (geometry optional) called `camera_frame` that is oriented such that its Z axis is flipped relative to the Z axis of `world`

Scan-N-Plan Application: Guidance

1. It's customary to put describing files that aren't code into their own "support" package. URDFs typically go into their own subfolder ''urdf/'‘. See the abb_irb2400_support package. Add a `urdf` sub-folder to your application support package.
2. Create a new `workcell.urdf` file inside the `myworkcell_support/urdf/` folder and insert the following XML skeleton:

```
<?xml version="1.0" ?>
<robot name="myworkcell" xmlns:xacro="http://ros.org/wiki/xacro">
</robot>
```

3. Add the required links. See the irb2400_macro.xacro example from an ABB2400. Remember that all URDF tags must be placed **between** the `<robot> ... </robot>` tags.

   (a) Add the `world` frame as a "virtual link" (no geometry).

```
<link name="world"/>
```

   (b) Add the `table` frame, and be sure to specify both collision & visual geometry tags. See the `box` type in the XML specification.

```
<link name="table">
  <visual>
    <geometry>
      <box size="1.0 1.0 0.05"/>
    </geometry>
  </visual>
  <collision>
    <geometry>
      <box size="1.0 1.0 0.05"/>
    </geometry>
  </collision>
</link>
```

   (c) Add the `camera_frame` frame as another virtual link (no geometry).

```
<link name="camera_frame"/>
```

   (d) Connect your links with a pair of fixed joints Use an `rpy` tag in the `world_to_camera` joint to set its orientation as described in the introduction.

```
<joint name="world_to_table" type="fixed">
  <parent link="world"/>
  <child link="table"/>
  <origin xyz="0 0 0.5" rpy="0 0 0"/>
</joint>

<joint name="world_to_camera" type="fixed">
  <parent link="world"/>
  <child link="camera_frame"/>
  <origin xyz="-0.25 -0.5 1.25" rpy="0 3.14159 0"/>
</joint>
```

   (e) It helps to visualize your URDF as you add links, to verify things look as expected:

```
roslaunch urdf_tutorial display.launch model:=<RELATIVE_PATH_TO_URDF>
```

If nothing shows up in Rviz, you may need to change the base frame in RVIZ (left panel at top) to the name of one of the links in your model.

3.3.2 Workcell XACRO

In this exercise, we will create an XACRO file representing a simple robot workcell. This will demonstrate both URDF and XACRO elements.

Motivation

Writing URDFs that involve more than just a few elements can quickly become a pain. Your file gets huge and duplicate items in your workspace means copy-pasting a bunch of links and joints while having to change their names just slightly. It's really easy to make a mistake that may (or may not) be caught at startup. It'd be nice if we could take some guidance from programming languages themselves: define a component once, then re-use it anywhere without excessive duplication. Functions and classes do that for programs, and XACRO macros do that for URDFs. XACRO has other cool features too, like a file include system (think #include), constant variables, math expression evaluation (e.g., say PI/2.0 instead of 1.57), and more.

Reference Example

Cleaning Up URDF with XACRO Tutorial

Further Information and Resources

Xacro Extension Documentation

Creating a URDF for an Industrial Robot

Scan-N-Plan Application: Problem Statement

In the previous exercise we created a workcell consisting of only static geometry. In this exercise, we'll add a UR5 robot *assembly* using XACRO tools.

Specifically, you will need to:

1. Convert the `*.urdf` file you created in the previous sample into a XACRO file with the `xacro` extension.
2. Include a file containing the xacro-macro definition of a `UR5`
3. Instantiate a `UR5` in your workspace and connect it to the *table* link.

Scan-N-Plan Application: Guidance

1. Rename the `workcell.urdf` file from the previous exercise to `workcell.xacro`
2. Bring in the `ur_description` package into your ROS environment. You have a few options:
   (a) You can install the debian packages: `sudo apt install ros-kinetic-ur-description ros-kinetic-ur-kinematics`
   (b) You can clone it from GitHub to your catkin workspace:

```
cd ~/catkin_ws/src
git clone https://github.com/ros-industrial/universal_robot.git
catkin build
source ~/catkin_ws/devel/setup.bash
```

It's not uncommon for description packages to put each "module", "part", or "assembly" into its own file. In many cases, a package will also define extra files that define a complete cell with the given part so that we can easily visually inspect the result. The UR package defines such a file for the UR5 (ur5_robot.urdf.xacro): It's a great example for this module.

3. Locate the xacro file that implements the UR5 macro and include it in your newly renamed `workcell.xacro` file. Add this include line near the top of your `workcell.xacro` file, beneath the `<robot>` tag:

```
<xacro:include filename="$(find ur_description)/urdf/ur5.urdf.xacro" />
```

If you explore the UR5 definition file, or just about any other file that defines a Xacro macro, you'll find a lot of uses of `${prefix}` in element names. Xacro evaluates anything inside a "${}" at run-time. It can do basic math, and it can look up variables that come to it via properties (ala-global variables) or macro parameters. Most macros will take a "prefix" parameter to allow a user to create multiple instances of said macro. It's the mechanism by which we can make the eventual URDF element names unique, otherwise we'd get duplicate link names and URDF would complain.

4. Including the `ur5.urdf.xacro` file does not actually create a UR5 robot in our URDF model. It defines a macro, but we still need to call the macro to create the robot links and joints. *Note the use of the* `prefix` *tag, as discussed above.*

```
<xacro:ur5_robot prefix="" joint_limited="true"/>
```

Macros in Xacro are just fancy wrappers around copy-paste. You make a macro and it gets turned into a chunk of links and joints. You still have to connect the rest of your world to that macro's results. This means you have to look at the macro and see what the base link is and what the end link is. Hopefully your macro follows a standard, like the ROS-Industrial one, that says that base links are named "base_link" and the last link is called "tool0".

5. Connect the UR5 `base_link` to your existing static geometry with a fixed link.

```
<joint name="table_to_robot" type="fixed">
  <parent link="table"/>
  <child link="base_link"/>
  <origin xyz="0 0 0" rpy="0 0 0"/>
</joint>
```

6. Create a new `urdf.launch` file (in the `myworkcell_support` package) to load the URDF model and (optionally) display it in rviz:

```
<launch>
  <arg name="gui" default="true"/>
  <param name="robot_description" command="$(find xacro)/xacro --inorder '$(find␣
↪myworkcell_support)/urdf/workcell.xacro'" />
  <node name="robot_state_publisher" pkg="robot_state_publisher" type="robot_
↪state_publisher"/>
  <node name="joint_state_publisher" pkg="joint_state_publisher" type="joint_
↪state_publisher">
    <param name="use_gui" value="$(arg gui)"/>
  </node>
  <node name="rviz" pkg="rviz" type="rviz" if="$(arg gui)"/>
</launch>
```

7. Check the updated URDF in RViz, using the launch file you just created:

   ```
   roslaunch myworkcell_support urdf.launch
   ```

   - Set the 'Fixed Frame' to 'world' and add the RobotModel and TF displays to the tree view on the left, to show the robot and some transforms.
   - Try moving the joint sliders to see the UR5 robot move.

3.3.3 Coordinate Tranforms using TF

In this exercise, we will explore the terminal and C++ commands used with TF, the transform library.

Motivation

It's hard to imagine a useful, physical "robot" that doesn't move itself or watch something else move. A useful application in ROS will inevitably have some component that needs to monitor the position of a part, robot link, or tool. In ROS, the "eco-system" and library that facilitates this is called TF. TF is a fundamental tool that allows for the lookup the transformation between any connected frames, even back through time. It allows you to ask questions like: "What was the transform between A and B 10 seconds ago." That's useful stuff.

Reference Example

ROS TF Listener Tutorial

Further Information and Resources

- Wiki Documentation
- TF Tutorials
- TF Listener API

Scan-N-Plan Application: Problem Statement

The part pose information returned by our (simulated) camera is given in the optical reference frame of the camera itself. For the robot to do something with this data, we need to transform the data into the robot's reference frame.

Specifically, edit the service callback inside the vision_node to transform the last known part pose from `camera_frame` to the service call's `base_frame` request field.

Scan-N-Plan Application: Guidance

1. Specify `tf` as a dependency of your core package.
   - Edit `package.xml` (1 line) and `CMakeLists.txt` (2 lines) as in previous exercises
2. Add a `tf::TransformListener` object to the vision node (as a class member variable).

   ```
   #include <tf/transform_listener.h>
   ...
   tf::TransformListener listener_;
   ```

3. Add code to the existing `localizePart` method to convert the reported target pose from its reference frame ("camera_frame") to the service-request frame:

   (a) For better or worse, ROS uses lots of different math libraries. You'll need to transform the over-the-wire format of `geometry_msgs::Pose` into a `tf::Transform object`:

   ```
   tf::Transform cam_to_target;
   tf::poseMsgToTF(p->pose.pose, cam_to_target);
   ```

   (b) Use the listener object to lookup the latest transform between the `request.base_frame` and the reference frame from the `ARMarker` message (which should be "camera_frame"):

   ```
   tf::StampedTransform req_to_cam;
   listener_.lookupTransform(req.base_frame, p->header.frame_id, ros::Time(0),␣
   ↪req_to_cam);
   ```

   (c) Using the above information, transform the object pose into the target frame.

   ```
   tf::Transform req_to_target;
   req_to_target = req_to_cam * cam_to_target;
   ```

   (d) Return the transformed pose in the service response.

   ```
   tf::poseTFToMsg(req_to_target, res.pose);
   ```

4. Run the nodes to test the transforms:

   ```
   catkin build
   roslaunch myworkcell_support urdf.launch
   roslaunch myworkcell_support workcell.launch
   ```

5. Change the "base_frame" parameter in `workcell.launch` (e.g. to "table"), relaunch the `workcell.launch` file, and note the different pose result. Change the "base_frame" parameter back to "world" when you're done.

3.3.4 Build a MoveIt! Package

In this exercise, we will create a MoveIt! package for an industrial robot. This package creates the configuration and launch files required to use a robot with the MoveIt! Motion-Control nodes. In general, the MoveIt! package does not contain any C++ code.

Motivation

MoveIt! is a free-space motion planning framework for ROS. It's an incredibly useful and easy-to-use tool for planning motions between two points in space without colliding with anything. Under the hood MoveIt is quite complicated, but unlike most ROS libraries, it has a really nice GUI Wizard to get you going.

Reference Example

Using MoveIt with ROS-I

Further Information and Resources

MoveIt's Standard Wizard Guide

Scan-N-Plan Application: Problem Statement

In this exercise, you will generate a MoveIt package for the UR5 workcell you built in a previous step. This process will mostly involve running the MoveIt! Setup Assistant. At the end of the exercise you should have the following:

1. A new package called `myworkcell_moveit_config`
2. A moveit configuration with one group ("manipulator"), that consists of the kinematic chain between the UR5's `base_link` and `tool0`.

Scan-N-Plan Application: Guidance

1. Start the MoveIt! Setup Assistant (don't forget auto-complete with tab):

   ```
   roslaunch moveit_setup_assistant setup_assistant.launch
   ```

2. Select "Create New MoveIt Configuration Package", select the `workcell.xacro` you created previously, then "Load File".
3. Work your way through the tabs on the left from the top down.
   (a) Generate a self-collision matrix.
   (b) Add a fixed virtual base joint. e.g.

   ```
   name = 'FixedBase' (arbitrary)
   child = 'world' (should match the URDF root link)
   parent = 'world' (reference frame used for motion planning)
   type = 'fixed'
   ```

   (c) Add a planning group called `manipulator` that names the kinematic chain between `base_link` and `tool0`. Note: Follow ROS naming guidelines/requirements and don't use any whitespace, anywhere.

   a. Set the kinematics solver to `KDLKinematicsPlugin`

   (d) Create a few named positions (e.g. "home", "allZeros", etc.) to test with motion-planning.
   (e) Don't worry about adding end effectors/grippers or passive joints for this exercise.
   (f) Enter author / maintainer info.

   Yes, it's required, but doesn't have to be valid

   (g) Generate a new package and name it `myworkcell_moveit_config`.
   - make sure to create the package inside your `catkin_ws/src` directory

   (h) The current MoveIt! Settup Assistant has a bug that causes some minor errors and abnormal behaviors. To fix these errors:

   i. Edit the `myworkcell_core_moveit_config/config/ompl_planning.yaml` file.
   ii. Append the text string `kConfigDefault` to each planner name
   - e.g. `SBL:` -> `SBLkConfigDefault`, etc.

The outcome of these steps will be a new package that contains a large number of launch and configuration files. At this point, it's possible to do motion planning, but not to execute the plan on any robot. To try out your new configuration:

```
catkin build
source ~/catkin_ws/devel/setup.bash
roslaunch myworkcell_moveit_config demo.launch
```

Don't worry about learning how to use RViz to move the robot; that's what we'll cover in the next session!

Using MoveIt! with Physical Hardware

MoveIt!'s setup assistant generates a suite of files that, upon launch:

- Loads your workspace description to the parameter server.
- Starts a node `move_group` that offers a suite of ROS services & actions for doing kinematics, motion planning, and more.
- An internal simulator that publishes the last planned path on a loop for other tools (like RViz) to visualize.

Essentially, MoveIt can publish a ROS message that defines a trajectory (joint positions over time), but it doesn't know how to pass that trajectory to your hardware.

To do this, we need to define a few extra files.

1. Create a `controllers.yaml` file (`myworkcell_moveit_config/config/controllers.yaml`) with the following contents:

```
controller_list:
  - name: ""
    action_ns: joint_trajectory_action
    type: FollowJointTrajectory
    joints: [shoulder_pan_joint, shoulder_lift_joint, elbow_joint, wrist_1_joint,␣
↪wrist_2_joint, wrist_3_joint]
```

2. Create the `joint_names.yaml` file (`myworkcell_moveit_config/config/joint_names.yaml`):

```
controller_joint_names: [shoulder_pan_joint, shoulder_lift_joint, elbow_joint,␣
↪wrist_1_joint, wrist_2_joint, wrist_3_joint]
```

3. Fill in the existing, but blank, controller_manager launch file (`myworkcell_moveit_config/launch/myworkcell_moveit_controller_manager.launch.xml`):

```
<launch>
  <arg name="moveit_controller_manager"
       default="moveit_simple_controller_manager/MoveItSimpleControllerManager"/>
  <param name="moveit_controller_manager"
         value="$(arg moveit_controller_manager)"/>

  <rosparam file="$(find myworkcell_moveit_config)/config/controllers.yaml"/>
</launch>
```

4. Create a new `myworkcell_planning_execution.launch` (in `myworkcell_moveit_config/launch`):

```
<launch>
  <!-- The planning and execution components of MoveIt! configured to run -->
  <!-- using the ROS-Industrial interface. -->

  <!-- Non-standard joint names:
       - Create a file [robot_moveit_config]/config/joint_names.yaml
           controller_joint_names: [joint_1, joint_2, ... joint_N]
       - Update with joint names for your robot (in order expected by rbt␣
↪controller)
```

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```
       - and uncomment the following line: -->
  <rosparam command="load" file="$(find myworkcell_moveit_config)/config/joint_
↪names.yaml"/>

  <!-- the "sim" argument controls whether we connect to a Simulated or Real␣
↪robot -->
  <!--  - if sim=false, a robot_ip argument is required -->
  <arg name="sim" default="true" />
  <arg name="robot_ip" unless="$(arg sim)" />

  <!-- load the robot_description parameter before launching ROS-I nodes -->
  <include file="$(find myworkcell_moveit_config)/launch/planning_context.launch"␣
↪>
   <arg name="load_robot_description" value="true" />
  </include>

  <!-- run the robot simulator and action interface nodes -->
  <group if="$(arg sim)">
    <include file="$(find industrial_robot_simulator)/launch/robot_interface_
↪simulator.launch" />
  </group>

  <!-- run the "real robot" interface nodes -->
  <!--   - this typically includes: robot_state, motion_interface, and joint_
↪trajectory_action nodes -->
  <!--   - replace these calls with appropriate robot-specific calls or launch␣
↪files -->
  <group unless="$(arg sim)">
    <include file="$(find ur_bringup)/launch/ur5_bringup.launch" />
  </group>

  <!-- publish the robot state (tf transforms) -->
  <node name="robot_state_publisher" pkg="robot_state_publisher" type="robot_
↪state_publisher" />

  <include file="$(find myworkcell_moveit_config)/launch/move_group.launch">
    <arg name="publish_monitored_planning_scene" value="true" />
  </include>

  <include file="$(find myworkcell_moveit_config)/launch/moveit_rviz.launch">
    <arg name="config" value="true"/>
  </include>

</launch>
```

5. Now let's test the new launch files we created:

```
roslaunch myworkcell_moveit_config myworkcell_planning_execution.launch
```

3.3.5 Motion Planning using RViz

In this exercise, we will (finally) learn how to use the MoveIt! RViz plugin to plan and execute motion on a simulated robot. We will explore the different options and constraints associated with both MoveIt! and the RViz plugin.

Launch the Planning Environment

1. Source your catkin workspace.
2. Bring up the planning environment, connected to a ROS-I Simulator node:

```
roslaunch myworkcell_moveit_config myworkcell_planning_execution.launch
```

Plugin Display Options

1. Find and test the following display options in the Displays panel, *Motion Planning* display
    - *Scene Robot -> Show Robot Visual*
    - *Scene Robot -> Show Robot Collision*
    - *Planning Request -> Query Start State*
    - *Planning Request -> Query Goal State*
2. For now, enable display of the *Show Robot Visual* and *Query Goal State*, leaving *Show Robot Collision* and *Query Start State* disabled
3. Select the `Panel -> Motion Planning - Trajectory Slider` menu option to display a trajectory-preview slider.
    - *this slider allows for detailed review of the last planned trajectory*

Basic Motion

1. In the *Motion Planning* panel, select the *Planning* tab
2. Under the *Query* section, expand the *Select Goal State* section
    - *select <random valid> and press Update*
    - *observe the goal position in the graphics window*
3. Click *Plan* to see the robot motion generated by the MoveIt! planning libraries
    - *deselect Displays -> Motion Planning -> Planned Path -> Loop Animation to stop the cyclic display*
    - *select Displays -> Motion Planning -> Planned Path -> Show Trail to show the swept path*
4. Click *Execute* to run the motion on the Industrial Robot Simulator
    - *observe that the multi-colored scene robot display updates to show that the robot has "moved" to the goal position*
5. Repeat steps 2-5 a few more times
    - *try using the interactive marker to manually move the robot to a desired position*
    - *try using a named pose (e.g. "straight up")*

Beyond the Basics

1. Experiment with different Planning Algorithms
    - *select Context tab, choose a Planning Algorithm (drop-down box next to "OMPL")*
    - *the RRTkConfigDefault algorithm is often much faster*

2. Environment Obstacles
    - Adjust the Goal State to move the robot into collision with an obstacle (e.g. the table)
        - note the colliding links are colored red
        - since the position is unreachable, you can see the robot search through different positions as it tries to find a solution
        - try disabling the Use Collision-Aware IK setting on the Context tab
        - see that the collisions are still detected, but the solver no longer searches for a collision-free solution
    - Try to plan a path through the obstacle
        - It may help to have "Collision-Aware IK" disabled when moving the Goal State
        - If the robot fails to plan, check the error log and try repeating the plan request
        - Because the default planners are sampling-based, they may produce different results on each execution
        - You can also try increasing the planning time to allow a successful plan to be created
        - Try different planning algorithms in this, more complex, planning task
    - Try adding a new obstacle to the scene:
        - Under the Scene Objects tab, add the `I-Beam.dae` CAD model
            - This file is located in the *industrial_training* repo: `~/industrial_training/exercises/3.4/I-Beam.dae`
        - Move the I-Beam into an interesting position, using the manipulation handles
        - Press Publish Scene, to push the updated position to MoveIt
        - Try to plan around the obstacle

3.4 Session 4 - Descartes and Perception

`Slides`

3.4.1 Motion Planning using C++

In this exercise, we'll explore MoveIt's C++ interface to programatically move a robot.

Motivation

Now that we've got a working MoveIt! configuration for your workcell and we've played a bit in RViz with the planning tools, let's perform planning and motion in code. This exercise will introduce you to the basic C++ interface for interacting with the MoveIt! node in your own program. There are lots of ways to use MoveIt!, but for simple applications this is the most straight forward.

Reference Example

Move Group Interface tutorial

3. Further Information and Resources

- MoveIt! Tutorials
- MoveIt! home-page

Scan-N-Plan Application: Problem Statement

In this exercise, your goal is to modify the `myworkcell_core` node to:

1. Move the robot's tool frame to the center of the part location as reported by the service call to your vision node.

Scan-N-Plan Application: Guidance

1. Edit your `myworkcell_node.cpp` file.

   (a) Add `#include <tf/tf.h>` to allow access to the tf library (for frame transforms/utilities).

   - Remember that we already added a dependency on the `tf` package in a previous exercise.

   (b) In the `ScanNPlan` class's `start` method, use the response from the `LocalizePart` service to initialize a new `move_target` variable:

```
geometry_msgs::Pose move_target = srv.response.pose;
```

   - make sure to place this code *after* the call to the vision_node's service.

2. Use the `MoveGroupInterface` to plan/execute a move to the `move_target` position:

   (a) In order to use the `MoveGroupInterface` class it is necessary to add the `moveit_ros_planning_interface` package as a dependency of your `myworkcell_core` package. Add the `moveit_ros_planning_interface` dependency by modifying your package's `CMakeLists.txt` (2 lines) and `package.xml` (1 line) as in previous exercises.

   (b) Add the appropriate "include" reference to allow use of the `MoveGroupInterface`:

```
#include <moveit/move_group_interface/move_group_interface.h>
```

   (c) Create a `moveit::planning_interface::MoveGroupInterface` object in the `ScanNPlan` class's `start()` method. It has a single constructor that takes the name of the planning group you defined when creating the workcell moveit package ("manipulator").

```
moveit::planning_interface::MoveGroupInterface move_group("manipulator");
```

   (d) Set the desired cartesian target position using the `move_group` object's `setPoseTarget` function. Call the object's `move()` function to plan and execute a move to the target position.

```
// Plan for robot to move to part
move_group.setPoseReferenceFrame(base_frame);
move_group.setPoseTarget(move_target);
move_group.move();
```

   (e) As described here, the `move_group.move()` command requires use of an "asynchronous" spinner, to allow processing of ROS messages during the blocking `move()` command. Initialize the spinner near the start of the `main()` routine after `ros::init(argc, argv, "myworkcell_node")`, and **replace** the existing `ros::spin()` command with `ros::waitForShutdown()`, as shown:

```
ros::AsyncSpinner async_spinner(1);
async_spinner.start();
...
ros::waitForShutdown();
```

3. Test the system!

```
catkin build
roslaunch myworkcell_moveit_config myworkcell_planning_execution.launch
roslaunch myworkcell_support workcell.launch
```

4. More to explore…

   - In RViz, add a “Marker” display of topic “/ar_pose_visual” to confirm that the final robot position matches the position published by `fake_ar_publisher`
   - Try repeating the motion planning sequence:
     (a) Use the MoveIt rviz interface to move the arm back to the “allZeros” position
     (b) Ctrl+C the `workcell.launch` file, then rerun
   - Try updating the `workcell_node`’s `start` method to automatically move back to the `allZeros` position after moving to the AR_target position. See here for a list of `move_group`’s available methods.
   - Try moving to an “approach position” located a few inches away from the target position, prior to the final move-to-target.

3.4.2 Introduction to Descartes Path Planning

In this exercise, we will use what was learned in the previous exercises by creating a Descartes planner to create a robot path.

Motivation

MoveIt! is a framework meant primarily for performing “free-space” motion where the objective is to move a robot from point A to point B and you don’t particularly care about how that gets done. These types of problems are only a subset of frequently performed tasks. Imagine any manufacturing ‘’process” like welding or painting. You very much care about where that tool is pointing the entire time the robot is at work.

This tutorial introduces you to Descartes, a ‘’Cartesian” motion planner meant for moving a robot along some process path. It’s only one of a number of ways to solve this kind of problem, but it’s got some neat properties:

- It’s deterministic and globally optimum (to a certain search resolution).
- It can search redundant degrees of freedom in your problem (say you have 7 robot joints or you have a process where the tool’s Z-axis rotation doesn’t matter).

Reference Example

Descartes Tutorial

Further Information and Resources

Descartes Wiki

APIs:

- descartes_core::PathPlannerBase
- descartes_planner::DensePlanner
- descartes_planner::SparsePlanner

Scan-N-Plan Application: Problem Statement

In this exercise, you will add a new node to your Scan-N-Plan application, based on a reference template, that:

1. Takes the nominal pose of the marker as input through a ROS service.
2. Produces a joint trajectory that commands the robot to trace the perimeter of the marker (as if it is dispensing adhesive).

Scan-N-Plan Application: Guidance

In the interest of time, we've included a file, `descartes_node.cpp`, that:

1. Defines a new node & accompanying class for our Cartesian path planning.
2. Defines the actual service and initializes the Descartes library.
3. Provides the high level work flow (see planPath function).

Left to you are the details of:

1. Defining a series of Cartesian poses that comprise a robot "path".
2. Translating those paths into something Descartes can understand.

Setup workspace

1. Clone the Descartes repository into your workspace src/ directory.

   ```
   cd ~/catkin_ws/src
   git clone -b kinetic-devel https://github.com/ros-industrial-consortium/descartes.git
   ```

2. Copy over the `ur5_demo_descartes` package into your workspace src/ directory.

   ```
   cp -r ~/industrial_training/exercises/4.1/src/ur5_demo_descartes .
   ```

3. Copy over the `descartes_node_unfinished.cpp` into your core package's src/ folder and rename it `descartes_node.cpp`.

   ```
   cp ~/industrial_training/exercises/4.1/src/descartes_node_unfinished.cpp myworkcell_core/src/descartes_node.cpp
   ```

4. Add dependencies for the following packages in the `CMakeLists.txt` & `package.xml` files, as in previous exercises.

   - `ur5_demo_descartes`

  - descartes_trajectory
  - descartes_planner
  - descartes_utilities

5. Create rules in the myworkcell_core package's CMakeLists.txt to build a new node called descartes_node. As in previous exercises, add these lines near similar lines in the template file (not as a block as shown below).

   ```
   add_executable(descartes_node src/descartes_node.cpp)
   add_dependencies(descartes_node ${${PROJECT_NAME}_EXPORTED_TARGETS} ${catkin_
   ↪EXPORTED_TARGETS})
   target_link_libraries(descartes_node ${catkin_LIBRARIES})
   ```

Complete Descartes Node

We will create a Service interface to execute the Descartes planning algorithm.

1. Define a new service named PlanCartesianPath.srv in the myworkcell_core package's srv/ directory. This service takes the central target position and computes a joint trajectory to trace the target edges.

   ```
   # request
   geometry_msgs/Pose pose

   ---

   # response
   trajectory_msgs/JointTrajectory trajectory
   ```

2. Add the newly-created service file to the add_service_file() rule in the package's CMakeLists.txt.
3. Since our new service references a message type from another package, we'll need to add that other package (trajectory_msgs) as a dependency in the myworkcell_core CMakeLists.txt (3 lines) and package.xml (1 line) files.
4. Review descartes_node.cpp to understand the code structure. In particular, the planPath method outlines the main sequence of steps.
5. Search for the TODO commands in the Descartes node file and expand on those areas:

   (a) In makeToolPoses, generate the remaining 3 sides of a path tracing the outside of our "AR Marker" target part.

   (b) In makeDescartesTrajectory, convert the path you created into a Descartes Trajectory, one point at a time.

   - *Don't forget to transform each nominal point by the specified reference pose: ref * point*

   (c) In makeTolerancedCartesianPoint, create a new AxialSymmetricPt from the given pose.

   - See here for more documentation on this point type
   - Allow the point to be symmetric about the Z-axis (AxialSymmetricPt::Z_AXIS), with an increment of 90 degrees (PI/2 radians)

6. Build the project, to make sure there are no errors in the new descartes_node

Update Workcell Node

With the Descartes node completed, we now want to invoke its logic by adding a new `ServiceClient` to the primary workcell node. The result of this service is a joint trajectory that we must then execute on the robot. This can be accomplished in many ways; here we will call the `JointTrajectoryAction` directly.

1. In `myworkcell_node.cpp`, add include statements for the following headers:

   ```
   #include <actionlib/client/simple_action_client.h>
   #include <control_msgs/FollowJointTrajectoryAction.h>
   #include <myworkcell_core/PlanCartesianPath.h>
   ```

   You do not need to add new dependenies for these libraries/messages, because they are pulled in transitively from moveit.

2. In your ScanNPlan class, add new private member variables: a ServiceClient for the `PlanCartesianPath` service and an action client for `FollowJointTrajectoryAction`:

   ```
   ros::ServiceClient cartesian_client_;
   actionlib::SimpleActionClient<control_msgs::FollowJointTrajectoryAction> ac_;
   ```

3. Initialize these new objects in your constructor. Note that the action client has to be initialized in what is called the `initializer list`.

   ```
   ScanNPlan(ros::NodeHandle& nh) : ac_("joint_trajectory_action", true)
   {
     // ... code
     cartesian_client_ = nh.serviceClient<myworkcell_core::PlanCartesianPath>("plan_
   ↪path");
   }
   ```

4. At the end of the `start()` function, create a new Cartesian service and make the service request:

   ```
   // Plan cartesian path
   myworkcell_core::PlanCartesianPath cartesian_srv;
   cartesian_srv.request.pose = move_target;
   if (!cartesian_client_.call(cartesian_srv))
   {
     ROS_ERROR("Could not plan for path");
     return;
   }
   ```

5. Continue adding the following lines, to execute that path by sending an action directly to the action server (bypassing MoveIt):

   ```
   // Execute descartes-planned path directly (bypassing MoveIt)
   ROS_INFO("Got cart path, executing");
   control_msgs::FollowJointTrajectoryGoal goal;
   goal.trajectory = cartesian_srv.response.trajectory;
   ac_.sendGoal(goal);
   ac_.waitForResult();
   ROS_INFO("Done");
   ```

6. Build the project, to make sure there are no errors in the new `descartes_node`

Test Full Application

1. Create a new `setup.launch` file (in `workcell_support` package) that brings up everything except your workcell_node:

```
<include file="$(find myworkcell_moveit_config)/launch/myworkcell_planning_
↪execution.launch"/>
<node name="fake_ar_publisher" pkg="fake_ar_publisher" type="fake_ar_publisher_
↪node" />
<node name="vision_node" type="vision_node" pkg="myworkcell_core" output="screen"/
↪>
<node name="descartes_node" type="descartes_node" pkg="myworkcell_core" output=
↪"screen"/>
```

2. Run the new setup file, then your main workcell node:

```
roslaunch myworkcell_support setup.launch
rosrun myworkcell_core myworkcell_node
```

   It's difficult to see what's happening with the rviz planning-loop always running. Disable this loop animation in rviz (Displays -> Planned Path -> Loop Animation), then rerun `myworkcell_node`.

Hints and Help

Hints:

- The path we define in `makeToolPoses()` is relative to some known reference point on the part you are working with. So a tool pose of (0, 0, 0) would be exactly at the reference point, and not at the origin of the world coordinate system.
- In `makeDescartesTrajectorty(...)` we need to convert the relative tool poses into world coordinates using the "ref" pose.
- In `makeTolerancedCartesianPoint(...)` consider the following documentation for specific implementations of common joint trajectory points:
  - http://docs.ros.org/indigo/api/descartes_trajectory/html/
- For additional help, review the completed reference code at `~/industrial_training/exercises/4.1/src`

3.4.3 Introduction to Perception

In this exercise, we will experiment with data generated from the Asus Xtion Pro (or Microsoft Kinect) sensor in order to become more familiar with processing 3D data. We will view its data stream and visualize the data in various ways under Rviz.

Point Cloud Data File

The start of most perception processing is ROS message data from a sensor. In this exercise, we'll be using 3D point cloud data from a common Kinect-style sensor.

1. First, publish the point cloud data as a ROS message to allow display in rviz.

   (a) Start `roscore` running in a terminal.

(b) Create a new directory for this exercise:

```
mkdir ~/ex4.2
cd ~/ex4.2
cp ~/industrial_training/exercises/4.2/table.pcd .
```

(c) Publish pointcloud messages from the pre-recorded `table.pcd` point cloud data file:

```
cd ~
rosrun pcl_ros pcd_to_pointcloud table.pcd 0.1 _frame_id:=map cloud_pcd:=orig_
↪cloud_pcd
```

(d) Verify that the `orig_cloud_pcd` topic is being published: `rostopic list`

Display the point cloud in RViz

1. Start an RViz window, to display the results of point-cloud processing

```
rosrun rviz rviz
```

2. Add a **PointCloud2** display item and set the desired topic.

   (a) Select **Add** at the bottom of the Displays panel

   (b) Select **PointCloud2**

   (c) Expand **PointCloud2** in the display tree, and select a topic from topic drop down.

   - *Hint: If you are using the point cloud file, the desired topic is `/orig_cloud_pcd`.*

Experiment with PCL

Next, we will experiment with various command line tool provided by PCL for processing point cloud data. There are over 140 command line tools available, but only a few will be used as part of this exercise. The intent is to get you familiar with the capabilities of PCL without writing any code, but these command line tools are a great place to start when writing your own. Although command line tools are helpful for testing various processing methods, most applications typically use the C++ libraries directly for "real" processing pipelines. The ROS-I Advanced training course explores these C++ PCL methods in more detail.

Each of the PCL commands below generates a new point cloud file (`.pcd`) with the result of the PCL processing command. Use either the `pcl_viewer` to view the results directly or the `pcd_to_pointcloud` command to publish the point cloud data as a ROS message for display in rviz. Feel free to stop the `pcd_to_pointcloud` command after reviewing the results in rviz.

Downsample the point cloud using the pcl_voxel_grid.

1. Downsample the original point cloud using a voxel grid with a grid size of (0.05,0.05,0.05). In a voxel grid, all points in a single grid cube are replaced with a single point at the center of the voxel. This is a common method to simplify overly complex/detailed sensor data, to speed up processing steps.

```
pcl_voxel_grid table.pcd table_downsampled.pcd -leaf 0.05,0.05,0.05
pcl_viewer table_downsampled.pcd
```

1. View the new point cloud in rviz.(optional)

```
rosrun pcl_ros pcd_to_pointcloud table_downsampled.pcd 0.1 _frame_id:=map cloud_
↪pcd:=table_downsampled
```

Note: For the PointCloud2 in rviz change the topic to */table_downsampled* to show the new data.

Extracting the table surface from point cloud using the pcl_sac_segmentation_plane.

1. Find the largest plane and extract points that belong to that plane (within a given threshold).

```
pcl_sac_segmentation_plane table_downsampled.pcd only_table.pcd -thresh 0.01
pcl_viewer only_table.pcd
```

View the new point cloud in rviz.(optional)

```
rosrun pcl_ros pcd_to_pointcloud only_table.pcd 0.1 _frame_id:=map cloud_pcd:=only_
↪table
```

Note: For the PointCloud2 in rviz change the topic to */only_table* to show the new data.

Extracting the largest cluster on the table from point cloud using the pcl_sac_segmentation_plane.

1. Extract the largest point-cluster not belonging to the table.

```
pcl_sac_segmentation_plane table.pcd object_on_table.pcd -thresh 0.01 -neg 1
pcl_viewer object_on_table.pcd
```

View the new point cloud in rviz.(optional)

```
rosrun pcl_ros pcd_to_pointcloud object_on_table.pcd 0.1 _frame_id:=map cloud_
↪pcd:=object_on_table
```

Note: For the PointCloud2 in rviz change the topic to */object_on_table* to show the new data.

Remove outliers from the cloud using the pcl_outlier_removal.

1. For this example, a statistical method will be used for removing outliers. This is useful to clean up noisy sensor data, removing false artifacts before further processing.

```
pcl_outlier_removal table.pcd table_outlier_removal.pcd -method statistical
pcl_viewer table_outlier_removal.pcd
```

1. View the new point cloud in rviz. (optional)

```
rosrun pcl_ros pcd_to_pointcloud table_outlier_removal.pcd 0.1 _frame_id:=map cloud_
↪pcd:=table_outlier_removal
```

Note: For the PointCloud2 in rviz change the topic to */table_outlier_removal* to show the new data.

Compute the normals for each point in the point cloud using the pcl_normal_estimation.

1. This example estimates the local surface normal (perpendicular) vectors at each point. For each point, the algorithm uses nearby points (within the specified radius) to fit a plane and calculate the normal vector. Zoom in to view the normal vectors in more detail.

```
pcl_normal_estimation only_table.pcd table_normals.pcd -radius 0.1
pcl_viewer table_normals.pcd -normals 10
```

Mesh a point cloud using the marching cubes reconstruction.

Point cloud data is often unstructured, but sometimes processing algorithms need to operate on a more structured surface mesh. This example uses the "marching cubes" algorithm to construct a surface mesh that approximates the point cloud data.

```
pcl_marching_cubes_reconstruction table_normals.pcd table_mesh.vtk -grid_res 20
pcl_viewer table_mesh.vtk
```

3.5 Application Demo 1 - Perception-Driven Manipulation

3.5.1 Application Demo 1 - Perception-Driven Manipulation

Perception-Driven Manipulation Introduction

Goal

- The purpose of these exercises is to implement a ROS node that drives a robot through a series of moves and actions in order to complete a pick and place task. In addition, they will serve as an example of how to integrate a variety of software capabilities (perception, controller drivers, I/O, inverse kinematics, path planning, collision avoidance, etc) into a ROS-based industrial application.

Objectives

- Understand the components and structure of a real or simulated robot application.
- Learn how to command robot moves using Moveit!.
- Learn how to move the arm to a joint or Cartesian position.
- Leverage perception capabilities including AR tag recognition and PCL.
- Plan collision-free paths for a pick and place task.
- Control robot peripherals such as a gripper.

Inspect the "pick_and_place_exercise" Package

> In this exercise, we will get familiar with all the files that you'll be interacting with throughout these exercises.

Acquire and initialize the Workspace

```
cp -r ~/industrial_training/exercises/Perception-Driven_Manipulation/template_ws ~/
↪perception_driven_ws
cd ~/perception_driven_ws
source /opt/ros/kinetic/setup.bash
catkin init
```

Download source dependencies

Use the wstool command to download the repositories listed in the `src/.rosinstall` file

```
cd ~/perception_driven_ws/src/
wstool update
```

Download debian dependencies

Make sure you have installed and configured the rosdep tool. Then, run the following command from the `src` directory of your workspace.

```
rosdep install --from-paths . --ignore-src -y
```

Build your workspace

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles'
```

If the build fails then revisit the previous two steps to make sure all the dependencies were downloaded.

Source the workspace

Run the following command from your workspace parent directory

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

Locate and navigate into the package

```
cd ~/perception_driven_ws/src/collision_avoidance_pick_and_place/
```

Look into each file in the launch directory

```
ur5_setup.launch      : Brings up the entire ROS system (MoveIt!, rviz, perception,␣
↪ROS-I drivers, robot I/O peripherals)
ur5_pick_and_place.launch   : Runs your pick and place node.
```

Look into the config directory

```
ur5/
 - pick_and_place_parameters.yaml    : List of parameters read by the pick and place␣
↪node.
 - rviz_config.rviz   : Rviz configuration file for display properties.
 - target_recognition_parameters.yaml    : Parameters used by the target recognition␣
↪service for detecting the box from the sensor data.
 - test_cloud_obstacle_descriptions.yaml    : Parameters used to generate simulated␣
↪sensor data (simulated sensor mode only)
 - collision_obstacles.txt   : Description of each obstacle blob added to the␣
↪simulated sensor data (simulated sensor mode only)
```

Look into the src directory

```
nodes:
 - pick_and_place_node.cpp : Main application thread. Contains all necessary headers␣
↪and function calls.

tasks: Source files with incomplete function definitions.  You will fill with code␣
↪where needed in order to complete the exercise.
 - create_motion_plan.cpp
 - create_pick_moves.cpp
 - create_place_moves.cpp
 - detect_box_pick.cpp
 - pickup_box.cpp
 - place_box.cpp
 - move_to_wait_position.cpp
 - set_attached_object.cpp
 - set_gripper.cpp

utilities:
 - pick_and_place_utilities.cpp : Contains support functions that will help you␣
↪complete the exercise.
```

Package Setup

In this exercise, we'll build our package dependencies and configure the package for the Qt Creator IDE.

Build Package Dependencies

In a terminal type:

```
cd ~/perception_driven_ws
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles'
source devel/setup.bash
```

Import Package into QTCreator

In QTCreator do the following:

```
File -> New -> Import ROS Project ->
```

Open the Main Thread Source File

In the project tab, navigate into the `[Source directory]/collision_avoidance_pick_and_place/src/nodes` directory and open the `pick_and_place_node.cpp` file

Start in Simulation Mode

> In this exercise, we will start a ROS system that is ready to move the robot in simulation mode.

Run setup launch file in simulation mode (simulated robot and sensor)

In a terminal

```
roslaunch collision_avoidance_pick_and_place ur5_setup.launch
```

Rviz will display all the workcell components including the robot in its default position; at this point your system is ready. However no motion will take place until we run the pick and place node.

Setup for real sensor and simulated robot

```
roslaunch collision_avoidance_pick_and_place ur5_setup.launch sim_sensor:=false
```

Setup for real robot and simulated sensor data

```
roslaunch collision_avoidance_pick_and_place ur5_setup.launch sim_robot:=false robot_
↪ip:= [robot ip]
```

Setup for real robot and real sensor

```
roslaunch collision_avoidance_pick_and_place ur5_setup.launch sim_robot:=false robot_
↪ip:= [robot ip] sim_sensor:=false sim_gripper:=false
```

Initialization and Global Variables

> In this exercise, we will take a first look at the main application "pick_and_place_node.cpp", its public variables, and how to properly initialize it as a ros node.

Application Variables

In QTCreator, open

```
[Source directory]/collision_avoidance_pick_and_place/include/collision_avoidance_
↪pick_and_place/pick_and_place_utilities.h
```

The c++ class ‘pick_and_place_config’ defines public global variables used in various parts of the program. These variables

```
    ARM_GROUP_NAME  = "manipulator";
    TCP_LINK_NAME   = "tcp_frame";
    MARKER_TOPIC = "pick_and_place_marker";
    PLANNING_SCENE_TOPIC = "planning_scene";
    TARGET_RECOGNITION_SERVICE = "target_recognition";
    MOTION_PLAN_SERVICE = "plan_kinematic_path";
    WRIST_LINK_NAME = "ee_link";
    ATTACHED_OBJECT_LINK_NAME = "attached_object_link";
    WORLD_FRAME_ID  = "world_frame";
    HOME_POSE_NAME  = "home";
    WAIT_POSE_NAME  = "wait";
    AR_TAG_FRAME_ID    = "ar_frame";
    GRASP_ACTION_NAME = "grasp_execution_action";
    BOX_SIZE        = tf::Vector3(0.1f, 0.1f, 0.1f);
    BOX_PLACE_TF    = tf::Transform(tf::Quaternion::getIdentity(), tf::Vector3(-0.8f,-
↪0.2f,BOX_SIZE.getZ()));
    TOUCH_LINKS = std::vector<std::string>();
    RETREAT_DISTANCE  = 0.05f;
    APPROACH_DISTANCE = 0.05f;
```

In the main program (`pick_and_place_node.cpp`), the global `application` object provides access to the program variables through its `cfg` member. For instance, in order to use the `WORLD_FRAME_ID` global variable we would do the following:

```
ROS_INFO_STREAM("world frame: " << application.cfg.WORLD_FRAME_ID)
```

Node Initialization

In the `pick_and_place_node.cpp` file, the following block of code in the “main” function initializes the `PickAndPlace` application class and its main ros and MoveIt! components.

```
int main(int argc,char** argv)
{
  geometry_msgs::Pose box_pose;
  std::vector<geometry_msgs::Pose> pick_poses, place_poses;

  /*␣
↪=========================================================================================*/
↪
  /*    INITIALIZING ROS NODE
      Goal:
      - Observe all steps needed to properly initialize a ros node.
      - Look into the 'cfg' member of PickAndPlace to take notice of the parameters␣
↪that
        are available for the rest of the program. */
  /*␣
↪=========================================================================================*/
↪
```

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```
  // ros initialization
  ros::init(argc,argv,"pick_and_place_node");
  ros::NodeHandle nh;
  ros::AsyncSpinner spinner(2);
  spinner.start();

  // creating pick and place application instance
  PickAndPlace application;

  // reading parameters
  if(application.cfg.init())
  {
    ROS_INFO_STREAM("Parameters successfully read");
  }
  else
  {
    ROS_ERROR_STREAM("Parameters not found");
    return 0;
  }

  // marker publisher
  application.marker_publisher = nh.advertise<visualization_msgs::Marker>(
          application.cfg.MARKER_TOPIC,1);

  // planning scene publisher
  application.planning_scene_publisher = nh.advertise<moveit_msgs::PlanningScene>(
        application.cfg.PLANNING_SCENE_TOPIC,1);

  // MoveIt! interface
  application.move_group_ptr = MoveGroupPtr(
          new move_group_interface::MoveGroup(application.cfg.ARM_GROUP_NAME));

  // motion plan client
  application.motion_plan_client = nh.serviceClient<moveit_msgs::GetMotionPlan>
↪(application.cfg.MOTION_PLAN_SERVICE);

  // transform listener
  application.transform_listener_ptr = TransformListenerPtr(new␣
↪tf::TransformListener());

  // marker publisher (rviz visualization)
  application.marker_publisher = nh.advertise<visualization_msgs::Marker>(
          application.cfg.MARKER_TOPIC,1);

  // target recognition client (perception)
  application.target_recognition_client = nh.serviceClient<collision_avoidance_pick_
↪and_place::GetTargetPose>(
          application.cfg.TARGET_RECOGNITION_SERVICE);

  // grasp action client (vacuum gripper)
  application.grasp_action_client_ptr = GraspActionClientPtr(
          new GraspActionClient(application.cfg.GRASP_ACTION_NAME,true));
```

Move Arm to Wait Position

The MoveGroup class in MoveIt! allows us to move the robot in various ways. With MoveGroup it is possible to move to a desired joint position, cartesian goal or a predefined pose created with the Setup Assistant. In this exercise, we will move the robot to a predefined joint pose.

Locate Function

- In the main program , locate the method call to application.move_to_wait_position().
- Go to the source file of that function by clicking in any part of the function and pressing "F2".
- Alternatively, browse to the file in [Source directory]/src/tasks/move_to_wait_position.cpp.
- Remove the fist line containing the following ROS_ERROR_STREAM ... so that the program runs.

Complete Code

- Find every line that begins with the comment Fill Code: and read the description. Then, replace every instance of the comment ENTER CODE HERE with the appropriate line of code

```
/* Fill Code:
     .
     .
     .
*/
/* ========  ENTER CODE HERE ======== */
```

- The name of the predefined "wait" pose was saved in the global variable cfg.WAIT_POSE_NAME during initialization.

Build Code and Run

- Compile the pick and place node:
  - in QTCreator: Build -> Build Project
  - Alternatively, in a terminal:

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles' --pkg collision_avoidance_
↪pick_and_place
source ./devel/setup.bash
```

- Run your node with the launch file:

```
roslaunch collision_avoidance_pick_and_place ur5_pick_and_place.launch
```

- If the robot is not already in the wait position, it should move to the wait position. In the terminal, you will see something like the following message:

```
[ INFO] [1400553673.460328538]: Move wait Succeeded
[ERROR] [1400553673.460434627]: set_gripper is not implemented yet.  Aborting.
```

API References

setNamedTarget()

move()

Open Gripper

In this exercise, the objective is to use a "grasp action client" to send a grasp goal that will open the gripper.

Locate Function

- In the main program, locate the function call to `application.set_gripper()`.
- Go to the source file of that function by clicking in any part of the function and pressing "F2".
- Remove the fist line containing the following `ROS_ERROR_STREAM ...` so that the program runs.

Complete Code

- Find every line that begins with the comment `Fill Code:` and read the description. Then, replace every instance of the comment `ENTER CODE HERE` with the appropriate line of code.

```
/* Fill Code:
     .
     .
     .
*/
/* ========  ENTER CODE HERE ======== */
```

- The `grasp_goal.goal` property can take on three possible values:

```
    grasp_goal.goal = object_manipulation_msgs::GraspHandPostureExecutionGoal::GRASP;
    grasp_goal.goal = object_manipulation_
↪msgs::GraspHandPostureExecutionGoal::RELEASE;
    grasp_goal.goal = object_manipulation_msgs::GraspHandPostureExecutionGoal::PRE_
↪GRASP;
```

- Once the grasp flag has been set you can send the goal through the grasp action client

Build Code and Run

- Compile the pick and place node:
  - in QTCreator: `Build -> Build Project`
  - Alternatively, in a terminal:

```
catkin build collision_avoidance_pick_and_place
```

- Run your node with the launch file:

```
roslaunch collision_avoidance_pick_and_place ur5_pick_and_place.launch
```

- If the task succeeds you will see something like the following in the terminal (below). The robot will not move, only gripper I/O is triggered:

```
[ INFO] [1400553290.464877904]: Move wait Succeeded
[ INFO] [1400553290.720864559]: Gripper opened
[ERROR] [1400553290.720985315]: detect_box_pick is not implemented yet.  Aborting.
```

API References

sendGoal()

Detect Box Pick Point

The coordinate frame of the box's pick can be requested from a ros service that detects it by processing the sensor data. In this exercise, we will learn how to use a service client to call that ros service for the box pick pose.

Locate Function

- In the main program, locate the function call to `application.detect_box_pick()`.
- Go to the source file of that function by clicking in any part of the function and pressing "F2".
- Remove the first line containing the following `ROS_ERROR_STREAM ...` so that the program runs.

Complete Code

- Find every line that begins with the comment `Fill Code:` and read the description. Then, replace every instance of the comment `ENTER CODE HERE` with the appropriate line of code

```
/* Fill Code:
     .
     .
     .
*/
/* ========  ENTER CODE HERE ======== */
```

- The `target_recognition_client` object in your programs can use the `call()` method to send a request to a ros service.
- The ros service that receives the call will process the sensor data and return the pose for the box pick in the service structure member `srv.response.target_pose`.

Build Code and Run

- Compile the pick and place node:
  - in QTCreator: `Build -> Build Project`
  - Alternatively, in a terminal:

```
catkin build --pkg collision_avoidance_pick_and_place
```

- Run your node with the launch file:

```
roslaunch collision_avoidance_pick_and_place ur5_pick_and_place.launch
```

- A blue box and voxel grid obstacles will be displayed in rviz. In the terminal you should see a message like the following:

```
[ INFO] [1400554224.057842127]: Move wait Succeeded
[ INFO] [1400554224.311158465]: Gripper opened
[ INFO] [1400554224.648747043]: target recognition succeeded
[ERROR] [1400554224.649055043]: create_pick_moves is not implemented yet.  Aborting.
```

API References

call()

Create Pick Moves

The gripper moves through three poses in order to do a pick: Approach, target and retreat. In this exercise, we will use the box pick transform to create the pick poses for the TCP (Tool Center Point) coordinate frame and then transform them to the arm's wrist coordinate frame

Locate Function

- In the main program , locate the function call to `application.create_pick_moves()`.
- Go to the source file of that function by clicking in any part of the function and pressing "F2".
- Remove the fist line containing the following `ROS_ERROR_STREAM ...` so that the program runs.

Complete Code

- Find every line that begins with the comment `Fill Code:` and read the description. Then, replace every instance of the comment `ENTER CODE HERE` with the appropriate line of code

```
/* Fill Code:
     .
     .
     .
*/
/* ========  ENTER CODE HERE ======== */
```

- The `create_manipulation_poses()` uses the values of the approach and retreat distances in order to create the corresponding poses at the desired target.
- Since moveit plans the robot path for the arm's wrist, then it is necessary to convert all the pick poses to the wrist coordinate frame.
- The lookupTransform method can provide the pose of a target relative to another pose.

Build Code and Run

- Compile the pick and place node
  - In QtCreator, use : `Build -> Build Project`
  - Alternatively, in a terminal:

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles' --pkg collision_avoidance_
↪pick_and_place
source ./devel/setup.bash
```

- Run your node with the launch file:

```
roslaunch collision_avoidance_pick_and_place ur5_pick_and_place.launch
```

- The tcp and wrist position at the pick will be printed in the terminal. You should see something like this:

```
[ INFO] [1400555434.918332145]: Move wait Succeeded
[ INFO] [1400555435.172714267]: Gripper opened
[ INFO] [1400555435.424279410]: target recognition succeeded
[ INFO] [1400555435.424848964]: tcp position at pick: [-0.8, 0.2, 0.17]
[ INFO] [1400555435.424912520]: tcp z direction at pick: [8.65611e-17, -8.66301e-17, -
↪1]
[ INFO] [1400555435.424993675]: wrist position at pick: x: -0.81555
y: 0.215563
z: 0.3

[ERROR] [1400555435.425051853]: pickup_box is not implemented yet.  Aborting.
```

API References

lookupTransform

TF Transforms and other useful data types

Pick Up Box

In this exercise, we will move the robot through the pick motion while avoiding obstacles in the environment. This is to be accomplished by planning for each pose and closing or opening the vacuum gripper when apropriate. Also, it will be demonstrated how to create a motion plan that MoveIt! can understand and solve.

Locate Function

- In the main program, locate the function call to `application.pickup_box()`.
- Go to the source file of that function by clicking in any part of the function and pressing “F2”.
- Remove the first line containing the following `ROS_ERROR_STREAM ...` so that the program runs.

Complete Code

- Find every line that begins with the comment `Fill Code:` and read the description. Then, replace every instance of the comment `ENTER CODE HERE` with the appropriate line of code

```
/* Fill Code:
     .
     .
     .
*/
/* ========  ENTER CODE HERE ======== */
```

- Inspect the `set_attached_object` method to understand how to manipulate a `robot_state` object which will then be used to construct a motion plan.
- Inspect the `create_motion_plan` method to see how an entire motion plan request is defined and sent.
- The execute() method sends a motion plan to the robot.

Build Code and Run

- Compile the pick and place node:
  - in QTCreator: `Build -> Build Project`
  - Alternatively, in a terminal:

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles' --pkg collision_avoidance_
↪pick_and_place
```

- Run your node with the launch file:

```
roslaunch collision_avoidance_pick_and_place ur5_pick_and_place.launch
```

- The robot should go through the pick moves (Approach, pick and retreat) in addition to the moves from the previous exercises. In the terminal you will see something like:

```
[ INFO] [1400555978.404435764]: Execution completed: SUCCEEDED
[ INFO] [1400555978.404919764]: Pick Move 2 Succeeded
[ERROR] [1400555978.405061541]: create_place_moves is not implemented yet.  Aborting.
```

API References

MoveGroupInterface class

Create Place Moves

The gripper moves through three poses in order to place the box: Approach, place and retreat. In this exercise, we will create these place poses for the *tcp* coordinate frame and then transform them to the arm's wrist coordinate frame.

Locate Function

- In the main program , locate the function call to `application.create_place_moves()`.
- Go to the source file of that function by clicking in any part of the function and pressing “F2”.
- Remove the fist line containing the following `ROS_ERROR_STREAM ...` so that the program runs.

Complete Code

- Find every line that begins with the comment `Fill Code:` and read the description. Then, replace every instance of the comment `ENTER CODE HERE` with the appropriate line of code

```
/* Fill Code:
     .
     .
     .
*/
/* ========  ENTER CODE HERE ======== */
```

- The box’s position at the place location is saved in the global variable `cfg.BOX_PLACE_TF`.
- The `create_manipulation_poses()` uses the values of the approach and retreat distances in order to create the corresponding poses at the desired target.
- Since moveit plans the robot path for the arm’s wrist, then it is necessary to convert all the place poses to the wrist coordinate frame.
- The lookupTransform method can provide the pose of a target relative to another pose.

Build Code and Run

- Compile the pick and place node:
  - In QtCreator: `Build -> Build Project`
  - Alternatively, in a terminal:

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles' --workspace collision_
↪avoidance_pick_and_place
```

- Run your node with the launch file:

```
roslaunch collision_avoidance_pick_and_place ur5_pick_and_place.launch
```

- The tcp and wrist position at the place location will be printed on the terminal. You should see something like:

```
[ INFO] [1400556479.404133995]: Execution completed: SUCCEEDED
[ INFO] [1400556479.404574973]: Pick Move 2 Succeeded
[ INFO] [1400556479.404866351]: tcp position at place: [-0.4, 0.6, 0.17]
[ INFO] [1400556479.404934796]: wrist position at place: x: -0.422
y: 0.6
z: 0.3

[ERROR] [1400556479.404981729]: place_box is not implemented yet.  Aborting.
```

API References

lookupTransform

TF Transforms and other useful data types

Place Box

In this exercise, we will move the robot through the place motions while avoiding obstacles with an attached payload. In addition, the gripper must be opened or close at the appropriate time in order to complete the task.

Locate Function

- In the main program, locate the function call to `application.place_box()`.
- Go to the source file of that function by clicking in any part of the function and pressing "F2".
- Remove the first line containing the following `ROS_ERROR_STREAM ...` so that the program runs.

Complete Code

- Find every line that begins with the comment `Fill Code:` and read the description. Then, replace every instance of the comment `ENTER CODE HERE` with the appropriate line of code

```
/* Fill Code:
     .
     .
     .
*/
/* ========  ENTER CODE HERE ======== */
```

- The execute() method sends a motion plan to the robot.

Build Code and Run

- Compile the pick and place node:
  - in QTCreator: `Build -> Build Project`
  - Alternatively, in a terminal:

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles' --pkg collision_avoidance_
↪pick_and_place
```

- Run your node with the launch file:

```
roslaunch collision_avoidance_pick_and_place ur5_pick_and_place.launch
```

- At this point your exercise is complete and the robot should move through the pick and place motions and then back to the wait pose. Congratulations!

API References

MoveGroupInterface class

3.6 Application Demo 2 - Descartes Planning and Execution

3.6.1 Application Demo 2 - Descartes Planning and Execution

Introduction

Goal

- This application will demonstrate how to use the various components in the Descartes library for planning and executing a robot path from a semi-constrained trajectory of points.

Objectives

- Become familiar with the Descartes workflow.
- Learn how to load a custom Descartes RobotModel.
- Learn how to create a semi-constrained trajectory from 6DOF tool poses.
- Plan a robot path with a Descartes Planner.
- Convert a Descartes Path into a MoveIt! message for execution.
- Executing the path on the robot.

Application Structure

In this exercise, we'll take a look at all the packages and files that will be used during the completion of these exercises.

Acquire and initialize the Workspace

```
cd ~/industrial_training/exercises/Descartes_Planning_and_Execution
cp -r template_ws ~/descartes_ws
cd ~/descartes_ws
source /opt/ros/kinetic/setup.bash
catkin init
```

Download source dependencies

Use the wstool command to download the repositories listed in the `src/.rosinstall` file

```
cd ~/descartes_ws/src/
wstool update
```

Download debian dependencies

Make sure you have installed and configured the rosdep tool. Then, run the following command from the `src` directory of your workspace.

```
rosdep install --from-paths . --ignore-src -y
```

Build your workspace

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles'
```

If the build fails, then revisit the previous two steps to make sure all the dependencies were downloaded.

Source the workspace

Run the following command from your workspace parent directory

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

List All the Packages in the Application

```
cd ~/descartes_ws/src
ls -la
```

- `plan_and_run` : Contains the source code for the `plan_and_run` application. You'll be completing the exercises by editing source files in this package
- `ur5_demo_moveit_config` : Contains support files for planning and execution robot motions with Moveit. This package was generated with the Moveit Setup Assistant
- `ur5_demo_support` : Provides the robot definition as a URDF file. This URDF is loaded at run time by our `plan_and_run` application.
- `ur5_demo_descartes` : Provides a custom Descartes Robot Model for the UR5 arm. It uses a Inverse-Kinematics closed form solution; which is significantly faster than the numerical approach used by the **Moveit-StateAdapter**.

The `plan_and_run` package

```
roscd plan_and_run
ls -la
```

- `src` : Application source files.
- `src/demo_application.cpp` : A class source file that contains the application implementation code.
- `src/plan_and_run.cpp` : The application main access point. It invokes all the tasks in the application and wraps them inside the "`main`" routine.
- `src/tasks` : A directory that contains all of the source files that you'll be editing or completing as you make progress through the exercises.

- include : Header files
- include/plan_and_run/demo_application.h : Defines the application skeleton and provides a number of global variables for passing data at various points in the exercises.
- launch: Launch files needed to run the application
- launch/demo_setup.launch : Loads roscore, moveit and the runtime resources needed by our application.
- launch/demo_run.launch : Starts our application main executable as a ROS node.
- config: Directory that contains non-critical configuration files.

Main Application Source File

In the "plan_and_run/src/plan_and_run_node.cpp" you'll find the following code:

```
int main(int argc,char** argv)
{
  ros::init(argc,argv,"plan_and_run");
  ros::AsyncSpinner spinner(2);
  spinner.start();

  // creating application
  plan_and_run::DemoApplication application;

  // loading parameters
  application.loadParameters();

  // initializing ros components
  application.initRos();

  // initializing descartes
  application.initDescartes();

  // moving to home position
  application.moveHome();

  // generating trajectory
  plan_and_run::DescartesTrajectory traj;
  application.generateTrajectory(traj);


  // planning robot path
  plan_and_run::DescartesTrajectory output_path;
  application.planPath(traj,output_path);

  // running robot path
  application.runPath(output_path);

  // exiting ros node
  spinner.stop();

  return 0;
}
```

In short, this program will run through each exercise by calling the corresponding function from the application object. For instance, in order to initialize Descartes the program calls application.iniDescartes(). Thus each exercise consists of editing the source file where that exercise is implemented, so for `application.initDescartes()` you'll be editing the `plan_and_run/src/tasks/init_descartes.src` source file.

The DemoApplication Class

In the header file "`plan_and_run/include/plan_and_run/demo_application.h`" you'll find the definition for the application's main class along with several support constructs. Some of the important components to take notice of are as follows:

- Program Variables: Contain hard coded values that are used at various points in the application.

```
const std::string ROBOT_DESCRIPTION_PARAM = "robot_description";
const std::string EXECUTE_TRAJECTORY_ACTION = "execute_trajectory";
const std::string VISUALIZE_TRAJECTORY_TOPIC = "visualize_trajectory_curve";
const double SERVER_TIMEOUT = 5.0f; // seconds
const double ORIENTATION_INCREMENT = 0.5f;
const double EPSILON = 0.0001f;
const double AXIS_LINE_LENGHT = 0.01;
const double AXIS_LINE_WIDTH = 0.001;
const std::string PLANNER_ID = "RRTConnectkConfigDefault";
const std::string HOME_POSITION_NAME = "home";
```

- Trajectory Type: Convenience type that represents an array of Descartes Trajectory Points.

```
typedef std::vector<descartes_core::TrajectoryPtPtr> DescartesTrajectory;
```

- **DemoConfiguration Data Structure**: Provides variables whose values are initialize at run-time from corresponding ros parameters.

```
struct DemoConfiguration
{
  std::string group_name;                 /* Name of the manipulation group␣
↪containing the relevant links in the robot */
  std::string tip_link;                   /* Usually the last link in the kinematic␣
↪chain of the robot */
  std::string base_link;                  /* The name of the base link of the robot */
  std::string world_frame;                /* The name of the world link in the URDF␣
↪file */
  std::vector<std::string> joint_names;   /* A list with the names of the mobile␣
↪joints in the robot */


  /* Trajectory Generation Members:
   *  Used to control the attributes (points, shape, size, etc) of the robot␣
↪trajectory.
   *  */
  double time_delay;              /* Time step between consecutive points in the␣
↪robot path */
  double foci_distance;           /* Controls the size of the curve */
  double radius;                  /* Controls the radius of the sphere on which the␣
↪curve is projected */
  int num_points;                 /* Number of points per curve */
  int num_lemniscates;            /* Number of curves*/
  std::vector<double> center;     /* Location of the center of all the lemniscate␣
↪curves */
  std::vector<double> seed_pose;  /* Joint values close to the desired start of the␣
↪robot path */
```

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```
  /*
   * Visualization Members
   * Used to control the attributes of the visualization artifacts
   */
  double min_point_distance;      /* Minimum distance between consecutive trajectory␣
↪points. */
};
```

- **DemoApplication Class**: Main component of the application which provides functions for each step in our program. It also contains several constructs that turn this application into a ROS node.

```
class DemoApplication
{
public:
  /*  Constructor
   *    Creates an instance of the application class
   */
  DemoApplication();
  virtual ~DemoApplication();

  /* Main Application Functions
   *  Functions that allow carrying out the various steps needed to run a
   *  plan an run application.  All these functions will be invoked from within
   *  the main routine.
   */

  void loadParameters();
  void initRos();
  void initDescartes();
  void moveHome();
  void generateTrajectory(DescartesTrajectory& traj);
  void planPath(DescartesTrajectory& input_traj,DescartesTrajectory& output_path);
  void runPath(const DescartesTrajectory& path);

protected:

  /* Support methods
   *  Called from within the main application functions in order to perform␣
↪convenient tasks.
   */

  static bool createLemniscateCurve(double foci_distance, double sphere_radius,
                                    int num_points, int num_lemniscates,
                                    const Eigen::Vector3d& sphere_center,
                                    EigenSTL::vector_Affine3d& poses);

  void fromDescartesToMoveitTrajectory(const DescartesTrajectory& in_traj,
                                              trajectory_msgs::JointTrajectory& out_
↪traj);

  void publishPosesMarkers(const EigenSTL::vector_Affine3d& poses);


protected:
```

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```
  /* Application Data
   *  Holds the data used by the various functions in the application.
   */
  DemoConfiguration config_;



  /* Application ROS Constructs
   *  Components needed to successfully run a ros-node and perform other important
   *  ros-related tasks
   */
  ros::NodeHandle nh_;                        /* Object used for creating and␣
↪managing ros application resources*/
  ros::Publisher marker_publisher_;           /* Publishes visualization message to␣
↪Rviz */
  std::shared_ptr<actionlib::SimpleActionClient<moveit_msgs::ExecuteTrajectoryAction>>
↪   moveit_run_path_client_ptr_; /* Sends a robot trajectory to moveit for execution␣
↪*/



  /* Application Descartes Constructs
   *  Components accessing the path planning capabilities in the Descartes library
   */
  descartes_core::RobotModelPtr robot_model_ptr_; /* Performs tasks specific to the␣
↪Robot
                                                     such IK, FK and collision␣
↪detection*/
  descartes_planner::SparsePlanner planner_;      /* Plans a smooth robot path given␣
↪a trajectory of points */

};
```

Application Launch File

This file starts our application as a ROS node and loads up the necessary parameters into the ROS parameter server. Observe how this is done by opening the "plan_and_run/launch/demo_run.launch" file:

```
<launch>
  <node name="plan_and_run_node" type="plan_and_run_node" pkg="plan_and_run" output=
↪"screen">
    <param name="group_name" value="manipulator"/>
    <param name="tip_link" value="tool"/>
    <param name="base_link" value="base_link"/>
    <param name="world_frame" value="world"/>
    <param name="trajectory/time_delay" value="0.1"/>
    <param name="trajectory/foci_distance" value="0.07"/>
    <param name="trajectory/radius" value="0.08"/>
    <param name="trajectory/num_points" value="200"/>
    <param name="trajectory/num_lemniscates" value="4"/>
    <rosparam param="trajectory/center">[0.36, 0.2, 0.1]</rosparam>
    <rosparam param="trajectory/seed_pose">[0.0, -1.03, 1.57 , -0.21, 0.0, 0.0]</
↪rosparam>
    <param name="visualization/min_point_distance" value="0.02"/>
  </node>
```

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```
</launch>
```

- Some of the important parameters are explained as follows:
- group_name: A namespace that points to the list of links in the robot that are included in the arm's kinematic chain (base to end-of-tooling links). This list is defined in the `ur5_demo_moveit_config` package.
- tip_link: Name of the last link in the kinematic chain, usually the tool link.
- base_link: Name for the base link of the robot.
- world_frame: The absolute coordinate frame of reference for all the objects defined in the planning environment.
- The parameters under the "`trajectory`" namespace are used to generate the trajectory that is feed into the Descartes planner.
- trajectory/seed_pose: This is of particular importance because it is used to indicate preferred start and end joint configurations of the robot when planning the path. If a ''seed_pose" wasn't specified then planning would take longer since multiple start and end joint configurations would have to be taken into account, leading to multiple path solutions that result from combining several start and end poses.

General Instructions

In this exercise, we'll demonstrate how to run the demo as you make progress through the exercises. Also, it will be shown how to run the system in simulation mode and on the real robot.

Main Objective

In general, you'll be implementing a `plan_and_run` node incrementally. This means that in each exercise you'll be adding individual pieces that are needed to complete the full application demo. Thus, when an exercise is completed run the demo in simulation mode in order to verify your results. Only when all of the exercises are finished should you run it on the real robot.

Complete Exercises

1. To complete an exercise, open the corresponding source file under the `src/plan_and_run/src/tasks/` directory. For instance, in Exercise 1 you'll open `load_parameters.cpp`.
2. Take a minute to read the header comments for specific instructions for how to complete this particular exercise. For instance, the `load_parameters.cpp` file contains the following instructions and hints:

```
/* LOAD PARAMETERS
  Goal:
    - Load missing application parameters into the node from the ros parameter server.
    - Use a private NodeHandle in order to load parameters defined in the node's␣
↪namespace.
  Hints:
    - Look at how the 'config_' structure is used to save the parameters.
    - A private NodeHandle can be created by passing the "~" string to its␣
↪constructor.
*/
```

1. Don't forget to comment out the line:

```
ROS_ERROR_STREAM("Task '"<<__FUNCTION__ <<"' is incomplete. Exiting"); exit(-1);
```

This line is usually located at the beginning of each function. Omitting this step will cause the program to exit immediately when it reaches this point.

1. When you run into a comment block that starts with `/* Fill Code:` this means that the line(s) of code that follow are incorrect, commented out or incomplete at best. Read the instructions following `Fill Code` and complete that task as described. An example of instructions comment block is the following:

```
  /*  Fill Code:
   * Goal:
   * - Create a private handle by passing the "~" string to its constructor
   * Hint:
   * - Replace the string in ph below with "~" to make it a private node.
   */
```

1. The `[ COMPLETE HERE ]` entries are meant to be replaced by the appropriate `code entry`. The right code entries could either be program variables, strings or numeric constants. One example is shown below:

```
ros::NodeHandle ph("[ COMPLETE HERE ]: ?? ");
```

In this case the correct replacement would be the string `"~"`, so this line would look like this:

```
ros::NodeHandle ph("~");
```

1. As you are completing each task in this exercise, you can run the demo (see following sections) to verify that it was completed properly.

Run Demo in Simulation Mode

1. In a terminal, run the setup launch file as follows:

```
roslaunch plan_and_run demo_setup.launch
```

- When the virtual robot is ready , Rviz should be up and running with a UR5 arm in the home position and you'll see the following messages in the terminal:

```
      .
      .
      .
********************************************************
* MoveGroup using:
*     - CartesianPathService
*     - ExecutePathService
*     - KinematicsService
*     - MoveAction
*     - PickPlaceAction
*     - MotionPlanService
*     - QueryPlannersService
*     - StateValidationService
*     - GetPlanningSceneService
*     - ExecutePathService
********************************************************

[ INFO] [1430359645.694537917]: MoveGroup context using planning plugin ompl_
↪interface/OMPLPlanner
```

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```
[ INFO] [1430359645.694700640]: MoveGroup context initialization complete

All is well! Everyone is happy! You can start planning now!
```

- This launch file only needs to be run once.

1. In a separate terminal, run the application launch file:

```
roslaunch plan_and_run demo_run.launch
```

- Look in the Rviz window and the arm should start moving.

Run Demo on the Real Robot

Notes

- Make sure that you can `ping` the robot and that there aren't any obstacles near it.

1. In a terminal, run the setup launch file as follows:

```
roslaunch plan_and_run demo_setup.launch sim:=false robot_ip:=000.000.0.00
```

Notes:

- Enter the robot's actual IP address into the `robot_ip` argument. The robot model in Rviz should be in about the same position as the real robot.

1. In a separate terminal, run the application launch file:

```
roslaunch plan_and_run demo_run.launch
```

- This time the real robot should start moving.

Load Parameters

In this exercise, we'll load some ROS parameters to initialize important variables within our program.

Locate Exercise Source File

- Go to the main application source file located in `plan_and_run/src/plan_and_run_node.cpp`.
- In the main program, locate the function call to `application.loadParameters()`.
- Go to the source file for that function located in the `plan_and_run/src/tasks/load_parameters.cpp`. Alternatively, in Eclipse you can click in any part of the function and press "F2" to bring up that file.
- Comment out the first line containing the `ROS_ERROR_STREAM ...` entry so that the function doesn't quit immediately.

Complete Code

- Find comment block that starts with `/* Fill Code:` and complete as described.
- Replace every instance of `[ COMPLETE HERE ]` accordingly.

Build Code and Run

- `cd` into your catkin workspace and run:

```
catkin build --cmake-args -G 'CodeBlocks - Unix Makefiles'
source ./devel/setup.bash
```

- Then run the application launch file:

```
roslaunch plan_and_run demo_setup.launch
roslaunch plan_and_run demo_run.launch
```

API References

ros::NodeHandle

NodeHandle::getParam()

Initialize ROS

In this exercise, we'll initialize the ros components that our application needs in order to communicate to MoveIt! and other parts of the system.

Locate Exercise Source File

- Go to the main application source file located in `plan_and_run/src/plan_and_run_node.cpp`.
- In the main program, locate the function call to `application.initRos()`.
- Go to the source file for that function located in the `plan_and_run/src/tasks/init_ros.cpp`.
    - *Alternatively, in QTCreator, click on any part of the function and press "F2" to bring up that file.*
- Comment out the first line containing the `ROS_ERROR_STREAM ...` entry so that the function doesn't quit immediately.

Complete Code

- Observe how the ros Publisher `marker_publisher_` variable is initialized. The node uses it to publish a `visualization_msgs::!MarkerArray` message for visualizing the trajectory in RViz.
- Initialize the `moveit_run_path_client_ptr_` action client with the `ExecuteTrajectoryAction` type.
- Find comment block that starts with `/* Fill Code:` and complete as described.
- Replace every instance of `[ COMPLETE HERE ]` accordingly.

Build Code and Run

- `cd` into your catkin workspace and run `catkin build`
- Then run the application launch file:

```
roslaunch plan_and_run demo_run.launch
```

API References

visualization_msgs::MarkerArray

NodeHandle::serviceClient()

Initialize Descartes

> This exercise consists of setting up the Descartes Robot Model and Path Planner that our node will use to plan a path from a semi-constrained trajectory of the tool.

Locate Exercise Source File

- Go to the main application source file located in `plan_and_run/src/plan_and_run_node.cpp`.
- In the main program, locate the function call to `application.initDescartes()`.
- Go to the source file for that function located in the `plan_and_run/src/tasks/init_descartes.cpp`.
  - Alternatively, in QTCreator, you can click in any part of the function and press "F2" to bring up that file.
- Comment out the first line containing the `ROS_ERROR_STREAM( ...` entry so that the function doesn't quit immediately.

Complete Code

- Invoke the descartes_core::RobotModel::initialize() method in order to properly initialize the robot.
- Similarly, initialize the Descartes planner by passing the `robot_model_` variable into the `descartes_core::!DensePlanner::initialize()` method.
- Find comment block that starts with `/* Fill Code:` and complete as described.
- Replace every instance of `[ COMPLETE HERE ]` accordingly.

Build Code and Run

- `cd` into your catkin workspace and run `catkin build`
- Then run the application launch file:

```
roslaunch plan_and_run demo_run.launch
```

API References

descartes_core::RobotModel descartes_planner::DensePlanner

Move Home

In this exercise, we'll be using MoveIt! in order to move the arm.

Locate Exercise Source File

- Go to the main application source file located in `plan_and_run/src/plan_and_run_node.cpp`.
- In the main program , locate the function call to `application.moveHome()`.
- Go to the source file for that function located in the `plan_and_run/src/tasks/move_home.cpp`.
  - Alternatively, in QTCreator, click on any part of the function and press "F2" to bring up that file.
- Comment out the first line containing the `ROS_ERROR_STREAM( ...` entry so that the function doesn't quit immediately.

Complete Code

- Use the MoveGroupInterface::move() method in order to move the robot to a target.
- The moveit_msgs::MoveItErrorCodes structure contains constants that you can use to check the result after calling the `move()` function.
- Find comment block that starts with `/* Fill Code:` and complete as described.
- Replace every instance of `[ COMPLETE HERE ]` accordingly.

Build Code and Run

- `cd` into your catkin workspace and run `catkin build`
- Then run the application launch file:

```
roslaunch plan_and_run demo_run.launch
```

API References

setNamedTarget()

MoveGroupInterface class

Generate a Semi-Constrained Trajectory

In this exercise, we'll be creating a Descartes trajectory from an array of cartesian poses. Each point will have rotational freedom about the z axis of the tool.

Locate exercise source file

- Go to the main application source file located in `plan_and_run/src/plan_and_run_node.cpp`.
- In the main program, locate the function call to `application.generateTrajectory()`.

- Go to the source file for that function located in the `plan_and_run/src/tasks/generate_trajectory.cpp`.
  - Alternatively, in QTCreator, click on any part of the function and press "F2" to bring up that file.
- Comment out the first line containing the `ROS_ERROR_STREAM( ...` entry so that the function doesn't quit immediately.

Complete Code

- Observe how the 'createLemniscate()' is invoked in order to generate all the poses of the tool for the trajectory. The poses from it are then used to create the Descartes Trajectory.
- Use the AxialSymmetric constructor to specify a point with rotational freedom about the z-axis.
- The AxialSymmetricPt::FreeAxis::Z_AXIS enumeration constant allows you to specify the **Z** as the free rotational axis
- Find comment block that starts with `/* Fill Code:` and complete as described .
- Replace every instance of `[ COMPLETE HERE ]` accordingly.

Build Code and Run

- CD into your catkin workspace and run `catkin build`
- The run the application launch file

```
roslaunch plan_and_run demo_run.launch
```

API References

descartes_trajectory::AxialSymmetricPt

Plan a Robot Path

In this exercise, we'll pass our trajectory to the Descartes planner in order to plan a robot path.

Locate Exercise Source File

- Go to the main application source file located in `plan_and_run/src/plan_and_run_node.cpp`.
- In the main program, locate the function call to `application.planPath()`.
- Go to the source file for that function located in the `plan_and_run/src/tasks/plan_path.cpp`. Alternatively, in Eclipse you can click in any part of the function and press "F2" to bring up that file.
- Comment out the first line containing the `ROS_ERROR_STREAM( ...` entry so that the function doesn't quit immediately.

Complete Code

- Observe the use of the AxialSymmetricPt::getClosesJointPose() in order to get the joint values of the robot that is closest to an arbitrary joint pose. Furthermore, this step allows us to select a single joint pose for the start and end rather than multiple valid joint configurations.
- Call the DensePlanner::planPath() method in order to compute a motion plan.
- When planning succeeds, use the DensePlanner::getPath() method in order to retrieve the path from the planner and save it into the `output_path` variable.
- Find comment block that starts with `/* Fill Code:` and complete as described.
- Replace every instance of `[ COMPLETE HERE ]` accordingly.

Build Code and Run

- `cd` into your catkin workspace and run `catkin build`
- Then run the application launch file:

```
roslaunch plan_and_run demo_run.launch
```

API References

descartes_planner::DensePlanner

Run a Robot Path

In this exercise, we'll convert our Descartes path into a MoveIt! trajectory and then send it to the robot.

Locate Exercise Source File

- Go to the main application source file located in `plan_and_run/src/plan_and_run_node.cpp`.
- In the main program, locate the function call to `application.runPath()`.
- Go to the source file for that function located in the `plan_and_run/src/tasks/run_path.cpp`.
  - Alternatively, in QTCreator, click on any part of the function and press "F2" to bring up that file.
- Comment out the first line containing the `ROS_ERROR_STREAM( ...` entry so that the function doesn't quit immediately.

Complete Code

- Find comment block that starts with `/* Fill Code:` and complete as described.
- Replace every instance of `[ COMPLETE HERE ]` accordingly.

Build Code and Run

- `cd` into your catkin workspace and run `catkin build`
- Then run the application launch file:

```
roslaunch plan_and_run demo_run.launch
```

API References

MoveGroupInterface::move()

CHAPTER 4

Advanced Topics

4.1 Session 5 - Path Planning and Building a Perception Pipeline

`Slides`

4.1.1 Advanced Descartes Path Planning

> In this exercise, we will use advanced features with Descartes to solve a complex path for part being held by the robot which gets processed by a stationary tool.

Motivation

MoveIt! is a framework meant primarily for performing “free-space” motion where the objective is to move a robot from point A to point B and you don’t particularly care about how that gets done. These types of problems are only a subset of frequently performed tasks. Imagine any manufacturing ‘’process” like welding or painting. You very much care about where that tool is pointing the entire time the robot is at work.

This tutorial introduces you to Descartes, a ‘’Cartesian” motion planner meant for moving a robot along some process path. It’s only one of a number of ways to solve this kind of problem, but it’s got some neat properties:

- It’s deterministic and globally optimum (to a certain search resolution).
- It can search redundant degrees of freedom in your problem (say you have 7 robot joints or you have a process where the tool’s Z-axis rotation doesn’t matter).

Reference Example

Descartes Tutorial

Further Information and Resources

Descartes Wiki

APIs:

- descartes_core::PathPlannerBase
- descartes_planner::DensePlanner
- descartes_planner::SparsePlanner

Scan-N-Plan Application: Problem Statement

In this exercise, you will add two new nodes, two xacro, and config file to your Scan-N-Plan application, that:

1. Takes the config file `puzzle_bent.csv` and creates a descartes trajectory where the part is held by the robot and manipulated around a stationary tool.
2. Produces a joint trajectory that commands the robot to trace the perimeter of the marker (as if it is dispensing adhesive).

Scan-N-Plan Application: Guidance

In the interest of time, we've included several files:

1. The first is a template node `adv_descartes_node.cpp` where most of the exercise is spent creating the complicated trajectory for deburring a complicated part.
2. The second node, `adv_myworkcell_node.cpp`, is a duplicate of the `myworkcell_node.cpp` that has been updated to call the `adv_plan_path` service provided by `adv_descartes_node.cpp`.
3. The config file `puzzle_bent.csv` which contains the path relative to the part coordinate system.
4. The two xacro files `puzzle_mount.xacro` and `grinder.xacro` which are used to update the urdf/xacro `workcell.xacro` file.

Left to you are the details of:

1. Updating the workcell.xacro file to include the two new xacro files.
2. Updating the moveit_config package to define a new Planning Group for this exercise, including the new end-effector links.
3. Defining a series of Cartesian poses that comprise a robot "path".
4. Translating those paths into something Descartes can understand.

Setup workspace

1. This exercise uses the same workspace from the Basic Training course. If you don't have this workspace (completed through Exercise 4.1), copy the completed reference code and pull in other required dependencies as shown below. Otherwise move to the next step.

```
mkdir ~/catkin_ws
cd ~/catkin_ws
cp -r ~/industrial_training/exercises/4.1/src .
cd src
git clone https://github.com/jmeyer1292/fake_ar_publisher.git
```

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```
git clone -b kinetic-devel https://github.com/ros-industrial-consortium/descartes.
↪git
sudo apt install ros-kinetic-ur-kinematics
sudo apt install ros-kinetic-ur-description
```

2. Copy over the `adv_descartes_node_unfinished.cpp` into your core package's src/ folder and rename it `adv_descartes_node.cpp`.

```
cp ~/industrial_training/exercises/5.0/src/adv_descartes_node_unfinished.cpp␣
↪myworkcell_core/src/adv_descartes_node.cpp
```

3. Create rules in the `myworkcell_core` package's `CMakeLists.txt` to build a new node called `adv_descartes_node`. As in previous exercises, add these lines near similar lines in the template file (not as a block as shown below).

```
add_executable(adv_descartes_node src/adv_descartes_node.cpp)
add_dependencies(adv_descartes_node ${${PROJECT_NAME}_EXPORTED_TARGETS} ${catkin_
↪EXPORTED_TARGETS})
target_link_libraries(adv_descartes_node ${catkin_LIBRARIES})
```

4. Copy over the `adv_myworkcell_node.cpp` into your core package's src/ folder.

```
cp ~/industrial_training/exercises/5.0/src/myworkcell_core/src/adv_myworkcell_
↪node.cpp myworkcell_core/src/
```

5. Create rules in the `myworkcell_core` package's `CMakeLists.txt` to build a new node called `adv_myworkcell_node`. As in previous exercises, add these lines near similar lines in the template file (not as a block as shown below).

```
add_executable(adv_myworkcell_node src/adv_myworkcell_node.cpp)
add_dependencies(adv_myworkcell_node ${${PROJECT_NAME}_EXPORTED_TARGETS} ${catkin_
↪EXPORTED_TARGETS})
target_link_libraries(adv_myworkcell_node ${catkin_LIBRARIES})
```

6. Copy over the necessesary config file:

```
mkdir ~/catkin_ws/src/myworkcell_core/config
cp ~/industrial_training/exercises/5.0/src/myworkcell_core/config/puzzle_bent.csv␣
↪myworkcell_core/config/
cp ~/industrial_training/exercises/5.0/src/myworkcell_support/urdf/grinder.xacro␣
↪myworkcell_support/urdf/
cp ~/industrial_training/exercises/5.0/src/myworkcell_support/urdf/puzzle_mount.
↪xacro myworkcell_support/urdf/
mkdir ~/catkin_ws/src/myworkcell_support/meshes
cp ~/industrial_training/exercises/5.0/src/myworkcell_support/meshes/* myworkcell_
↪support/meshes/
```

7. Add new package dependencies:

   - Add `tf_conversions` to `CMakeLists.txt` (2 places) and `package.xml` (1 place)

Update your workcell.xacro file.

1. Add two `<include>` tags for the new `grinder.xacro` and `puzzle_mount.xacro` files.
2. Attach the grinder to the **world** link with the following offset:

```
<origin xyz="0.0 -0.4 0.6" rpy="0 3.14159 0"/>
```

- Look in the `grinder.xacro` file to locate the appropriate `<child_link>` name.
- Copy one of the other `<joint>` tag definitions and modify as appropriate.

3. Attach the puzzle mount to the robot's **tool0** frame with the following offset:

```
<origin xyz="0 0 0" rpy="1.5708 0 0"/>
```

- Look in the `puzzle_mount.xacro` file to locate the appropriate `<child_link>` name. You may need to study its various `<link>` and `<joint>` definitions to find the root link of this part.
- The `tool0` frame is standardized across most ROS-I URDFs to be the robot's end-effector mounting flange.

4. Launch the demo.launch file within your moveit_config package to verify the workcell. There should be a grinder sticking out of the table and a puzzle-shaped part attached to the robot.

```
roslaunch myworkcell_moveit_config demo.launch
```

Add new planning group to your moveit_config package.

1. Re-run the MoveIt! Setup Assistant and create a new Planning Group named **puzzle**. Define the kinematic chain to extend from the **base_link** to the new **part** link.

```
roslaunch myworkcell_moveit_config setup_assistant.launch
```

- *Note: Since you added geometry, you should also regenerate the allowed collision matrix.*

Complete Advanced Descartes Node

1. First, the function `makePuzzleToolPoses()` needs to be completed. The file path for **puzzle_bent.csv** is needed. For portability, don't hardcode the full path. Please use the ROS tool `ros::package::getPath()` to retrieve the root path of the relevant package.
   - reference getPath() API
2. Next, the function `makeDescartesTrajectory()` needs to be completed. The transform between **world** and **grinder_frame** needs to be found. Also Each point needs to have the orientation tolerance set for the z-axis to +/- PI;
   - reference lookupTransform() API
   - reference tf::conversions namespace
   - reference TolerancedFrame definition
   - reference OrientationTolerance definition

Update the setup.launch file.

1. Update the file to take a boolean argument named **adv** so that either the basic or advanced descartes node can be launched. Use `<if>` and `<unless>` modifiers to control which node is launched.
   - reference roslaunch XML wiki

Test Full Application

1. Run the new setup file, then your main advanced workcell node:

```
roslaunch myworkcell_support setup.launch adv:=true
rosrun myworkcell_core adv_myworkcell_node
```

   - Descartes can take **several minutes** to plan this complex path, so be patient.
   - It's difficult to see what's happening with the rviz planning-loop animation always running. Disable this loop animation in rviz (Displays -> Planned Path -> Loop Animation) before running `adv_myworkcell_node`.

4.1.2 Building a Perception Pipeline

In this exercise, we will fill in the appropriate pieces of code to build a perception pipeline. The end goal will be to broadcast a transform with the pose information of the object of interest.

Prepare New Workspace:

We will create a new catkin workspace, since this exercise does not overlap with the previous exercises.

1. Disable automatic sourcing of your previous catkin workspace:

   (a) `gedit ~/.bashrc`

   (b) comment out (#) the last line, sourcing your `~/catkin_ws/devel/setup.bash`

   Note: This means you'll need to manually source the setup file from your new catkin workspace in each new terminal window.

   i. Close gedit and source ROS into your environment

```
source /opt/ros/kinetic/setup.bash
```

2. Copy the template workspace layout and files:

```
cp -r ~/industrial_training/exercises/5.1/template_ws ~/perception_ws
cd ~/perception_ws/
```

1. Initialize and Build this new workspace

```
catkin init
catkin build
```

2. Source the workspace

```
source ~/perception_ws/devel/setup.bash
```

1. Copy the PointCloud file from prior Exercise 4.2 to your home directory (~):

```
cp ~/industrial_training/exercises/4.2/table.pcd ~
```

2. Import the new workspace into your QTCreator IDE:

   - In QTCreator: *File -> New File or Project -> Other Project -> ROS Workspace -> ~/perception_ws*

Intro (Review Existing Code)

Most of the infrastructure for a ros node has already been completed for you; the focus of this exercise is the perception algorithms/pipleline. The *CMakelists.txt* and *package.xml* are complete and an executable has been provided. You could run the executable as is, but you would get errors. At this time we will explore the source code that has been provided - browse the provided *perception_node.cpp* file. The following are highlights of what is included.

1. Headers:
   - You will have to uncomment the PCL related headers as you go
2. int main():
   - The `main` function has been provided along with a while loop within the main function
3. ROS initialization:
   - Both `ros::init` and `ros::NodeHandle` have been called/initialized. Additionally there is a private nodehandle to use if you need to get parameters from a launch file within the node's namespace.
4. Set up parameters:
   - Currently there are three string parameters included in the example: the world frame, the camera frame and the topic being published by the camera. It would be easy to write up a few `nh.getParam` lines which would read these parameters in from a launch file. If you have the time, you should set this up because there will be many parameters for the pcl methods that would be better adjusted via a launch file than hardcoded.
5. Set up publishers:
   - Two publishers have been set up to publish ros messages for point clouds. It is often useful to visualize your results when working with image or point cloud processing.
6. Listen for PointCloud2 (within while loop):
   - Typically one would listen for a ros message using the ros subscribe method with a callback function, as done here. However it is often useful to do this outside of a callback function, so we show an example of listening for a message using `ros::topic::waitForMessage`.
7. Transform PointCloud2 (within while loop):
   - While we could work in the camera frame, things are more understandable/useful if we are looking at the points of a point cloud in an xyz space that makes more sense with our environment. In this case we are transforming the points from the camera frame to a world frame.
8. Convert PointCloud2 (ROS to PCL) (within while loop)
9. Convert PointCloud2 (PCL to ROS) and publish (within while loop):
   - This step is not necessary, but visualizing point cloud processing results is often useful, so conversion back into a ROS type and creating the ROS message for publishing is done for you.

So it seems that a lot has been done! Should be easy to finish up. All you need to do is fill in the middle section.

Primary Task: Filling in the blanks

The task of filling in the middle section containing the perception algorithms is an iterative process, so each step has been broken up into its own sub-task.

Implement Voxel Filter

1. Uncomment the *voxel_grid* include header, near the top of the file.
2. Change code:

   The first step in most point cloud processing pipelines is the voxel filter. This filter not only helps to downsample your points, but also eliminates any NAN values so that any further filtering or processing is done on real values. See PCL Voxel Filter Tutorial for hints, otherwise you can copy the below code snippet.

   Within `perception_node.cpp`, find section

   ```
   /* ========================================
    * Fill Code: VOXEL GRID
    * ========================================*/
   ```

   Copy and paste the following beneath that banner.

   ```
   pcl::PointCloud<pcl::PointXYZ>::Ptr cloud_ptr (new pcl::PointCloud<pcl::PointXYZ>␣
    ↪(cloud));
   pcl::PointCloud<pcl::PointXYZ>::Ptr cloud_voxel_filtered (new pcl::PointCloud
    ↪<pcl::PointXYZ> ());
   pcl::VoxelGrid<pcl::PointXYZ> voxel_filter;
   voxel_filter.setInputCloud (cloud_ptr);
   voxel_filter.setLeafSize (float(0.002), float(0.002), float(0.002));
   voxel_filter.filter (*cloud_voxel_filtered);
   ```

3. Update Publisher Within `perception_node.cpp`, find section

   ```
   /* ========================================
    * CONVERT POINTCLOUD PCL->ROS
    * PUBLISH CLOUD
    * Fill Code: UPDATE AS NECESSARY
    * ========================================*/
   ```

   Uncomment `pcl::toROSMsg`, and replace `*cloud_ptr` with `*cloud_voxel_filtered`

   After each new update, we'll be swapping out which point-cloud is published for rviz viewing

   ---

   Note: If you have the time/patience, I would suggest creating a ros publisher for each type of filter. It is often useful to view the results of multiple filters at once in Rviz and just toggle different clouds.

   ---

4. Compile

   ```
   catkin build
   ```

Viewing Results

1. Run the (currently small) perception pipeline. Note: In rviz change the global frame to **kinect_link**.

   ```
   cd ~
   roscore
   rosrun tf2_ros static_transform_publisher 0 0 0 0 0 0 world_frame kinect_link
   rosrun pcl_ros pcd_to_pointcloud table.pcd 0.1 _frame_id:=kinect_link cloud_
    ↪pcd:=kinect/depth_registered/points
   ```

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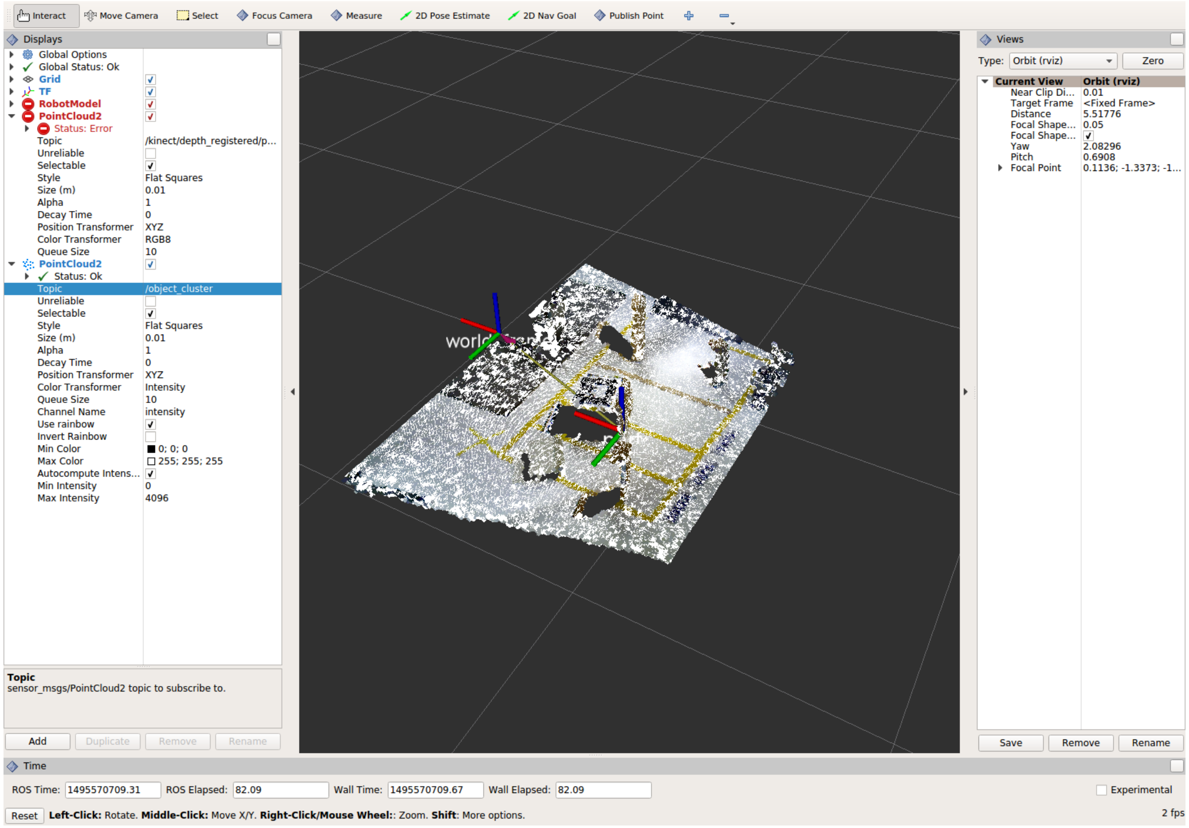
```
rosrun rviz rviz
rosrun lesson_perception perception_node
```

2. View results

   Within Rviz, add a *PointCloud2* Display subscribed to the topic "object_cluster". What you see will be the results of the voxel filter overlaid on the original point cloud (assuming you have completed exercise 4.2 and saved a new default config or saved a config for that exercise).



Global Options	
Global Status: Ok	
Grid	☑
TF	☑
RobotModel	☑
PointCloud2	☑
Status: Error	
Topic	/kinect/depth_registered/p...
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	RGB8
Queue Size	10
PointCloud2	☑
Status: Ok	
Topic	/object_cluster
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	Intensity
Queue Size	10
Channel Name	intensity
Use rainbow	☑
Invert Rainbow	□
Min Color	■ 0; 0; 0
Max Color	□ 255; 255; 255
Autocompute Intens...	☑
Min Intensity	0
Max Intensity	4096

Topic
sensor_msgs/PointCloud2 topic to subscribe to.

Type: Orbit (rviz)

Current View	Orbit (rviz)
Near Clip Di...	0.01
Target Frame	<Fixed Frame>
Distance	5.51776
Focal Shape...	0.05
Focal Shape...	☑
Yaw	2.08296
Pitch	0.6908
Focal Point	0.1136; -1.3373; -1...

ROS Time: 1495570709.31 ROS Elapsed: 82.09 Wall Time: 1495570709.67 Wall Elapsed: 82.09 □ Experimental

Left-Click: Rotate. **Middle-Click:** Move X/Y. **Right-Click/Mouse Wheel:**: Zoom. **Shift**: More options. 2 fps

3. When you are done viewing the results, try changing the voxel filter size from 0.002 to 0.100 and view the results again. Reset the filter to 0.002 when done.

   - To see the results of this change, use Ctrl+C to kill the perception node, re-build, and re-run the perception node.

Note: You do not need to stop any of the other nodes (rviz, ros, etc).

1. When you are satisfied with the voxel filter, use Ctrl+C to stop the perception node.

Implement Pass-through Filters

1. As before, uncomment the PassThrough filter include-header near the top of the file.
2. Change code:

   The next set of useful filtering to get the region of interest, is a series of pass-through filters. These filters crop your point cloud down to a volume of space (if you use x y and z filter). At this point you should apply a series of pass-through filters, one for each the x, y, and z directions. See PCL Pass-Through Filter Tutorial for hints, or use code below.

Within perception_node.cpp, find section

```
/* ========================================
 * Fill Code: PASSTHROUGH FILTER(S)
 * ========================================*/
```

Copy and paste the following beneath that banner.

```
pcl::PointCloud<pcl::PointXYZ> xf_cloud, yf_cloud, zf_cloud;
pcl::PassThrough<pcl::PointXYZ> pass_x;
pass_x.setInputCloud(cloud_voxel_filtered);
pass_x.setFilterFieldName("x");
pass_x.setFilterLimits(-1.0,1.0);
pass_x.filter(xf_cloud);

pcl::PointCloud<pcl::PointXYZ>::Ptr xf_cloud_ptr(new pcl::PointCloud
 ↪<pcl::PointXYZ>(xf_cloud));
pcl::PassThrough<pcl::PointXYZ> pass_y;
pass_y.setInputCloud(xf_cloud_ptr);
pass_y.setFilterFieldName("y");
pass_y.setFilterLimits(-1.0, 1.0);
pass_y.filter(yf_cloud);

pcl::PointCloud<pcl::PointXYZ>::Ptr yf_cloud_ptr(new pcl::PointCloud
 ↪<pcl::PointXYZ>(yf_cloud));
pcl::PassThrough<pcl::PointXYZ> pass_z;
pass_z.setInputCloud(yf_cloud_ptr);
pass_z.setFilterFieldName("z");
pass_z.setFilterLimits(-1.0, 1.0);
pass_z.filter(zf_cloud);
```

You can change the filter limit values to see different results.

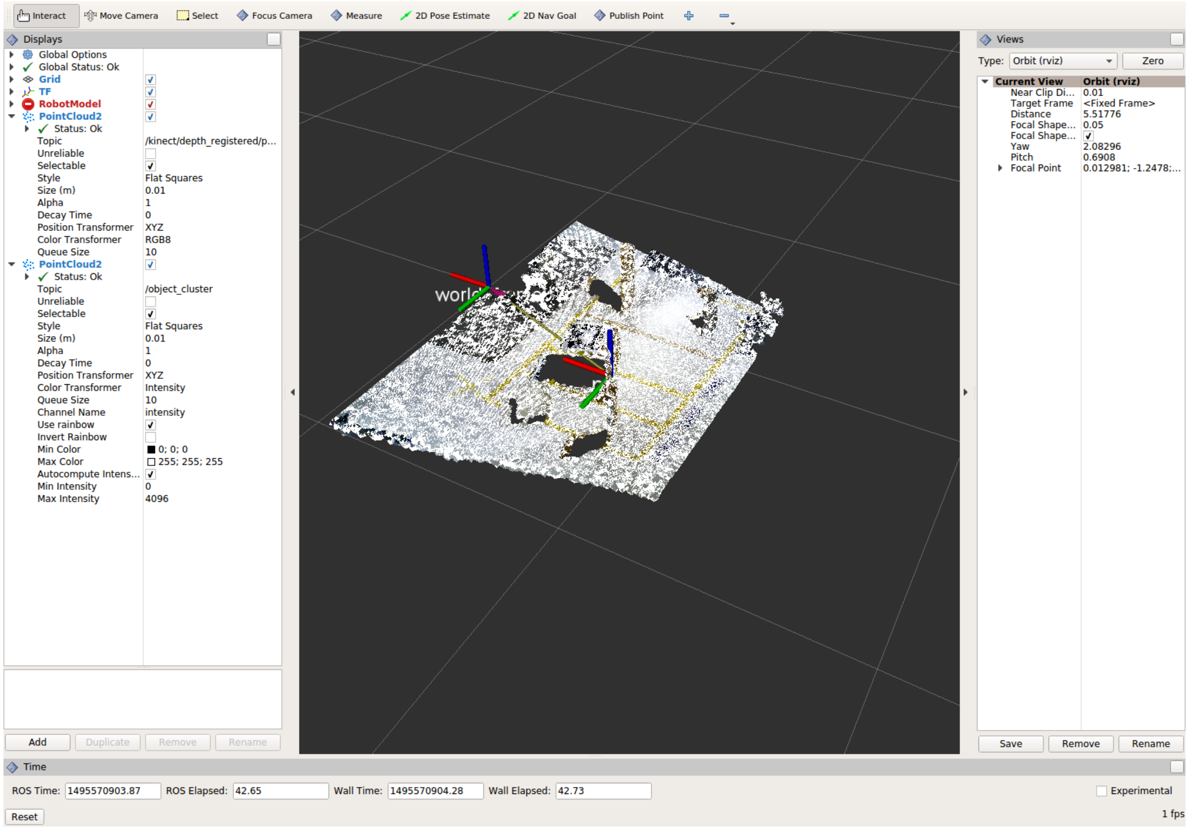
3. Find the `pcl::toROSMsg` call where the `pc2_cloud` is populated. This is the point cloud that is published to RViz display. Replace the current cloud (`*cloud_voxel_filter`) with the final Passthrough Filter result (`zf_cloud`).

4. Compile and run

```
catkin build
rosrun lesson_perception perception_node
```

5. View results

   Within Rviz, compare PointCloud2 displays based on the `/kinect/depth_registered/points` (original camera data) and `object_cluster` (latest processing step) topics. Part of the original point cloud has been "clipped" out of the latest processing result.



Global Options
Global Status: Ok
Grid ☑
TF ☑
RobotModel ☑
PointCloud2 ☑
Status: Ok
Topic /kinect/depth_registered/p...
Unreliable ☐
Selectable ☑
Style Flat Squares
Size (m) 0.01
Alpha 1
Decay Time 0
Position Transformer XYZ
Color Transformer RGB8
Queue Size 10
PointCloud2 ☑
Status: Ok
Topic /object_cluster
Unreliable ☐
Selectable ☑
Style Flat Squares
Size (m) 0.01
Alpha 1
Decay Time 0
Position Transformer XYZ
Color Transformer Intensity
Queue Size 10
Channel Name intensity
Use rainbow ☑
Invert Rainbow ☐
Min Color ■ 0; 0; 0
Max Color □ 255; 255; 255
Autocompute Intens... ☑
Min Intensity 0
Max Intensity 4096

Type: Orbit (rviz)
Current View Orbit (rviz)
Near Clip Di... 0.01
Target Frame <Fixed Frame>
Distance 5.51776
Focal Shape... 0.05
Focal Shape... ☑
Yaw 2.08296
Pitch 0.6908
Focal Point 0.012981; -1.2478;...

ROS Time: 1495570903.87 ROS Elapsed: 42.65 Wall Time: 1495570904.28 Wall Elapsed: 42.73 ☐ Experimental
1 fps

Note: Try modifying the X/Y/Z FilterLimits (e.g. +/- 0.5), re-build, and re-run. Observe the effects in rviz. When complete, reset the limite to +/- 1.0.

1. When you are satisfied with the pass-through filter results, press Ctrl+C to kill the node. There is no need to close or kill the other terminals/nodes.

Plane Segmentation

1. Change code

   This method is one of the most useful for any application where the object is on a flat surface. In order to isolate the objects on a table, you perform a plane fit to the points, which finds the points which comprise the table, and then subtract those points so that you are left with only points corresponding to the object(s) above the table. This is the most complicated PCL method we will be using and it is actually a combination of two: the RANSAC segmentation model, and the extract indices tool. An in depth example can be found on the PCL Plane Model Segmentation Tutorial; otherwise you can copy the below code snippet.

   Within perception_node.cpp, find section:

```
/* ========================================
 * Fill Code: PLANE SEGEMENTATION
 * ========================================*/
```

   Copy and paste the following beneath that banner.

```
pcl::PointCloud<pcl::PointXYZ>::Ptr cropped_cloud(new pcl::PointCloud
↪<pcl::PointXYZ>(zf_cloud));
pcl::PointCloud<pcl::PointXYZ>::Ptr cloud_f (new pcl::PointCloud<pcl::PointXYZ>);
pcl::PointCloud<pcl::PointXYZ>::Ptr cloud_filtered (new pcl::PointCloud
↪<pcl::PointXYZ>);
pcl::PointCloud<pcl::PointXYZ>::Ptr cloud_plane (new pcl::PointCloud
↪<pcl::PointXYZ> ());
// Create the segmentation object for the planar model and set all the parameters
pcl::SACSegmentation<pcl::PointXYZ> seg;
pcl::PointIndices::Ptr inliers (new pcl::PointIndices);
pcl::ModelCoefficients::Ptr coefficients (new pcl::ModelCoefficients);
seg.setOptimizeCoefficients (true);
seg.setModelType (pcl::SACMODEL_PLANE);
seg.setMethodType (pcl::SAC_RANSAC);
seg.setMaxIterations (200);
seg.setDistanceThreshold (0.004);
// Segment the largest planar component from the cropped cloud
seg.setInputCloud (cropped_cloud);
seg.segment (*inliers, *coefficients);
if (inliers->indices.size () == 0)
{
  ROS_WARN_STREAM ("Could not estimate a planar model for the given dataset.") ;
  //break;
}
```

Once you have the inliers (points which fit the plane model), then you can extract the indices within the pointcloud data structure of the points which make up the plane.

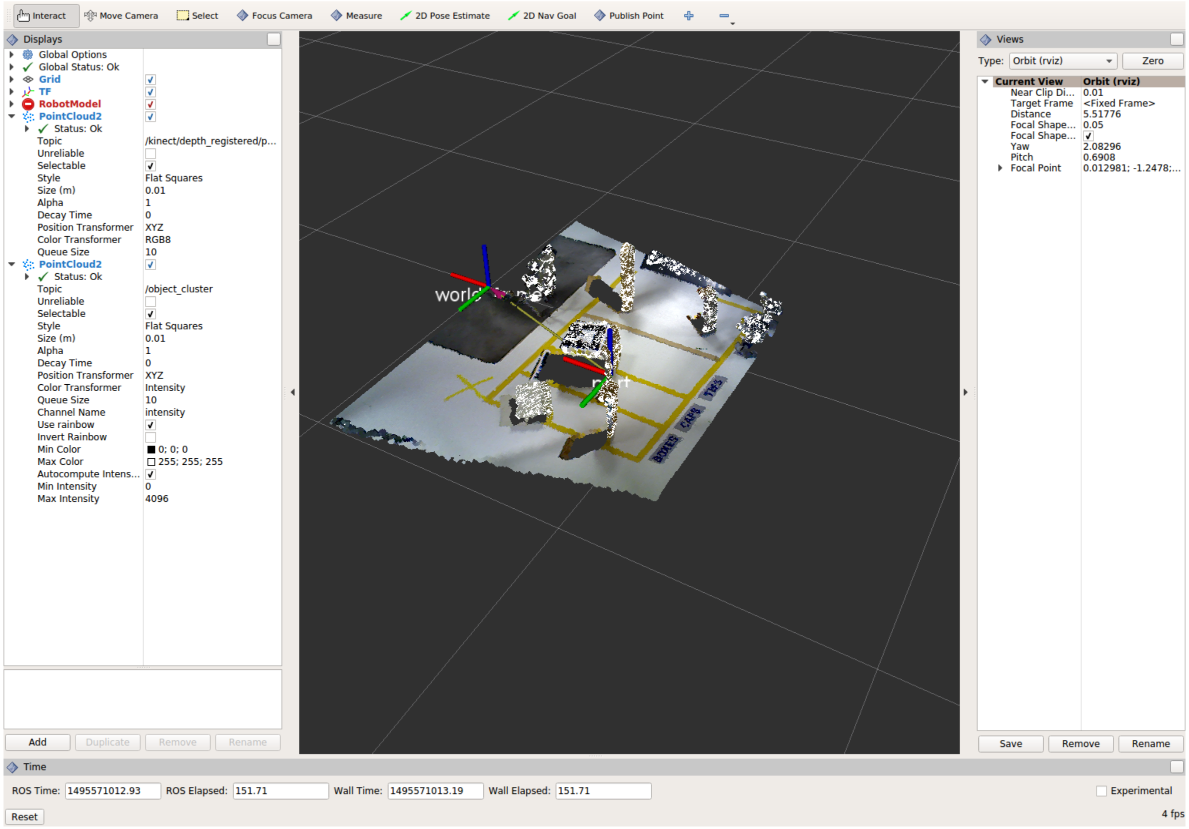
```
// Extract the planar inliers from the input cloud
pcl::ExtractIndices<pcl::PointXYZ> extract;
extract.setInputCloud (cropped_cloud);
extract.setIndices(inliers);
extract.setNegative (false);

// Get the points associated with the planar surface
extract.filter (*cloud_plane);
ROS_INFO_STREAM("PointCloud representing the planar component: " << cloud_plane->
↪points.size () << " data points." );
```

Then of course you can subtract or filter out these points from the cloud to get only points above the plane.

```
// Remove the planar inliers, extract the rest
extract.setNegative (true);
extract.filter (*cloud_f);
```

2. Find the `pcl::toROSMsg` call where the `pc2_cloud` is populated. This is the point cloud that is published to RViz display. Replace the current cloud (`zf_cloud`) with the plane-fit outliers result (`*cloud_f`).
3. **Compile and run, as in previous steps.** Did you forget to uncomment the new headers used in this step?
4. Evaluate Results

   Within Rviz, compare PointCloud2 displays based on the `/kinect/depth_registered/points` (original camera data) and `object_cluster` (latest processing step) topics. Only points lying above the table plane remain in the latest processing result.



Displays	
Global Options	
Global Status: Ok	
Grid	☑
TF	☑
RobotModel	☑
PointCloud2	☑
Status: Ok	
Topic	/kinect/depth_registered/p...
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	RGB8
Queue Size	10
PointCloud2	☑
Status: Ok	
Topic	/object_cluster
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	Intensity
Queue Size	10
Channel Name	intensity
Use rainbow	☑
Invert Rainbow	□
Min Color	■ 0; 0; 0
Max Color	□ 255; 255; 255
Autocompute Intens...	☑
Min Intensity	0
Max Intensity	4096

Type: Orbit (rviz)

Current View	Orbit (rviz)
Near Clip Di...	0.01
Target Frame	<Fixed Frame>
Distance	5.51776
Focal Shape...	0.05
Focal Shape...	☑
Yaw	2.08296
Pitch	0.6908
Focal Point	0.012981; -1.2478;...

ROS Time: 1495571012.93 ROS Elapsed: 151.71 Wall Time: 1495571013.19 Wall Elapsed: 151.71 □ Experimental

4 fps

5. When you are done viewing the results you can go back and change the"setMaxIterations" and "setDistanceThreshold" values to control how tightly the plane-fit classifies data as inliers/outliers, and view the results again. Try using values of `MaxIterations=100` and `DistanceThreshold=0.010`

6. When you are satisfied with the plane segmentation results, use Ctrl+C to kill the node. There is no need to close or kill the other terminals/nodes.

Euclidean Cluster Extraction (optional, but recommended)

1. Change code

   This method is useful for any application where there are multiple objects. This is also a complicated PCL method. An in depth example can be found on the PCL Euclidean Cluster Extration Tutorial.

   Within perception_node.cpp, find section

   ```
   /* ========================================
    * Fill Code: EUCLIDEAN CLUSTER EXTRACTION (OPTIONAL/RECOMMENDED)
    * ========================================*/
   ```

   Follow along with the PCL tutorial, insert code in this section.

   Copy and paste the following beneath the banner.

   ```
   // Creating the KdTree object for the search method of the extraction
   pcl::search::KdTree<pcl::PointXYZ>::Ptr tree (new pcl::search::KdTree
   ↪<pcl::PointXYZ>);
   *cloud_filtered = *cloud_f;
   tree->setInputCloud (cloud_filtered);
   ```

(continues on next page)

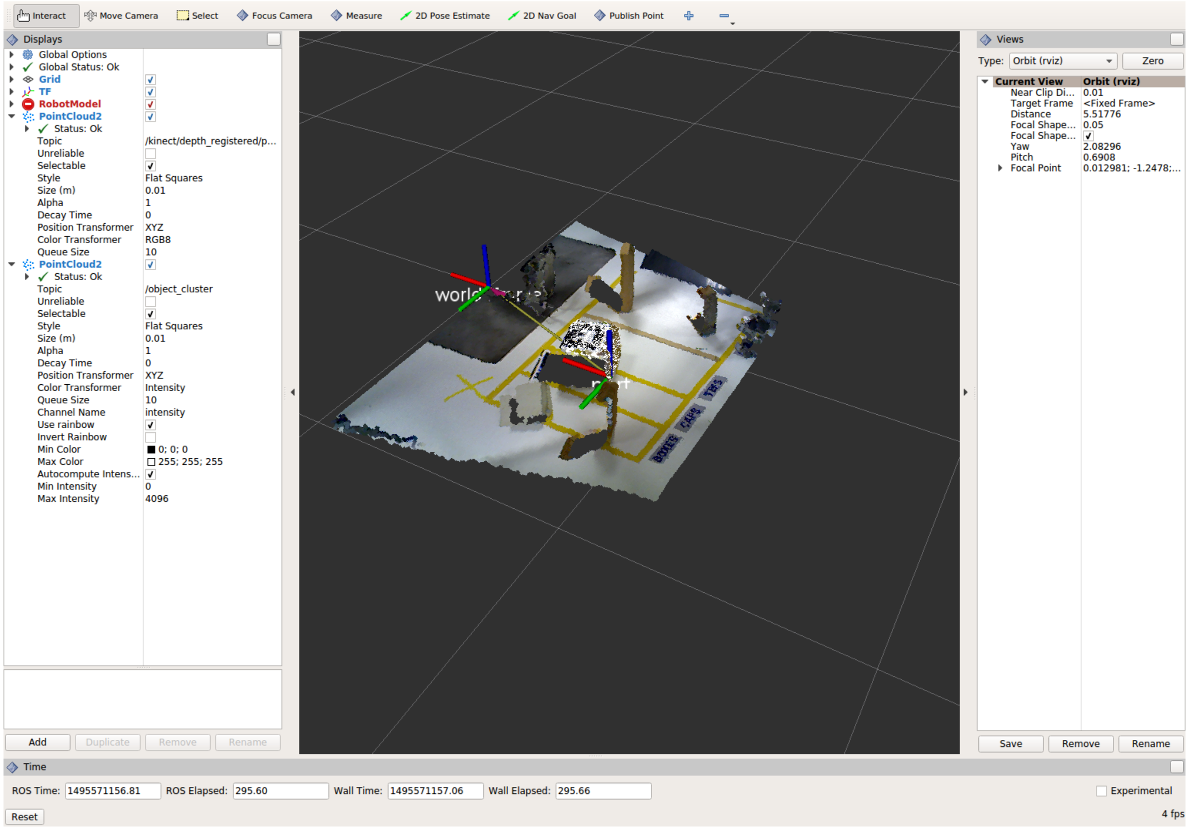
(continued from previous page)

```
std::vector<pcl::PointIndices> cluster_indices;
pcl::EuclideanClusterExtraction<pcl::PointXYZ> ec;
ec.setClusterTolerance (0.01); // 2cm
ec.setMinClusterSize (300);
ec.setMaxClusterSize (10000);
ec.setSearchMethod (tree);
ec.setInputCloud (cloud_filtered);
ec.extract (cluster_indices);

std::vector<sensor_msgs::PointCloud2::Ptr> pc2_clusters;
std::vector<pcl::PointCloud<pcl::PointXYZ>::Ptr > clusters;
for (std::vector<pcl::PointIndices>::const_iterator it = cluster_indices.begin ();
↪ it != cluster_indices.end (); ++it)
{
  pcl::PointCloud<pcl::PointXYZ>::Ptr cloud_cluster (new pcl::PointCloud
↪<pcl::PointXYZ>);
  for (std::vector<int>::const_iterator pit = it->indices.begin (); pit != it->
↪indices.end (); pit++)
    cloud_cluster->points.push_back(cloud_filtered->points[*pit]);
  cloud_cluster->width = cloud_cluster->points.size ();
  cloud_cluster->height = 1;
  cloud_cluster->is_dense = true;
  std::cout << "Cluster has " << cloud_cluster->points.size() << " points.\n";
  clusters.push_back(cloud_cluster);
  sensor_msgs::PointCloud2::Ptr tempROSMsg(new sensor_msgs::PointCloud2);
  pcl::toROSMsg(*cloud_cluster, *tempROSMsg);
  pc2_clusters.push_back(tempROSMsg);
}
```

2. Find the `pcl::toROSMsg` call where the `pc2_cloud` is populated. This is the point cloud that is published to RViz display. Replace the current cloud (`*cloud_f`) with the largest cluster (`*(clusters.at(0))`).

3. Compile and run, as in previous steps.

4. View results in rviz. Experiment with `setClusterTolerance`, `setMinClusterSize`, and `setMaxClusterSize` parameters, observing their effects in rviz.



Global Options	
Global Status: Ok	
Grid	☑
TF	☑
RobotModel	☑
PointCloud2	☑
Status: Ok	
Topic	/kinect/depth_registered/p...
Unreliable	☐
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	RGB8
Queue Size	10
PointCloud2	☑
Status: Ok	
Topic	/object_cluster
Unreliable	☐
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	Intensity
Queue Size	10
Channel Name	intensity
Use rainbow	☑
Invert Rainbow	☐
Min Color	■ 0; 0; 0
Max Color	□ 255; 255; 255
Autocompute Intens...	☑
Min Intensity	0
Max Intensity	4096

Type: Orbit (rviz)

Current View	Orbit (rviz)
Near Clip Di...	0.01
Target Frame	<Fixed Frame>
Distance	5.51776
Focal Shape...	0.05
Focal Shape...	☑
Yaw	2.08296
Pitch	0.6908
Focal Point	0.012981; -1.2478;...

ROS Time: 1495571156.81 ROS Elapsed: 295.60 Wall Time: 1495571157.06 Wall Elapsed: 295.66 ☐ Experimental

4 fps

5. When you are satisfied with the cluster extraction results, use Ctrl+C to kill the node. There is no need to close or kill the other terminals/nodes.

Create a CropBox Filter

1. Change code

   This method is similar to the pass-through filter from Sub-Task 2, but instead of using three pass-through filters in series, you can use one CropBox filter. Documentation on the CropBox filter and necessary header file can be found here.

   Within perception_node.cpp, find section

```
/* ========================================
 * Fill Code: CROPBOX (OPTIONAL)
 * Instead of three passthrough filters, the cropbox filter can be used
 * The user should choose one or the other method
 * ========================================*/
```

   This CropBox filter should replace your passthrough filters, you may delete or comment the passthrough filters. There is no PCL tutorial to guide you, only the PCL documentation at the link above. The general setup will be the same (set the output, declare instance of filter, set input, set parameters, and filter).

   Set the output cloud:

```
pcl::PointCloud<pcl::PointXYZ> xyz_filtered_cloud;
```

   Declare instance of filter:

```
pcl::CropBox<pcl::PointXYZ> crop;
```

Set input:

```
crop.setInputCloud(cloud_voxel_filtered);
```

Set parameters - looking at documentation, CropBox takes an Eigen Vector4f as inputs for max and min values:

```
Eigen::Vector4f min_point = Eigen::Vector4f(-1.0, -1.0, -1.0, 0);
Eigen::Vector4f max_point = Eigen::Vector4f(1.0, 1.0, 1.0, 0);
crop.setMin(min_point);
crop.setMax(max_point);
```

Filter:

```
crop.filter(xyz_filtered_cloud);
```

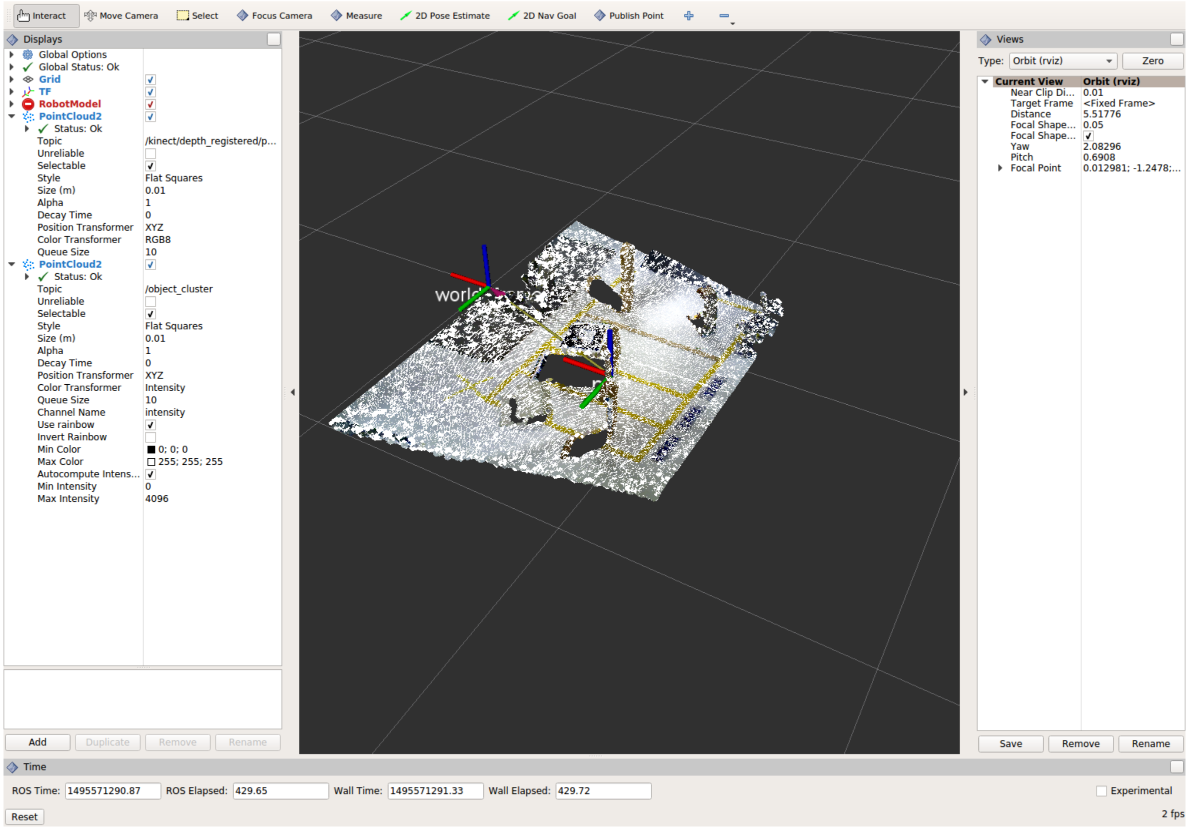
If you delete or comment the passthrough filters and have already written the plane segmentation code, then make sure you update the name of the cloud you are passing into the plane segmentation. Replace zf_cloud with xyz_filtered_cloud:

```
pcl::PointCloud<pcl::PointXYZ>::Ptr cropped_cloud(new pcl::PointCloud
↪<pcl::PointXYZ>(xyz_filtered_cloud));
```

2. Find the `pcl::toROSMsg` call where the `pc2_cloud` is populated. This is the point cloud that is published to RViz display. Replace the current cloud with the new filtered results (`xyz_filtered_cloud`).

3. Compile and run, as in previous steps

   The following image of the CropBox filter in use will closely resemble the Plane Segmentation filter image.



Global Options	
Global Status: Ok	
Grid	☑
TF	☑
RobotModel	☑
PointCloud2	☑
Status: Ok	
Topic	/kinect/depth_registered/p...
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	RGB8
Queue Size	10
PointCloud2	☑
Status: Ok	
Topic	/object_cluster
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	Intensity
Queue Size	10
Channel Name	intensity
Use rainbow	☑
Invert Rainbow	□
Min Color	■ 0; 0; 0
Max Color	□ 255; 255; 255
Autocompute Intens...	☑
Min Intensity	0
Max Intensity	4096

Type: Orbit (rviz)

Current View	Orbit (rviz)
Near Clip Di...	0.01
Target Frame	<Fixed Frame>
Distance	5.51776
Focal Shape...	0.05
Focal Shape...	☑
Yaw	2.08296
Pitch	0.6908
Focal Point	0.012981; -1.2478;...

ROS Time: 1495571290.87 ROS Elapsed: 429.65 Wall Time: 1495571291.33 Wall Elapsed: 429.72 □ Experimental

2 fps

Create a Statistical Outlier Removal

1. Change code

   This method does not necessarily add complexity or information to our end result, but it is often useful. A tutorial can be found here.

   Within perception_node.cpp, find section

```
/* ========================================
 * Fill Code: STATISTICAL OUTLIER REMOVAL (OPTIONAL)
 * ========================================*/
```

   The general setup will be the same (set the output, declare instance of filter, set input, set parameters, and filter).

   Set the output cloud:

```
pcl::PointCloud<pcl::PointXYZ>::Ptr cluster_cloud_ptr= clusters.at(0);
pcl::PointCloud<pcl::PointXYZ>::Ptr sor_cloud_filtered(new pcl::PointCloud
↪<pcl::PointXYZ>);
```

   Declare instance of filter:

```
pcl::StatisticalOutlierRemoval<pcl::PointXYZ> sor;
```

   Set input:

```
sor.setInputCloud (cluster_cloud_ptr);
```

Set parameters - looking at documentation, S.O.R. uses the number of neighbors to inspect and the standard-deviation threshold to use for outlier rejection:

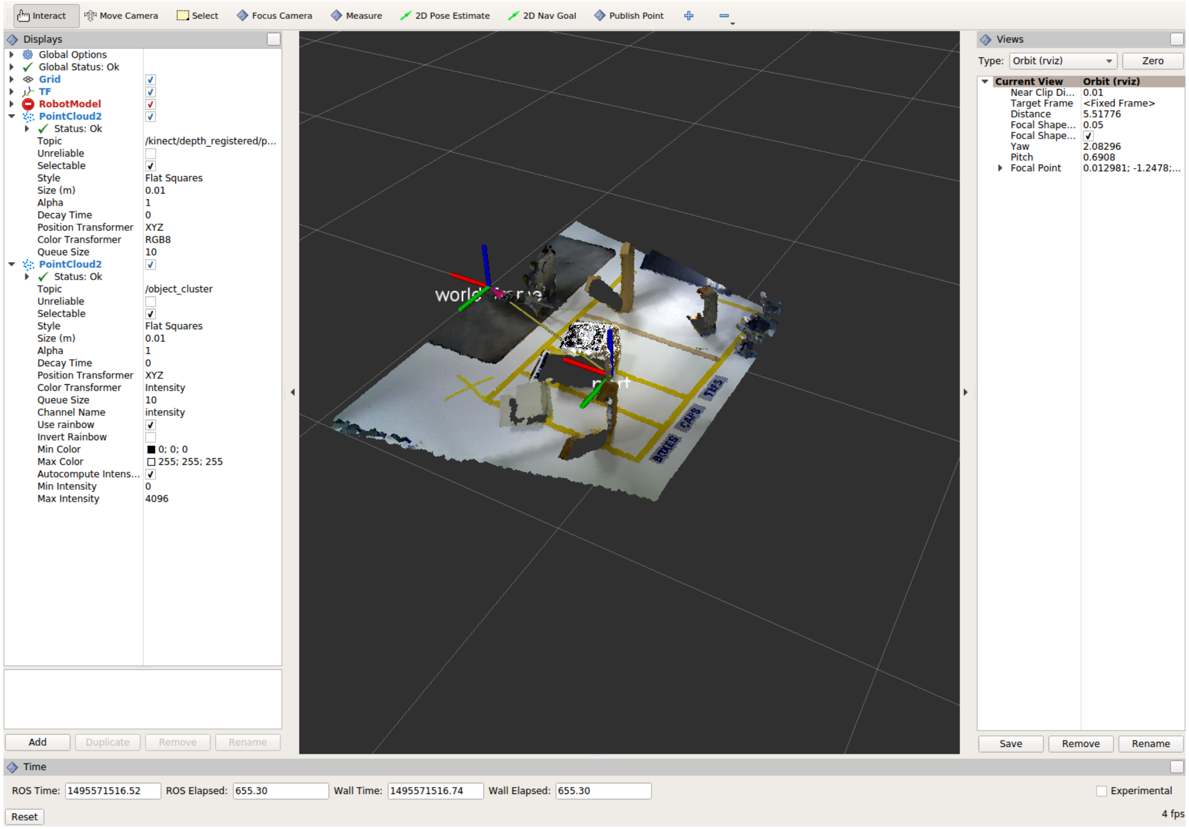
```
sor.setMeanK (50);
sor.setStddevMulThresh (1.0);
```

Filter:

```
sor.filter (*sor_cloud_filtered);
```

2. Find the `pcl::toROSMsg` call where the `pc2_cloud` is populated. Replace the current cloud with the new filtered results (`*sor_cloud_filtered`).

3. Compile and run, as in previous steps



Displays	
Global Options	
Global Status: Ok	
Grid	☑
TF	☑
RobotModel	☑
PointCloud2	☑
Status: Ok	
Topic	/kinect/depth_registered/p...
Unreliable	☐
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	RGB8
Queue Size	10
PointCloud2	☑
Status: Ok	
Topic	/object_cluster
Unreliable	☐
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	Intensity
Queue Size	10
Channel Name	intensity
Use rainbow	☑
Invert Rainbow	☐
Min Color	■ 0; 0; 0
Max Color	□ 255; 255; 255
Autocompute Intens...	☑
Min Intensity	0
Max Intensity	4096

Type: Orbit (rviz)

Current View	Orbit (rviz)
Near Clip Di...	0.01
Target Frame	<Fixed Frame>
Distance	5.51776
Focal Shape...	0.05
Focal Shape...	☑
Yaw	2.08296
Pitch	0.6908
Focal Point	0.012981; -1.2478;...

ROS Time: 1495571516.52 ROS Elapsed: 655.30 Wall Time: 1495571516.74 Wall Elapsed: 655.30 ☐ Experimental

4 fps

Create a Broadcast Transform

While this is not a filter method, it demonstrates how to publish the results of a processing pipeline for other nodes to use. Often, the goal of a processing pipeline is to generate a measurement, location, or some other message for other nodes to use. This sub-task broadcasts a TF transform to define the location of the largest box on the table. This transform could be used by other nodes to identify the position/orientation of the box for grasping.

1. Change/Insert code

Within perception_node.cpp, find section

```
/* ========================================
 * BROADCAST TRANSFORM (OPTIONAL)
 * ========================================*/
```

Follow along with the ROS tutorial. The important modifications to make are within the setting of the position and orientation information (setOrigin(tf::Vector3(msg->x, msg->y, 0.0)), and setRotation(q)). Create a transform:

```
static tf::TransformBroadcaster br;
tf::Transform part_transform;

//Here in the tf::Vector3(x,y,z) x,y, and z should be calculated based on the␣
↪pointcloud filtering results
part_transform.setOrigin( tf::Vector3(sor_cloud_filtered->at(1).x, sor_cloud_
↪filtered->at(1).y, sor_cloud_filtered->at(1).z) );
tf::Quaternion q;
q.setRPY(0, 0, 0);
part_transform.setRotation(q);
```

Remember that when you set the origin or set the rpy, this is where you should use the results from all the filters you've applied. At this point the origin is set arbitrarily to the first point within. Broadcast that transform:

```
br.sendTransform(tf::StampedTransform(part_transform, ros::Time::now(), world_
↪frame, "part"));
```

2. Compile and Run as usual. In this case, add a TF display to Rviz and observe the new "part" transform located at the top of the box.

Create a Polygonal Segmentation

When using sensor data for collision detection, it is sometimes necessary to exclude "known" objects from the scene to avoid interference from these objects. MoveIt! contains methods for masking out a robot's own geometry as a "Self Collision" filtering feature. This example shows how to do something similar using PCL's Polygonal Segmentation filtering.

1. Change code

   This method is similar to the plane segmentation from Sub-Task 3, but instead of segmenting out a plane, you can segment and remove a prism. Documentation on the PCL Polygonal Segmentation can be found here and here. The goal in this sub-task is to remove the points that correspond to a known object (e.g. the box we detected earlier). This particular filter is applied to the entire point cloud (original sensor data), but only after we've already completed the processing steps to identify the position/orientation of the box.

   Within perception_node.cpp, add `#include <tf_conversions/tf_eigen.h>` and find section

```
/* ========================================
 * Fill Code: POLYGONAL SEGMENTATION (OPTIONAL)
 * ========================================*/
```

   Set the input cloud:

```
pcl::PointCloud<pcl::PointXYZ>::Ptr sensor_cloud_ptr (new pcl::PointCloud
↪<pcl::PointXYZ>(cloud));
pcl::PointCloud<pcl::PointXYZ>::Ptr prism_filtered_cloud (new pcl::PointCloud
↪<pcl::PointXYZ>);
pcl::PointCloud<pcl::PointXYZ>::Ptr pick_surface_cloud_ptr(new pcl::PointCloud
↪<pcl::PointXYZ>);
```

   Declare instance of filter:

```
pcl::ExtractPolygonalPrismData<pcl::PointXYZ> prism;
```

Set extraction indices:

```
pcl::ExtractIndices<pcl::PointXYZ> extract_ind;
```

Set input and output:

```
prism.setInputCloud(sensor_cloud_ptr);
pcl::PointIndices::Ptr pt_inliers (new pcl::PointIndices());
```

Set parameters - looking at documentation, ExtractPolygonalPrismData uses a pointcloud defining the polygon vertices as its input.

```
// create prism surface
double box_length=0.25;
double box_width=0.25;
pick_surface_cloud_ptr->width = 5;
pick_surface_cloud_ptr->height = 1;
pick_surface_cloud_ptr->points.resize(5);

pick_surface_cloud_ptr->points[0].x = 0.5f*box_length;
pick_surface_cloud_ptr->points[0].y = 0.5f*box_width;
pick_surface_cloud_ptr->points[0].z = 0;

pick_surface_cloud_ptr->points[1].x = -0.5f*box_length;
pick_surface_cloud_ptr->points[1].y = 0.5f*box_width;
pick_surface_cloud_ptr->points[1].z = 0;

pick_surface_cloud_ptr->points[2].x = -0.5f*box_length;
pick_surface_cloud_ptr->points[2].y = -0.5f*box_width;
pick_surface_cloud_ptr->points[2].z = 0;

pick_surface_cloud_ptr->points[3].x = 0.5f*box_length;
pick_surface_cloud_ptr->points[3].y = -0.5f*box_width;
pick_surface_cloud_ptr->points[3].z = 0;

pick_surface_cloud_ptr->points[4].x = 0.5f*box_length;
pick_surface_cloud_ptr->points[4].y = 0.5f*box_width;
pick_surface_cloud_ptr->points[4].z = 0;

Eigen::Affine3d eigen3d;
tf::transformTFToEigen(part_transform,eigen3d);
pcl::transformPointCloud(*pick_surface_cloud_ptr,*pick_surface_cloud_ptr,
 ↪Eigen::Affine3f(eigen3d));

prism.setInputPlanarHull( pick_surface_cloud_ptr);
prism.setHeightLimits(-10,10);
```

Segment:

```
prism.segment(*pt_inliers);
```

Remember that after you use the segmentation algorithme that you either want to include or exclude the segmented points using an index extraction.

Set input:

```
extract_ind.setInputCloud(sensor_cloud_ptr);
extract_ind.setIndices(pt_inliers);
```

This time, we invert the index extraction, so that we remove points inside the filter and keep points outside the filter.

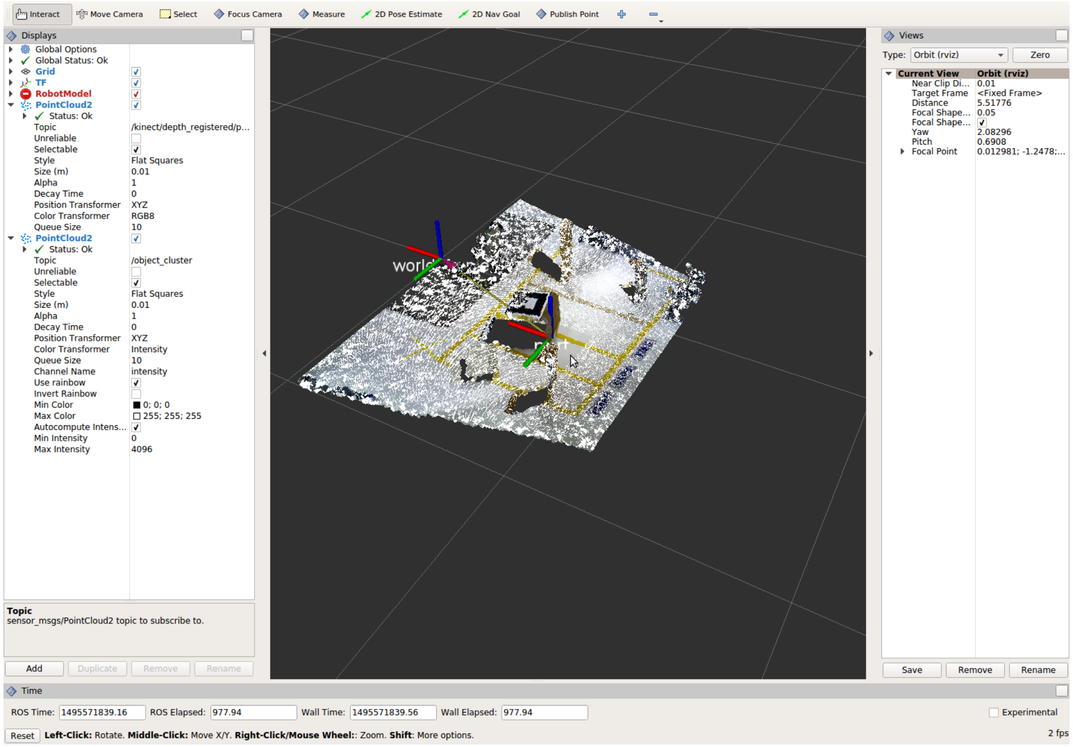
```
extract_ind.setNegative(true);
```

Filter:

```
extract_ind.filter(*prism_filtered_cloud);
```

2. Find the `pcl::toROSMsg` call where the `pc2_cloud` is populated. This is the point cloud that is published to RViz display. Replace the current cloud with the new filtered results (`*prism_filtered_cloud`).

3. Compile and run as before.



Displays

Global Options	
✓ Global Status: Ok	
Grid	☑
TF	☑
RobotModel	☑
PointCloud2	☑
✓ Status: Ok	
Topic	/kinect/depth_registered/p...
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	RGB8
Queue Size	10
PointCloud2	☑
✓ Status: Ok	
Topic	/object_cluster
Unreliable	□
Selectable	☑
Style	Flat Squares
Size (m)	0.01
Alpha	1
Decay Time	0
Position Transformer	XYZ
Color Transformer	Intensity
Queue Size	10
Channel Name	intensity
Use rainbow	☑
Invert Rainbow	□
Min Color	■ 0; 0; 0
Max Color	□ 255; 255; 255
Autocompute Intens...	☑
Min Intensity	0
Max Intensity	4096

Topic
sensor_msgs/PointCloud2 topic to subscribe to.

Views

Type: Orbit (rviz) Zero

Current View	Orbit (rviz)
Near Clip Di...	0.01
Target Frame	<Fixed Frame>
Distance	5.51776
Focal Shape...	0.05
Focal Shape...	☑
Yaw	2.08296
Pitch	0.6908
Focal Point	0.012981; -1.2478;...

Time

ROS Time: 1495571839.16 ROS Elapsed: 977.94 Wall Time: 1495571839.56 Wall Elapsed: 977.94 □ Experimental

Left-Click: Rotate. **Middle-Click:** Move X/Y. **Right-Click/Mouse Wheel:**: Zoom. **Shift**: More options. 2 fps

Note: Notice that the target box has been removed from the point cloud display.

Write a launch file

While this is not a filter method, it is useful when using PCL or other perception methods because of the number of parameters used in the different methods.

1. Change/Insert code

   If you are really awesome and read the Task 1 write-up thoroughly, you will note that it was suggested that you put your parameters in one place.

   Within perception_node.cpp, find section

```
/*
 * SET UP PARAMETERS (COULD TO BE INPUT FROM LAUNCH FILE/TERMINAL)
 */
```

Ideally, as the given parameter examples showed, you would *declare* a parameter of a certain type (std::string frame;), then assign a value for that parameter (frame=”some_name”;). Below is an example of some of the parameters you could have set.

```
world_frame="kinect_link";
camera_frame="kinect_link";
cloud_topic="kinect/depth_registered/points";
voxel_leaf_size=0.002f;
x_filter_min=-2.5;
x_filter_max=2.5;
y_filter_min=-2.5;
y_filter_max=2.5;
z_filter_min=-2.5;
z_filter_max=1.0;
plane_max_iter=50;
plane_dist_thresh=0.05;
cluster_tol=0.01;
cluster_min_size=100;
cluster_max_size=50000;
```

If you took this step, you will be in great shape to convert what you have into something that can be input from a launch file, or yaml file. You could use the “getParam” method as described in this tutorial. But a better choice might be to use the param method, which returns a default value if the parameter is not found on the parameter server. Get params from ros parameter server/launch file, replacing your previous hardcoded values (but leave the variable declarations!)

```
cloud_topic = priv_nh_.param<std::string>("cloud_topic", "kinect/depth_registered/points");
world_frame = priv_nh_.param<std::string>("world_frame", "kinect_link");
camera_frame = priv_nh_.param<std::string>("camera_frame", "kinect_link");
voxel_leaf_size = param<float>("voxel_leaf_size", 0.002);
x_filter_min = priv_nh_.param<float>("x_filter_min", -2.5);
x_filter_max = priv_nh_.param<float>("x_filter_max",  2.5);
y_filter_min = priv_nh_.param<float>("y_filter_min", -2.5);
y_filter_max = priv_nh_.param<float>("y_filter_max",  2.5);
z_filter_min = priv_nh_.param<float>("z_filter_min", -2.5);
z_filter_max = priv_nh_.param<float>("z_filter_max",  2.5);
plane_max_iter = priv_nh_.param<int>("plane_max_iterations", 50);
plane_dist_thresh = priv_nh_.param<float>("plane_distance_threshold", 0.05);
cluster_tol = priv_nh_.param<float>("cluster_tolerance", 0.01);
cluster_min_size = priv_nh_.param<int>("cluster_min_size", 100);
cluster_max_size = priv_nh_.param<int>("cluster_max_size", 50000);
```

2. Write launch file.

   Using gedit or some other text editor, make a new file (‘’lesson_perception/launch/processing_node.launch’‘) and put the following in it.

```
<launch>
  <node name="processing_node" pkg="lesson_perception" type="perception_node" output="screen">
    <rosparam>
      cloud_topic: "kinect/depth_registered/points"
```

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```
      world_frame: "world_frame"
      camera_frame: "kinect_link"
      voxel_leaf_size: 0.001 <!-- mm -->
      x_filter_min: -2.5 <!-- m -->
      x_filter_max: 2.5 <!-- m -->
      y_filter_min: -2.5 <!-- m -->
      y_filter_max: 2.5 <!-- m -->
      z_filter_min: -2.5 <!-- m -->
      z_filter_max: 2.5 <!-- m -->
      plane_max_iterations: 100
      plane_distance_threshold: 0.03
      cluster_tolerance: 0.01
      cluster_min_size: 250
      cluster_max_size: 500000
    </rosparam>
  </node>
</launch>
```

3. Compile as usual…

But this time, run the new launch file that was created instead of using rosrun to start the processing node.

The results should look similar to previous runs. However, now you can edit these configuration parameters much easier! No recompile step is required; just edit the launch-file values and relaunch the node. In a real application, you could take this approach one step further and implement dynamic_reconfigure support in your node. That would allow you to see the results of parameter changes in RViz in real-time!

> When you are satisfied with the results, go to each terminal and *CTRL-C*.
>
> We're all done! So it's best to make sure everything is wrapped up and closed.

4.1.3 Introduction to STOMP

Motivation

- Learn how to plan with STOMP through !MoveIt!.

Information and Resources

- STOMP for MoveIt!
- Plugins for MoveIt!

Objectives

- Integrate STOMP into !MoveIt! by changing and adding files to a **moveit_config** package.
- We'll then generate STOMP plans from the Rviz Motion Planning Plugin

Setup

- Create a workspace

```
mkdir --parent ~/catkin_ws/src
cd ~/catkin_ws
catkin init
catkin build
source devel/setup.bash
```

- Copy over existing exercise

```
cd ~/catkin_ws/src
cp -r ~/industrial_training/exercises/4.1 .
```

- Clone industrial_moveit repository into your workspace

```
cd ~/catkin_ws/src
git clone https://github.com/ros-industrial/industrial_moveit.git
git checkout kinetic-devel
```

- Install Missing Dependencies

```
cd ~/catkin_ws/src/4.1
rosinstall . .rosinstall
catkin build
```

- Create a **moveit_config** package created with the MoveIt! Setup Assistant

Add STOMP

1. Create a "*stomp_planning_pipeline.launch.xml*" file in the **launch** directory of your **moveit_config** package. The file should contain the following:

```
<launch>

  <!-- Stomp Plugin for MoveIt! -->
  <arg name="planning_plugin" value="stomp_moveit/StompPlannerManager" />

  <!-- The request adapters (plugins) ORDER MATTERS -->
  <arg name="planning_adapters" value="default_planner_request_adapters/
↪FixWorkspaceBounds
                                       default_planner_request_adapters/
↪FixStartStateBounds
                                       default_planner_request_adapters/
↪FixStartStateCollision
                                       default_planner_request_adapters/
↪FixStartStatePathConstraints" />

  <arg name="start_state_max_bounds_error" value="0.1" />

  <param name="planning_plugin" value="$(arg planning_plugin)" />
  <param name="request_adapters" value="$(arg planning_adapters)" />
  <param name="start_state_max_bounds_error" value="$(arg start_state_max_bounds_
↪error)" />
  <rosparam command="load" file="$(find myworkcell_moveit_config)/config/stomp_
↪planning.yaml"/>

</launch>
```

!!! Take notice of the **stomp_planning.yaml** configuration file, this file must exists in moveit_config package.

1. Create the “*stomp_planning.yaml*” configuration file

   This file contains the parameters required by STOMP. The parameters are specific to each ‘’planning group” defined in the SRDF file. So if there are three planning groups “manipulator”, “manipulator_tool”, and “manipulator_rail” then the configuration file defines a specific set of parameters for each planning group:

```
stomp/manipulator_rail:
  group_name: manipulator_rail
  optimization:
    num_timesteps: 60
    num_iterations: 40
    num_iterations_after_valid: 0
    num_rollouts: 30
    max_rollouts: 30
    initialization_method: 1 #[1 : LINEAR_INTERPOLATION, 2 : CUBIC_POLYNOMIAL, 3␣
↪: MININUM_CONTROL_COST
    control_cost_weight: 0.0
  task:
    noise_generator:
      - class: stomp_moveit/NormalDistributionSampling
        stddev: [0.05, 0.8, 1.0, 0.8, 0.4, 0.4, 0.4]
    cost_functions:
      - class: stomp_moveit/CollisionCheck
        collision_penalty: 1.0
        cost_weight: 1.0
        kernel_window_percentage: 0.2
        longest_valid_joint_move: 0.05
    noisy_filters:
      - class: stomp_moveit/JointLimits
        lock_start: True
        lock_goal: True
      - class: stomp_moveit/MultiTrajectoryVisualization
        line_width: 0.02
        rgb: [255, 255, 0]
        marker_array_topic: stomp_trajectories
        marker_namespace: noisy
    update_filters:
      - class: stomp_moveit/PolynomialSmoother
        poly_order: 6
      - class: stomp_moveit/TrajectoryVisualization
        line_width: 0.05
        rgb: [0, 191, 255]
        error_rgb: [255, 0, 0]
        publish_intermediate: True
        marker_topic: stomp_trajectory
        marker_namespace: optimized
stomp/manipulator:
  group_name: manipulator
  optimization:
    num_timesteps: 40
    num_iterations: 40
    num_iterations_after_valid: 0
    num_rollouts: 10
    max_rollouts: 10
    initialization_method: 1 #[1 : LINEAR_INTERPOLATION, 2 : CUBIC_POLYNOMIAL, 3␣
↪: MININUM_CONTROL_COST
    control_cost_weight: 0.0
  task:
```

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```
    noise_generator:
      - class: stomp_moveit/NormalDistributionSampling
        stddev: [0.05, 0.4, 1.2, 0.4, 0.4, 0.1]
    cost_functions:
      - class: stomp_moveit/CollisionCheck
        kernel_window_percentage: 0.2
        collision_penalty: 1.0
        cost_weight: 1.0
        longest_valid_joint_move: 0.05
    noisy_filters:
      - class: stomp_moveit/JointLimits
        lock_start: True
        lock_goal: True
      - class: stomp_moveit/MultiTrajectoryVisualization
        line_width: 0.04
        rgb: [255, 255, 0]
        marker_array_topic: stomp_trajectories
        marker_namespace: noisy
    update_filters:
      - class: stomp_moveit/PolynomialSmoother
        poly_order: 5
      - class: stomp_moveit/TrajectoryVisualization
        line_width: 0.02
        rgb: [0, 191, 255]
        error_rgb: [255, 0, 0]
        publish_intermediate: True
        marker_topic: stomp_trajectory
        marker_namespace: optimized
```

!!! *Save this file in the* **config** *directory of the moveit_config package*

2. Modify the **move_group.launch** file: Open the **move_group.launch** in the launch directory and change the `pipeline` parameter value to `stomp` as shown below:

```
    .
    .
    .
<!-- move_group settings -->
<arg name="allow_trajectory_execution" default="true"/>
<arg name="fake_execution" default="false"/>
<arg name="max_safe_path_cost" default="1"/>
<arg name="jiggle_fraction" default="0.05" />
<arg name="publish_monitored_planning_scene" default="true"/>

<!-- Planning Functionality -->
<include ns="move_group" file="$(find myworkcell_moveit_config)/launch/planning_
↪pipeline.launch.xml">
  <arg name="pipeline" value="stomp" />
</include>


    .
    .
    .
```

Run MoveIt! with STOMP

1. In a sourced terminal, run the **demo.launch** file:

```
roslaunch myworkcell_moveit_config demo.launch
```

2. In Rviz, select robot start and goal positions and plan:

- In the “Motion Planning” panel, go to the “Planning” tab.
- Click the “Select Start State” drop-down, select “allZeros” and click “Update”
- Click the “Select Goal State” drop-down, select “home” and click “Update”
- Click the “Plan” button and watch the arm move past obstacles to reach the goal position. The blue line shows the tool path.

Explore STOMP

1. In Rviz, select other “Start” and “Goal” positions and then hit plan and see the robot move.
2. Display the *Noisy Trajectories* by clicking on the “Marker Array” checkbox in the “Displays” Rviz panel. Hit the “Plan” button again and you’ll see the noisy trajectory markers as yellow lines.

   Note: STOMP explores the workspace by generating a number of noisy trajectories as a result of applying noise onto the current trajectory. The degree of noise applied can be be changed by adjusting the “stddev” parameters in the “*stomp_config.yaml*” file. Larger “stddev” values correspond to larger motions of the joints.

Configure STOMP

We’ll now change the parameters in the **stomp_config.yaml** and see what effect those changes have on the planning.

1. Ctrl-C in the terminal where you ran the **demo.launch** file earlier to stop the **move_group** planning node.
2. Locate and open up the **stomp_config.yaml** with your preferred editor.
3. Under the “manipulator_rail” group, take notice of the values assigned to “stddev” parameter. Each value is the amplitude of the noise applied to the joint at that position in the array. For instance, the leftmost value in the array will be the value used to set the noise of the first joint “rail_to_base”; which moves the rail along the x direction. Since the “rail_to_base” is a prismatic joint then its units are in meters; for revolute joints the units are radians.
4. Change the “stddev” values (preferably one entry at a time), save the file and rerun the “demo.launch” file in the terminal.
5. Go back to the Rviz window and select arbitrary “Start” and “Goal” positions to see what effect your changes have had on the planning performance.

More info on the STOMP parameters

The STOMP wiki explains these parameter in more detail.

Code can be found at industrial_training repository in gh_pages folder. Use kinetic branch.

4.1.4 Building a Simple PCL Interface for Python

In this exercise, we will fill in the appropriate pieces of code to build a perception pipeline. The end goal will be to create point cloud filtering operations to demonstrate functionality between ROS and python.

Prepare New Workspace:

We will create a new catkin workspace, since this exercise does not overlap with the previous PlanNScan exercises.

1. Disable automatic sourcing of your previous catkin workspace:

   (a) `gedit ~/.bashrc`

   (b) comment out # the last line, sourcing your `~/catkin_ws/devel/setup.bash`

   ```
   source /opt/ros/kinetic/setup.bash
   ```

2. Copy the template workspace layout and files:

   ```
   cp -r ~/industrial_training/exercises/python-pcl_ws ~
   cd ~/python-pcl_ws/
   ```

3. Initialize and Build this new workspace

   ```
   catkin init
   catkin build
   ```

4. Source the workspace

   ```
   source ~/python-pcl_ws/devel/setup.bash
   ```

5. Download the PointCloud file and place the file in your home directory (~).

6. Import the new workspace into your QTCreator IDE: In QTCreator: File -> New Project -> Import -> Import ROS Workspace -> ~/python-pcl_ws

Intro (Review Existing Code)

Most of the infrastructure for a ros node has already been completed for you; the focus of this exercise is the perception algorithms/pipleline. The *CMakelists.txt* and *package.xml* are complete and a source file has been provided. You could build the source as is, but you would get errors. At this time we will explore the source code that has been provided - browse the provided *py_perception_node.cpp* file. This tutorial has been modified from training Exercise 5.1 Building a Perception Pipeline and as such the C++ code has already been set up. If something does not make sense, revisit that exercise. Open up the preception_node.cpp file and look over the filtering functions.

Create a Python Package

Now that we have converted several filters to C++ functions, we are ready to call it from a Python node. If you have not done so already, install PyCharm, community edition. This IDE has the necessary parser for editing, without it, you will not be able to review any syntax issues in Qt.

1. In the terminal, change the directory to your src folder. Create a new package inside your python-pcl_ws:

   ```
   cd ~/python-pcl_ws/src/
   catkin_create_pkg filter_call rospy roscpp perception_msgs
   ```

2. Check that your package was created:

```
ls
```

We will not be using 'perception_msgs' as we will not be creating custom messages in this course. It is included for further student knowledge. If you wish for a more in depth explanation including how to implement customer messages, here is a good MIT resource on the steps taken.

1. Open *CMakeLists.txt*. You can open the file in Pycharm or Qt (or you can use nano, emacs, vim, or sublime). Uncomment line 23, and save.

```
catkin_python_setup()
```

Creating setup.py

The *setup.py* file makes your python module available to the entire workspace and subsequent packages. By default, this isn't created by the *catkin_create_pkg* command.

1. In your terminal type

```
gedit filter_call/setup.py
```

2. Copy and paste the following to the *setup.py* file (to paste into a terminal, Ctrl+Shift+V)

```
## ! DO NOT MANUALLY INVOKE THIS setup.py, USE CATKIN INSTEAD
from distutils.core import setup
from catkin_pkg.python_setup import generate_distutils_setup
# fetch values from package.xml
setup_args = generate_distutils_setup(
packages=[''],
package_dir={'': 'include'},
)
setup(**setup_args)
```

Change `packages = [ . . . ]`, to your list of strings of the name of the folders inside your *include* folder. By convention, this will be the same name as the package, or `filter_call` . The configures `filter_call/include/filter_call` as a python module available to the whole workspace.

3. Save and close the file.

   In order for this folder to be accessed by any other python script, the `\__init__.py` file must exist.

4. Create one in the terminal by typing:

```
touch filter_call/include/filter_call/__init__.py
```

Publishing the Point Cloud

As iterated before, we are creating a ROS C++ node to filter the point cloud when requested by a Python node running a service request for each filtering operation, resulting in a new, aggregated point cloud. Let's start with modifying our C++ code to publish in a manner supportive to python. Remember, the C++ code is already done so all you need to do is write your python script and view the results in rviz.

Implement a Voxel Filter

1. In *py_perception_node.cpp*, uncomment the boolean function called `filterCallBack` (just above‘‘main‘‘) which performs in the service. This will be the service used by the python client to run subsequent filtering operations.

```cpp
bool filterCallback(lesson_perception::FilterCloud::Request& request,
                    lesson_perception::FilterCloud::Response& response)
{
  pcl::PointCloud<pcl::PointXYZ>::Ptr cloud (new pcl::PointCloud<pcl::PointXYZ>);
  pcl::PointCloud<pcl::PointXYZ>::Ptr filtered_cloud (new pcl::PointCloud
↪<pcl::PointXYZ>);

  if (request.pcdfilename.empty())
  {
    pcl::fromROSMsg(request.input_cloud, *cloud);
    ROS_INFO_STREAM("cloud size: " << cloud->size());
  }
  else
  {
    pcl::io::loadPCDFile(request.pcdfilename, *cloud);
  }

  if (cloud->empty())
  {
    ROS_ERROR("input cloud empty");
    response.success = false;
    return false;
  }

  switch (request.operation)
  {

    case lesson_perception::FilterCloud::Request::VOXELGRID :
    {
      filtered_cloud = voxelGrid(cloud, 0.01);
      break;
    }
    default :
    {
      ROS_ERROR("No valid request found");
      return false;
    }

   }

/*
 * SETUP RESPONSE
 */
  pcl::toROSMsg(*filtered_cloud, response.output_cloud);
  response.output_cloud.header=request.input_cloud.header;
  response.output_cloud.header.frame_id="kinect_link";
  response.success = true;
  return true;
}
```

2. Within `main`, uncomment line 240. Save and build.

```
priv_nh_.param<double>("leaf_size", leaf_size_, 0.0f);
```

3. Now that we have the framework for the filtering, open your terminal. Make sure you are in the filter_call directory. Create a *scripts* folder.

```
mkdir scripts
```

4. If Pycharm is still open, save and close. We need to open Pycharm from the terminal to make sure it is sourced correctly for C++ node to be heard. To open, source to the pycharm install directory:

```
cd ~/pycharm-community-2018.1.3/bin
./pycharm.sh
```

   Once open, locate and right click on the folder *scripts* and create a new python file. Call it *filter_call.py*

5. Copy and paste the following code at the top of *filter_call.py* to import necessary libraries:

```
#!/usr/bin/env python

import rospy
import lesson_perception.srv
from sensor_msgs.msg import PointCloud2
```

6. We will create an `if` statement to run our python node when this file is executed. Initalize as follows:

```
if __name__ == '__main__':
    try:

    except Exception as e:
        print("Service call failed: %s" % str(e))
```

7. Include a `rospy.spin()` in the `try` block to look like the following:

```
if __name__ == '__main__':
    try:
        rospy.spin()
    except Exception as e:
        print("Service call failed: %s" % str(e))
```

8. Copy and paste the following inside the `try` block:

```
# =======================
# VOXEL GRID FILTER
# =======================

srvp = rospy.ServiceProxy('filter_cloud', lesson_perception.srv.FilterCloud)
req = lesson_perception.srv.FilterCloudRequest()
req.pcdfilename = rospy.get_param('~pcdfilename', '')
req.operation = lesson_perception.srv.FilterCloudRequest.VOXELGRID
# FROM THE SERVICE, ASSIGN POINTS
req.input_cloud = PointCloud2()

# ERROR HANDLING
if req.pcdfilename == '':
    raise Exception('No file parameter found')

# PACKAGE THE FILTERED POINTCLOUD2 TO BE PUBLISHED
```

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```
res_voxel = srvp(req)
print('response received')
if not res_voxel.success:
    raise Exception('Unsuccessful voxel grid filter operation')

# PUBLISH VOXEL FILTERED POINTCLOUD2
pub = rospy.Publisher('/perception_voxelGrid', PointCloud2, queue_size=1,␣
↪latch=True)
pub.publish(res_voxel.output_cloud)
print("published: voxel grid filter response")
```

9. Paste the following lines above the `try` block (still within the `if` statement) to initialize the python node and wait for the C++ node's service.

```
rospy.init_node('filter_cloud', anonymous=True)
rospy.wait_for_service('filter_cloud')
```

10. We need to make the python file executable. In your terminal:

```
chmod +x filter_call/scripts/filter_call.py
```

Viewing Results

1. In your terminal, run

```
roscore
```

2. Source a new terminal and run the C++ filter service node

```
rosrun lesson_perception py_perception_node
```

3. Source a new terminal and run the python service caller node. Note your file path may be different.

```
rosrun filter_call filter_call.py _pcdfilename:="/home/ros-industrial/catkin_ws/
↪table.pcd"
```

4. Source a new terminal and run rviz

```
rosrun rviz rviz
```

5. Add a new PointCloud2 in rviz

6. In global options, change the fixed frame to kinect_link, and in the PointCloud 2, select your topic to be '/perception_voxelGrid'

Note: You may need to uncheck and recheck the PointCloud2.

Implement Pass-Through Filters

1. In *py_perception_node.cpp* in the `lesson_perception` package, within `main`, uncomment these two lines as well as their intilizations on lines 28 and 29.

```
priv_nh_.param<double>("passThrough_max", passThrough_max_, 1.0f);
priv_nh_.param<double>("passThrough_min", passThrough_min_, -1.0f);
```

2. Update the switch to look as shown below:

```
switch (request.operation)
{

  case lesson_perception::FilterCloud::Request::VOXELGRID :
  {
    filtered_cloud = voxelGrid(cloud, 0.01);
    break;
  }
  case lesson_perception::FilterCloud::Request::PASSTHROUGH :
  {
    filtered_cloud = passThrough(cloud);
    break;
  }
  default :
  {
    ROS_ERROR("No valid request found");
    return false;
  }

}
```

3. Save and build

   Edit the Python Code

4. Open the python node and copy paste the following code after the voxel grid, before the `rospy.spin()`. Keep care to maintain indents:

```
# =======================
# PASSTHROUGH FILTER
# =======================

srvp = rospy.ServiceProxy('filter_cloud', lesson_perception.srv.FilterCloud)
req = lesson_perception.srv.FilterCloudRequest()
req.pcdfilename = ''
req.operation = lesson_perception.srv.FilterCloudRequest.PASSTHROUGH
# FROM THE SERVICE, ASSIGN POINTS
req.input_cloud = res_voxel.output_cloud

# PACKAGE THE FILTERED POINTCLOUD2 TO BE PUBLISHED
res_pass = srvp(req)
print('response received')
if not res_voxel.success:
    raise Exception('Unsuccessful pass through filter operation')

# PUBLISH PASSTHROUGH FILTERED POINTCLOUD2
pub = rospy.Publisher('/perception_passThrough', PointCloud2, queue_size=1,␣
↪latch=True)
pub.publish(res_pass.output_cloud)
print("published: pass through filter response")
```

5. Save and run from the terminal, repeating steps outlined for the voxel filter.

   Within Rviz, compare PointCloud2 displays based on the `/kinect/depth_registered/points` (original camera data) and perception_passThrough (latest processing step) topics. Part of the original point cloud has been "clipped" out of the latest processing result.

When you are satisfied with the pass-through filter results, press Ctrl+C to kill the node. There is no need to close or kill the other terminals/nodes.

Plane Segmentation

This method is one of the most useful for any application where the object is on a flat surface. In order to isolate the objects on a table, you perform a plane fit to the points, which finds the points which comprise the table, and then subtract those points so that you are left with only points corresponding to the object(s) above the table. This is the most complicated PCL method we will be using and it is actually a combination of two: the RANSAC segmentation model, and the extract indices tool. An in depth example can be found on the PCL Plane Model Segmentation Tutorial; otherwise you can copy the below code snippet.

1. In py_perception_node.cpp, in main, uncomment the code below as well as their respective intilization parameters.

```
priv_nh_.param<double>("maxIterations", maxIterations_, 200.0f);
priv_nh_.param<double>("distThreshold", distThreshold_, 0.01f);
```

2. Update the switch statement in filterCallback to look as shown below:

```
switch (request.operation)
{

  case lesson_perception::FilterCloud::Request::VOXELGRID :
  {
    filtered_cloud = voxelGrid(cloud, 0.01);
    break;
  }
  case lesson_perception::FilterCloud::Request::PASSTHROUGH :
  {
    filtered_cloud = passThrough(cloud);
    break;
  }
  case lesson_perception::FilterCloud::Request::PLANESEGMENTATION :
  {
    filtered_cloud = planeSegmentation(cloud);
    break;
  }
  default :
  {
    ROS_ERROR("No valid request found");
    return false;
  }

}
```

3. Save and build

Edit the Python Code

4. Copy paste the following code in filter_call.py, after the passthrough filter section. Keep care to maintain indents:

```
# =======================
# PLANE SEGMENTATION
```

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```
# =======================

srvp = rospy.ServiceProxy('filter_cloud', lesson_perception.srv.FilterCloud)
req = lesson_perception.srv.FilterCloudRequest()
req.pcdfilename = ''
req.operation = lesson_perception.srv.FilterCloudRequest.PLANESEGMENTATION
# FROM THE SERVICE, ASSIGN POINTS
req.input_cloud = res_pass.output_cloud

# PACKAGE THE FILTERED POINTCLOUD2 TO BE PUBLISHED
res_seg = srvp(req)
print('response received')
if not res_voxel.success:
    raise Exception('Unsuccessful plane segmentation operation')

# PUBLISH PLANESEGMENTATION FILTERED POINTCLOUD2
pub = rospy.Publisher('/perception_planeSegmentation', PointCloud2, queue_size=1,␣
↪latch=True)
pub.publish(res_seg.output_cloud)
print("published: plane segmentation filter response")
```

5. Save and run from the terminal, repeating steps outlined for the voxel filter.

   Within Rviz, compare PointCloud2 displays based on the `/kinect/depth_registered/points` (original camera data) and `perception_planeSegmentation` (latest processing step) topics. Only points lying above the table plane remain in the latest processing result.

   (a) When you are done viewing the results you can go back and change the ”setMaxIterations” and “setDistanceThreshold” parameter values to control how tightly the plane-fit classifies data as inliers/outliers, and view the results again. Try using values of `maxIterations=100` and `distThreshold=0.010`

   (b) When you are satisfied with the plane segmentation results, use Ctrl+C to kill the node. There is no need to close or kill the other terminals/nodes.

Euclidian Cluster Extraction

This method is useful for any application where there are multiple objects. This is also a complicated PCL method. An in depth example can be found on the PCL Euclidean Cluster Extration Tutorial.

1. In py_perception_node.cpp `main` uncomment the following plus their intilization parameters.

```
priv_nh_.param<double>("clustTol", clustTol_, 0.01f);
priv_nh_.param<double>("clustMax", clustMax_, 10000.0);
priv_nh_.param<double>("clustMin", clustMin_, 300.0f);
```

2. Update the switch statement in `filterCallback` to look as shown below:

```
switch (request.operation)
{

  case lesson_perception::FilterCloud::Request::VOXELGRID :
  {
    filtered_cloud = voxelGrid(cloud, 0.01);
    break;
  }
  case lesson_perception::FilterCloud::Request::PASSTHROUGH :
```

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```
  {
    filtered_cloud = passThrough(cloud);
    break;
  }
  case lesson_perception::FilterCloud::Request::PLANESEGMENTATION :
  {
    filtered_cloud = planeSegmentation(cloud);
    break;
  }
  case lesson_perception::FilterCloud::Request::CLUSTEREXTRACTION :
  {
    std::vector<pcl::PointCloud<pcl::PointXYZ>::Ptr> temp␣
↪=clusterExtraction(cloud);
    if (temp.size()>0)
    {
      filtered_cloud = temp[0];
    }
    break;
  }
  default :
  {
    ROS_ERROR("No valid request found");
    return false;
  }

}
```

3. Save and build

   Edit the Python Code

4. Copy paste the following code in filter_call.py after the plane segmentation section. Keep care to maintain indents:

```
# =======================
# CLUSTER EXTRACTION
# =======================

srvp = rospy.ServiceProxy('filter_cloud', lesson_perception.srv.FilterCloud)
req = lesson_perception.srv.FilterCloudRequest()
req.pcdfilename = ''
req.operation = lesson_perception.srv.FilterCloudRequest.CLUSTEREXTRACTION
# FROM THE SERVICE, ASSIGN POINTS
req.input_cloud = res_seg.output_cloud

# PACKAGE THE FILTERED POINTCLOUD2 TO BE PUBLISHED
res_cluster = srvp(req)
print('response received')
if not res_voxel.success:
    raise Exception('Unsuccessful cluster extraction operation')

# PUBLISH CLUSTEREXTRACTION FILTERED POINTCLOUD2
pub = rospy.Publisher('/perception_clusterExtraction', PointCloud2, queue_size=1,␣
↪latch=True)
pub.publish(res_cluster.output_cloud)
print("published: cluster extraction filter response")
```

5. Save and run from the terminal, repeating steps outlined for the voxel filter.

(a) When you are satisfied with the cluster extraction results, use Ctrl+C to kill the node. If you are done experimenting with this tutorial, you can kill the nodes running in the other terminals.

Future Study

The student is encouraged to convert Exercise 5.1 into callable functions and further refine the filtering operations.

Furthermore, for simplicity, the python code was repeated for each filtering instance. The student is encouraged to create a loop to handle the publishing instead of repeating large chunks of code. The student can also leverage the full functionality of the parameter handling instead of just using defaults, can set those from python. There are several more filtering operations not outlined here, if the student wants practice creating those function calls.

4.1.5 OpenCV Image Processing (Python)

In this exercise, we will gain familiarity with both OpenCV and Python, through a simple 2D image-processing application.

Motivation

OpenCV is a mature, stable library for 2D image processing, used in a wide variety of applications. Much of ROS makes use of 3D sensors and point-cloud data, but there are still many applications that use traditional 2D cameras and image processing.

This tutorial uses python to build the image-processing pipeline. Python is a good choice for this application, due to its ease of rapid prototyping and existing bindings to the OpenCV library.

Further Information and Resources

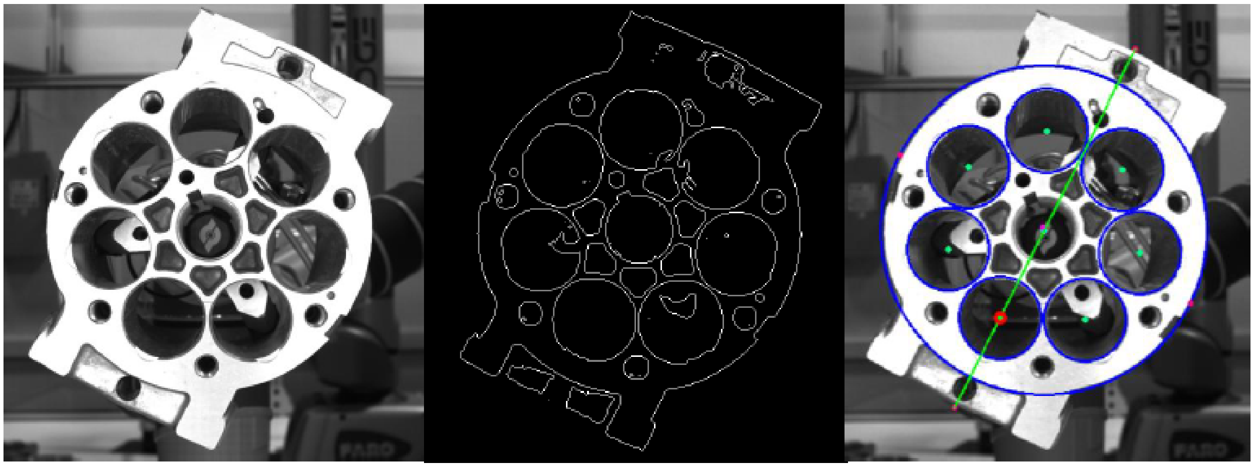
- OpenCV Website
- OpenCV API
- OpenCV Python Tutorials
- ROS cv_bridge package (Python)
- Writing a Publisher and Subscriber (Python)
- sensor_msgs/Image

Problem Statement

In this exercise, you will create a new node to determine the angular pose of a pump housing using the OpenCV image processing library. The pump's orientation is computed using a series of processing steps to extract and compare geometry features:

1. Resize the image (to speed up processing)
2. Threshold the image (convert to black & white)
3. Locate the pump's outer housing (circle-finding)
4. Locate the piston sleeve locations (blob detection)
5. Estimate primary axis using bounding box

6. Determine orientation using piston sleeve locations
7. Calculate the axis orientation relative to a reference (horizontal) axis



Implementation

Create package

This exercise uses a single package that can be placed in any catkin workspace. The examples below will use the ~/catkin_ws workspace from earlier exercises.

1. Create a new detect_pump package to contain the new python nodes we'll be making:

```
cd ~/catkin_ws/src
catkin create pkg detect_pump --catkin-deps rospy cv_bridge
```

   - all ROS packages depend on rospy
   - we'll use cv_bridge to convert between ROS's standard Image message and OpenCV's Image object
   - cv_bridge also automatically brings in dependencies on the relevant OpenCV modules

2. Create a python module for this package:

```
cd detect_pump
mkdir nodes
```

   - For a simple package such as this, the Python Style Guide recommends this simplified package structure.
   - More complex packages (e.g. with exportable modules, msg/srv defintions, etc.) should us a more complex package structure, with an __init__.py and setup.py.
     - reference Installing Python Scripts
     - reference Handling setup.py

Create an Image Publisher

The first node will read in an image from a file and publish it as a ROS Image message on the image topic.

- Note: ROS already contains an image_publisher package/node that performs this function, but we will duplicate it here to learn about ROS Publishers in Python.

1. Create a new python script for our image-publisher node (`nodes/image_pub.py`). Fill in the following template for a skeleton ROS python node:

   ```
   #!/usr/bin/env python
   import rospy

   def start_node():
       rospy.init_node('image_pub')
       rospy.loginfo('image_pub node started')

   if __name__ == '__main__':
       try:
           start_node()
       except rospy.ROSInterruptException:
           pass
   ```

2. Allow execution of the new script file:

   ```
   chmod u+x nodes/image_pub.py
   ```

3. Test run the image publisher:

   ```
   roscore
   rosrun detect_pump image_pump.py
   ```

   - You should see the "node started" message

4. Read the image file to publish, using the filename provided on the command line

   (a) Import the `sys` and `cv2` (OpenCV) modules:

   ```
   import sys
   import cv2
   ```

   (b) Pass the command-line argument into the `start_node` function:

   ```
   def start_node(filename):
   ...
   start_node( rospy.myargv(argv=sys.argv)[1] )
   ```

   - Note the use of `rospy.myargv()` to strip out any ROS-specific command-line arguments.

   (c) In the `start_node` function, call the OpenCV imread function to read the image. Then use imshow to display it:

   ```
   img = cv2.imread(filename)
   cv2.imshow("image", img)
   cv2.waitKey(2000)
   ```

   (d) Run the node, with the specified image file:

   ```
   rosrun detect_pump image_pub.py ~/industrial_training/exercises/5.4/pump.jpg
   ```

   - You should see the image displayed
   - Comment out the `imshow`/`waitKey` lines, as we won't need those any more
   - Note that you don't need to run `catkin build` after editing the python file, since no compile step is needed.

5. Convert the image from OpenCV Image object to ROS Image message:

   (a) Import the CvBridge and Image (ROS message) modules:

   ```
   from cv_bridge import CvBridge
   from sensor_msgs.msg import Image
   ```

   (b) Add a call to the CvBridge cv2_to_imgmsg method:

   ```
   bridge = CvBridge()
   imgMsg = bridge.cv2_to_imgmsg(img, "bgr8")
   ```

6. Create a ROS publisher to continually publish the Image message on the image topic. Use a loop with a 1 Hz throttle to publish the message.

```
pub = rospy.Publisher('image', Image, queue_size=10)
while not rospy.is_shutdown():
    pub.publish(imgMsg)
    rospy.Rate(1.0).sleep()  # 1 Hz
```

7. Run the node and inspect the newly-published image message

   (a) Run the node (as before):

   ```
   rosrun detect_pump image_pub.py ~/industrial_training/exercises/5.4/pump.jpg
   ```

   (b) Inspect the message topic using command-line tools:

   ```
   rostopic list
   rostopic hz /image
   rosnode info /image_pub
   ```

   (c) Inspect the published image using the standalone image_view node

   ```
   rosrun image_view image_view
   ```

Create the Detect_Pump Image-Processing Node

The next node will subscribe to the image topic and execute a series of processing steps to identify the pump's orientation relative to the horizontal image axis.

1. As before, create a basic ROS python node (detect_pump.py) and set its executable permissions:

```
#!/usr/bin/env python
import rospy

# known pump geometry
#  - units are pixels (of half-size image)
PUMP_DIAMETER = 360
PISTON_DIAMETER = 90
PISTON_COUNT = 7

def start_node():
    rospy.init_node('detect_pump')
    rospy.loginfo('detect_pump node started')

if __name__ == '__main__':
```

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```
    try:
        start_node()
    except rospy.ROSInterruptException:
        pass
```

```
chmod u+x nodes/detect_pump.py
```

- Note that we don't have to edit `CMakeLists` to create new build rules for each script, since python does not need to be compiled.

2. Add a ROS subscriber to the `image` topic, to provide the source for images to process.

   (a) Import the `Image` message header

   ```
   from sensor_msgs.msg import Image
   ```

   (b) Above the `start_node` function, create an empty callback (`process_image`) that will be called when a new Image message is received:

   ```
   def process_image(msg):
   try:
       pass
       except Exception as err:
           print err
   ```

   - The try/except error handling will allow our code to continue running, even if there are errors during the processing pipeline.

   (c) In the `start_node` function, create a ROS Subscriber object:

   - subscribe to the `image` topic, monitoring messages of type `Image`
   - register the callback function we defined above

   ```
   rospy.Subscriber("image", Image, process_image)
   rospy.spin()
   ```

   - reference: rospy.Subscriber
   - reference: rospy.spin

   (d) Run the new node and verify that it is subscribing to the topic as expected:

   ```
   rosrun detect_pump detect_pump.py
   rosnode info /detect_pump
   rqt_graph
   ```

3. Convert the incoming `Image` message to an OpenCV `Image` object and display it As before, we'll use the `CvBridge` module to do the conversion.

   (a) Import the `CvBridge` modules:

   ```
   from cv_bridge import CvBridge
   ```

   (b) In the `process_image` callback, add a call to the CvBridge imgmsg_to_cv2 method:

   ```
   # convert sensor_msgs/Image to OpenCV Image
   bridge = CvBridge()
   orig = bridge.imgmsg_to_cv2(msg, "bgr8")
   ```

- This code (and all other image-processing code) should go inside the `try` block, to ensure that processing errors don't crash the node.
- This should replace the placeholder `pass` command placed in the `try` block earlier

(c) Use the OpenCV `imshow` method to display the images received. We'll create a pattern that can be re-used to show the result of each image-processing step.

i. Import the OpenCV `cv2` module:

```
import cv2
```

ii. Add a display helper function above the `process_image` callback:

```
def showImage(img):
    cv2.imshow('image', img)
    cv2.waitKey(1)
```

iii. Copy the received image to a new "drawImg" variable:

```
drawImg = orig
```

iv. **Below** the `except` block (outside its scope; at `process_image` scope, display the `drawImg` variable:

```
# show results
showImage(drawImg)
```

(d) Run the node and see the received image displayed.

4. The first step in the image-processing pipeline is to resize the image, to speed up future processing steps. Add the following code inside the `try` block, then rerun the node.

```
# resize image (half-size) for easier processing
resized = cv2.resize(orig, None, fx=0.5, fy=0.5)
drawImg = resized
```

- you should see a smaller image being displayed
- reference: resize()

5. Next, convert the image from color to grayscale. Run the node to check for errors, but the image will still look the same as previously.

```
# convert to single-channel image
gray = cv2.cvtColor(resized, cv2.COLOR_BGR2GRAY)
drawImg = cv2.cvtColor(gray, cv2.COLOR_GRAY2BGR)
```

- Even though the original image looks gray, the JPG file, Image message, and `orig` OpenCV image are all 3-channel color images.
- Many OpenCV functions operate on individual image channels. Converting an image that appears gray to a "true" 1-channel grayscale image can help avoid confusion further on.
- We convert back to a color image for `drawImg` so that we can draw colored overlays on top of the image to display the results of later processing steps.
- reference: cvtColor()

6. Apply a thresholding operation to turn the grayscale image into a binary image. Run the node and see the thresholded image.

```
# threshold grayscale to binary (black & white) image
threshVal = 75
ret,thresh = cv2.threshold(gray, threshVal, 255, cv2.THRESH_BINARY)
drawImg = cv2.cvtColor(thresh, cv2.COLOR_GRAY2BGR)
```

You should experiment with the `threshVal` paramter to find a value that works best for this image. Valid values for this parameter lie between [0-255], to match the grayscale pixel intensity range. Find a value that clearly highlights the pump face geometry. I found that a value of `150` seemed good to me.

- reference threshold

7. Detect the outer pump-housing circle.

   This is not actually used to detect the pump angle, but serves as a good example of feature detection. In a more complex scene, you could use OpenCV's Region Of Interest (ROI) feature to limit further processing to only features inside this pump housing circle.

   (a) Use the `HoughCircles` method to detect a pump housing of known size:

   ```
   # detect outer pump circle
   pumpRadiusRange = ( PUMP_DIAMETER/2-2, PUMP_DIAMETER/2+2)
   pumpCircles = cv2.HoughCircles(thresh, cv2.HOUGH_GRADIENT, 1, PUMP_DIAMETER,␣
   ↪param2=2, minRadius=pumpRadiusRange[0], maxRadius=pumpRadiusRange[1])
   ```

   - reference: HoughCircles

   (b) Add a function to display all detected circles (above the `process_image` callback):

   ```
   def plotCircles(img, circles, color):
       if circles is None: return

       for (x,y,r) in circles[0]:
           cv2.circle(img, (int(x),int(y)), int(r), color, 2)
   ```

   (c) Below the circle-detect, call the display function and check for the expected # of circles (1)

   ```
   plotCircles(drawImg, pumpCircles, (255,0,0))
   if (pumpCircles is None):
       raise Exception("No pump circles found!")
   elif len(pumpCircles[0])<>1:
       raise Exception("Wrong # of pump circles: found {} expected {}".
   ↪format(len(pumpCircles[0]),1))
   else:
       pumpCircle = pumpCircles[0][0]
   ```

   (d) Run the node and see the detected circles.

   - Experiment with adjusting the `param2` input to `HoughCircles` to find a value that seems to work well. This parameter represents the sensitivity of the detector; lower values detect more circles, but also will return more false-positives.
   - Tru removing the `min/maxRadius` parameters or reducing the minimum distance between circles (4th parameter) to see what other circles are detected.
   - I found that a value of `param2=7` seemed to work well

8. Detect the piston sleeves, using blob detection.

   Blob detection analyses the image to identify connected regions (blobs) of similar color. Filtering of the resulting blob features on size, shape, or other characteristics can help identify features of interest. We will be using OpenCV's SimpleBlobDetector.

(a) Add the following code to run blob detection on the binary image:

```
# detect blobs inside pump body
pistonArea = 3.14159 * PISTON_DIAMETER**2 / 4
blobParams = cv2.SimpleBlobDetector_Params()
blobParams.filterByArea = True;
blobParams.minArea = 0.80 * pistonArea;
blobParams.maxArea = 1.20 * pistonArea;
blobDetector = cv2.SimpleBlobDetector_create(blobParams)
blobs = blobDetector.detect(thresh)
```

- Note the use of an Area filter to select blobs within 20% of the expected piston-sleeve area.
- By default, the blob detector is configured to detect black blobs on a white background. so no additional color filtering is required.

(b) Below the blob detection, call the OpenCV blob display function and check for the expected # of piston sleeves (7):

```
drawImg = cv2.drawKeypoints(drawImg, blobs, (), (0,255,0), cv2.DRAW_MATCHES_
↪FLAGS_DRAW_RICH_KEYPOINTS)
if len(blobs) <> PISTON_COUNT:
    raise Exception("Wring # of pistons: found {} expected {}".
↪format(len(blobs), PISTON_COUNT))
pistonCenters = [(int(b.pt[0]),int(b.pt[1])) for b in blobs]
```

(c) Run the node and see if all piston sleeves were properly identified

9. Detect the primary axis of the pump body.

This axis is used to identify the key piston sleeve feature. We'll reduce the image to contours (outlines), then find the largest one, fit a rectangular box (rotated for best-fit), and identify the major axis of that box.

(a) Calculate image contours and select the one with the largest area:

```
# determine primary axis, using largest contour
im2, contours, h = cv2.findContours(thresh, cv2.RETR_TREE, cv2.CHAIN_APPROX_
↪SIMPLE)
maxC = max(contours, key=lambda c: cv2.contourArea(c))
```

(b) Fit a bounding box to the largest contour:

```
boundRect = cv2.minAreaRect(maxC)
```

(c) Copy these 3 helper functions to calculate the endpoints of the rectangle's major axis (above the `process_image` callback):

```
import math
...

def ptDist(p1, p2):
    dx=p2[0]-p1[0]; dy=p2[1]-p1[1]
    return math.sqrt( dx*dx + dy*dy )

def ptMean(p1, p2):
    return ((int(p1[0]+p2[0])/2, int(p1[1]+p2[1])/2))

def rect2centerline(rect):
    p0=rect[0]; p1=rect[1]; p2=rect[2]; p3=rect[3];
```

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```
    width=ptDist(p0,p1); height=ptDist(p1,p2);

    # centerline lies along longest median
    if (height > width):
        cl = ( ptMean(p0,p1), ptMean(p2,p3) )
    else:
        cl = ( ptMean(p1,p2), ptMean(p3,p0) )

    return cl
```

(d) Call the `rect2centerline` function from above, with the bounding rectangle calculated earlier. Draw the centerline on top of our display image.

```
centerline = rect2centerline(cv2.boxPoints(boundRect))
cv2.line(drawImg, centerline[0], centerline[1], (0,0,255))
```

10. The final step is to identify the key piston sleeve (closest to centerline) and use position to calculate the pump angle.

(a) Add a helper function to calculate the distance between a point and the centerline:

```
def ptLineDist(pt, line):
    x0=pt[0]; x1=line[0][0]; x2=line[1][0];
    y0=pt[1]; y1=line[0][1]; y2=line[1][1];
    return abs((x2-x1)*(y1-y0)-(x1-x0)*(y2-y1))/(math.sqrt((x2-x1)*(x2-
↪x1)+(y2-y1)*(y2-y1)))
```

(b) Call the `ptLineDist` function to find which piston blob is closest to the centerline. Update the drawImg to show which blob was identified.

```
# find closest piston to primary axis
closestPiston = min( pistonCenters, key=lambda ctr: ptLineDist(ctr,␣
↪centerline))
cv2.circle(drawImg, closestPiston, 5, (255,255,0), -1)
```

(c) Calculate the angle between the 3 key points: piston sleeve centerpoint, pump center, and an arbitrary point along the horizontal axis (our reference "zero" position).

i. Add a helper function `findAngle` to calculate the angle between 3 points:

```
import numpy as np

def findAngle(p1, p2, p3):
    p1=np.array(p1); p2=np.array(p2); p3=np.array(p3);
    v1=p1-p2; v2=p3-p2;
    return math.atan2(-v1[0]*v2[1]+v1[1]*v2[0],v1[0]*v2[0]+v1[1]*v2[1]) *␣
↪180/3.14159
```

ii. Call the `findAngle` function with the appropriate 3 keypoints:

```
# calculate pump angle
p1 = (orig.shape[1], pumpCircle[1])
p2 = (pumpCircle[0], pumpCircle[1])
p3 = (closestPiston[0], closestPiston[1])
angle = findAngle(p1, p2, p3)
print "Found pump angle: {}".format(angle)
```

11. You're done! Run the node as before. The reported pump angle should be near 24 degrees.

Challenge Exercises

For a greater challenge, try the following suggestions to modify the operation of this image-processing example:

1. Modify the `image_pub` node to rotate the image by 10 degrees between each publishing step. The following code can be used to rotate an image:

```
def rotateImg(img, angle):
    rows,cols,ch = img.shape
    M = cv2.getRotationMatrix2D((cols/2,rows/2),angle,1)
    return cv2.warpAffine(img,M,(cols,rows))
```

2. Change the `detect_pump` node to provide a **service** that performs the image detection. Define a custom service type that takes an input image and outputs the pump angle. Create a new application node that subscribes to the `image` topic and calls the `detect_pump` service.

3. Try using `HoughCircles` instead of `BlobDetector` to locate the piston sleeves.

4.2 Session 6 - Documentation, Unit Tests, ROS Utilities and Debugging ROS

`Slides`

4.2.1 Documentation Generation

Motivation

The ROS Scan-N-Plan application is complete and tested. It is important to thoroughly document the code so that other developers may easily understand this program.

Information and Resources

doxygen generates documentation from annotated source code

rosdoc_lite is a ROS wrapper for doxygen

Scan-N-Plan Application: Problem Statement

We have completed and tested our Scan-N-Plan program and we need to release the code to the public. Your goal is to make documentation viewable in a browser. You may accomplish this by annotated the myworkcell_core package with doxygen syntax and generating documentation with rosdoc_lite.

Scan-N-Plan Application: Guidance

Annotate the Source Code

1. Open the myworkcell_node.cpp file from the previous example.

2. Annotate above the ScanNPlan Class:

```
/**
* @brief The ScanNPlan class is a client of the vision and path plan servers.  The ScanNPLan class takes
* these services, computes transforms and published commands to the robot.
*/
class ScanNPlan
```

1. Annotate above the start method

```
 /**
  * @brief start performs the robot alorithms functions of the ScanNPlan of
  * the node. The start method makes a service request for a transform that
  * localizes the part.  The start method moves the "manipulator"
  * move group to the localization target.  The start method requests
  * a cartesian path based on the localization target.  The start method
  * sends the cartesian path to the actionlib client for execution, bypassig
  * MoveIt!
  * @param base_frame is a string that specifies the reference frame
  * coordinate system.
  */
void start()
```

1. Annotate above the flipPose

```
 /**
  * @brief flipPose rotates the input transform by 180 degrees about the
  * x-axis
  * @param in geometry_msgs::Pose reference to the input transform
  * @return geometry_msgs::Pose of the flipped output transform
  */
geometry_msgs::Pose transformPose(const geometry_msgs::Pose& in) const
```

1. Annotate above the main function

```
/**
* @brief main is the ros interface for the ScanNPlan Class
* @param argc ROS uses this to parse remapping arguments from the command line.
* @param argv ROS uses this to parse remapping arguments from the command line.
* @return ROS provides typical return codes, 0 or -1, depending on the
* execution.
*/
int main(int argc, char** argv)
```

1. Additional annotations may be placed above private variables or other important code elements.

Generate documentation

1. Install rosdoc_lite:

```
sudo apt install ros-kinetic-rosdoc-lite
```

1. Build the package so we can source it later:

```
catkin build
```

1. Source the package

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

1. run rosdoc_lite to generate the documentation

```
roscd myworkcell_core
rosdoc_lite .
```

View the Documentation

1. Open the documentation in a browser:

```
firefox doc/html/index.html
```

1. Navigate to Classes -> ScanNPlan and view the documentation.

4.2.2 Unit Testing

In this exercise we will write a unit tests in the myworkcell_core package.

Motivation

The ROS Scan-N-Plan application is complete and documented. Now we want to test the program to make sure it behaves as expected.

Information and Resources

Google Test: C++ XUnit test framework

rostest: ROS wrapper for XUnit test framework

catkin testing: Building and running tests with catkin

Problem Statement

We have completed and and documented our Scan-N-Plan program. We need to create a test framework so we can be sure our program runs as intended after it is built. In addition to ensuring the code runs as intended, unit tests allow you to easily check if new code changes functionality in unexpected ways. Your goal is to create the unit test frame work and write a few tests.

Guidance

Create the unit test frame work

1. Create a *test* folder in the myworkcell_core/src folder. In the workspace directory:

   ```
   catkin build
   source devel/setup.bash
   roscd myworkcell_core
   mkdir src/test
   ```

2. Create utest.cpp file in the *myworkcell_core/src/test* folder:

```
touch src/test/utest.cpp
```

3. Open utest.cpp in QT and include ros & gtest:

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

4. Write a dummy test that will return true if executed. This will test our framework and we will replace it later with more useful tests:

```
TEST(TestSuite, myworkcell_core_framework)
{
  ASSERT_TRUE(true);
}
```

5. Next include the general main function, which will execute the unit tests we write later:

```
int main(int argc, char **argv)
{
  testing::InitGoogleTest(&argc, argv);
  return RUN_ALL_TESTS();
}
```

6. Edit myworkcell_core CMakeLists.txt to build the u_test.cpp file. Append CMakeLists.txt:

```
if(CATKIN_ENABLE_TESTING)
  find_package(rostest REQUIRED)
  add_rostest_gtest(utest_node test/utest_launch.test src/test/utest.cpp)
  target_link_libraries(utest_node ${catkin_LIBRARIES})
endif()
```

7. Create a test folder under myworkcell_core

```
mkdir test
```

8. Create a test launch file:

```
touch test/utest_launch.test
```

9. Open the utest_launch.test file in QT and populate the file:

```
<?xml version="1.0"?>
<launch>
    <node pkg="fake_ar_publisher" type="fake_ar_publisher_node" name="fake_ar_
↪publisher"/>
    <test test-name="unit_test_node" pkg="myworkcell_core" type="utest_node"/>
</launch>
```

10. Build and test the framework

```
catkin run_tests myworkcell_core
```

The console output should show (buried in the midst of many build messages):

```
[ROSTEST]------------------------------------------------------------------------

[myworkcell_core.rosunit-unit_test_node/myworkcell_core_framework][passed]

SUMMARY
 * RESULT: SUCCESS
 * TESTS: 1
 * ERRORS: 0
 * FAILURES: 0
```

This means our framework is functional and now we can add usefull unit tests.

Note: You can also run tests directly from the command line, using the launch file we made above: *rostest myworkcell_core utest_launch.test*. Note that test files are not built using the regular *catkin build* command, so use *catkin run_tests myworkcell_core* instead.

Add stock publisher tests

1. The rostest package provides several tools for inspecting basic topic characteristics hztest, paramtest, publishtest. We'll add some basic tests to verify that the *fake_ar_publisher* node is outputting the expected topics.
2. Add the test description to the *utest_launch.test* file:

```
<test name="publishtest" test-name="publishtest" pkg="rostest" type="publishtest">
    <rosparam>
      topics:
        - name: "/ar_pose_marker"
          timeout: 10
          negative: False
        - name: "/ar_pose_visual"
          timeout: 10
          negative: False
    </rosparam>
</test>
```

3. Run the test:

```
catkin run_tests myworkcell_core
```

You should see:

> Summary: 2 tests, 0 errors, 0 failures

Write specific unit tests

1. Since we will be testing the messages we get from the fake_ar_publisher package, include the relevant header file (in *utest.cpp*):

```
#include <fake_ar_publisher/ARMarker.h>
```

2. Declare a global variable:

```
fake_ar_publisher::ARMarkerConstPtr test_msg_;
```

3. Add a subscriber callback to copy incoming messages to the global variable:

```
void testCallback(const fake_ar_publisher::ARMarkerConstPtr &msg)
{
  test_msg_ = msg;
}
```

4. Write a unit test to check the reference frame of the ar_pose_marker:

```
TEST(TestSuite, myworkcell_core_fake_ar_pub_ref_frame)
{
    ros::NodeHandle nh;
    ros::Subscriber sub = nh.subscribe("/ar_pose_marker", 1, &testCallback);

    EXPECT_NE(ros::topic::waitForMessage<fake_ar_publisher::ARMarker>("/ar_pose_
↪marker", ros::Duration(10)), nullptr);
    EXPECT_EQ(1, sub.getNumPublishers());
    EXPECT_EQ(test_msg_->header.frame_id, "camera_frame");
}
```

5. Add some node-initialization boilerplate to the main() function, since our unit tests interact with a running ROS system. Replace the current main() function with the new code below:

```
int main(int argc, char **argv)
{
  testing::InitGoogleTest(&argc, argv);
  ros::init(argc, argv, "MyWorkcellCoreTest");

  ros::AsyncSpinner spinner(1);
  spinner.start();
  int ret = RUN_ALL_TESTS();
  spinner.stop();
  ros::shutdown();
  return ret;
}
```

6. Run the test:

```
catkin run_tests myworkcell_core
```

7. view the results of the test:

```
catkin_test_results build/myworkcell_core
```

You should see:

> Summary: 3 tests, 0 errors, 0 failures

4.2.3 Using rqt Tools for Analysis

In this exercise we will use rqt_console, rqt_graph and urdf_to_graphviz to understand behavior of the ROS system.

Motivation

When complicated multi-node ros systems are running it can be important to understand the interactions of nodes.

Information and Resources

Using a catkin workspace

Problem Statement

The Scan-N-Plan application is complete. We would like to further inspect the application using the various ROS rqt tools.

Guidance

`rqt_graph`: view node interaction

In complex applications, it may be helpful to get a visual representation of the ROS node interactions.

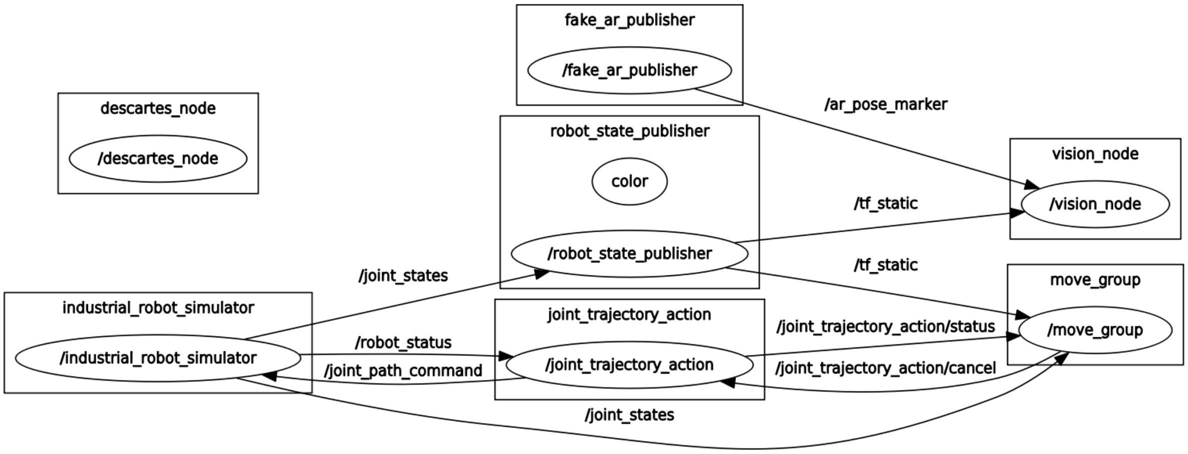
1. Launch the Scan-N-Plan workcell:

```
roslaunch myworkcell_support setup.launch
```

1. In a 2nd terminal, launch the rqt_graph:

```
rqt_graph
```

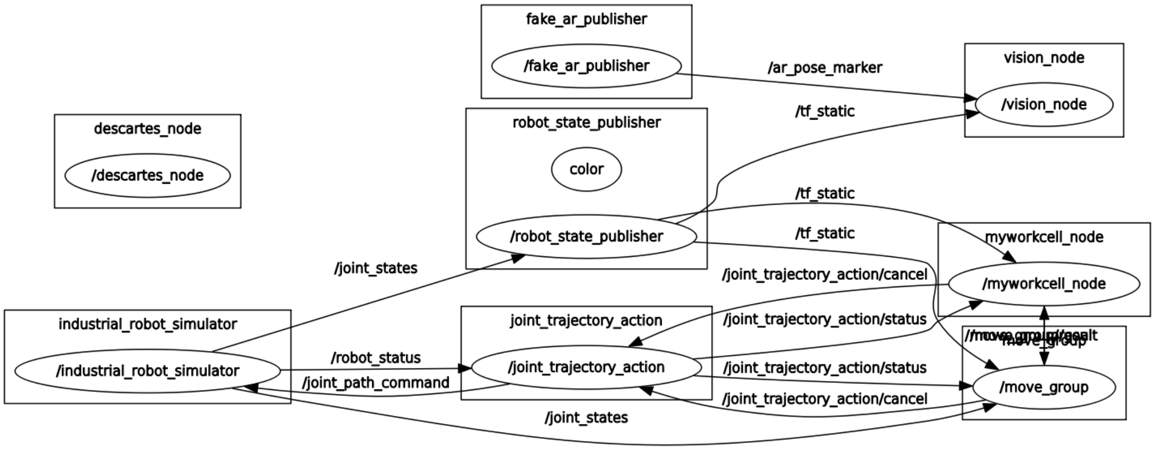
1. Here we can see the basic layout of our Scan-N-Plan application:



2. In a 3rd terminal, launch the descartes path planner.:

```
rosrun myworkcell_core myworkcell_node
```

1. You must update the graph while the node is running because the graph will not update automatically. After the update, we see our updated ROS network contains out myworkcell_node. Also, The myworkcell_node is publishing a new topic `/move_group/goal` which is subscribed by the move_group node.



`rqt_console`: view messages:

Now, we would like to see the output of the path planner. rqt_console is a great gui for viewing ROS topics.

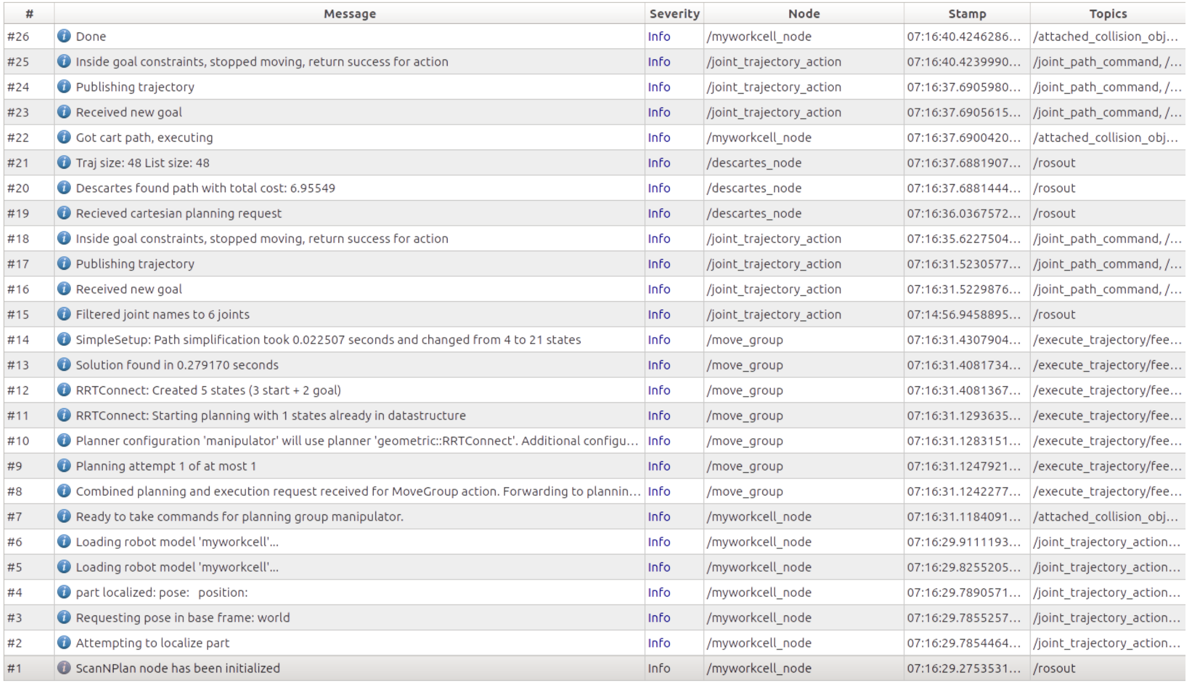
1. Kill the rqt_graph application in the 2nd terminal and run rqt_console:

```
rqt_console
```

1. Run the path planner:

```
rosrun myworkcell_core myworkcell_node
```

1. The rqt_console automatically updates, showing the logic behind the path planner:



#	Message	Severity	Node	Stamp	Topics
#26	Done	Info	/myworkcell_node	07:16:40.4246286...	/attached_collision_obj...
#25	Inside goal constraints, stopped moving, return success for action	Info	/joint_trajectory_action	07:16:40.4239990...	/joint_path_command, /...
#24	Publishing trajectory	Info	/joint_trajectory_action	07:16:37.6905980...	/joint_path_command, /...
#23	Received new goal	Info	/joint_trajectory_action	07:16:37.6905615...	/joint_path_command, /...
#22	Got cart path, executing	Info	/myworkcell_node	07:16:37.6900420...	/attached_collision_obj...
#21	Traj size: 48 List size: 48	Info	/descartes_node	07:16:37.6881907...	/rosout
#20	Descartes found path with total cost: 6.95549	Info	/descartes_node	07:16:37.6881444...	/rosout
#19	Recieved cartesian planning request	Info	/descartes_node	07:16:36.0367572...	/rosout
#18	Inside goal constraints, stopped moving, return success for action	Info	/joint_trajectory_action	07:16:35.6227504...	/joint_path_command, /...
#17	Publishing trajectory	Info	/joint_trajectory_action	07:16:31.5230577...	/joint_path_command, /...
#16	Received new goal	Info	/joint_trajectory_action	07:16:31.5229876...	/joint_path_command, /...
#15	Filtered joint names to 6 joints	Info	/joint_trajectory_action	07:14:56.9458895...	/rosout
#14	SimpleSetup: Path simplification took 0.022507 seconds and changed from 4 to 21 states	Info	/move_group	07:16:31.4307904...	/execute_trajectory/fee...
#13	Solution found in 0.279170 seconds	Info	/move_group	07:16:31.4081734...	/execute_trajectory/fee...
#12	RRTConnect: Created 5 states (3 start + 2 goal)	Info	/move_group	07:16:31.4081367...	/execute_trajectory/fee...
#11	RRTConnect: Starting planning with 1 states already in datastructure	Info	/move_group	07:16:31.1293635...	/execute_trajectory/fee...
#10	Planner configuration 'manipulator' will use planner 'geometric::RRTConnect'. Additional configu...	Info	/move_group	07:16:31.1283151...	/execute_trajectory/fee...
#9	Planning attempt 1 of at most 1	Info	/move_group	07:16:31.1247921...	/execute_trajectory/fee...
#8	Combined planning and execution request received for MoveGroup action. Forwarding to plannin...	Info	/move_group	07:16:31.1242277...	/execute_trajectory/fee...
#7	Ready to take commands for planning group manipulator.	Info	/myworkcell_node	07:16:31.1184091...	/attached_collision_obj...
#6	Loading robot model 'myworkcell'...	Info	/myworkcell_node	07:16:29.9111193...	/joint_trajectory_action...
#5	Loading robot model 'myworkcell'...	Info	/myworkcell_node	07:16:29.8255205...	/joint_trajectory_action...
#4	part localized: pose: position:	Info	/myworkcell_node	07:16:29.7890571...	/joint_trajectory_action...
#3	Requesting pose in base frame: world	Info	/myworkcell_node	07:16:29.7855257...	/joint_trajectory_action...
#2	Attempting to localize part	Info	/myworkcell_node	07:16:29.7854464...	/joint_trajectory_action...
#1	ScanNPlan node has been initialized	Info	/myworkcell_node	07:16:29.2753531...	/rosout

rqt_plot: view data plots

rqt_plot is an easy way to plot ROS data in real time. In this example, we will plot robot joint velocities from our path plan.

1. Kill the rqt_console application in the 2nd terminal and run rqt_plot:

```
rqt_plot
```

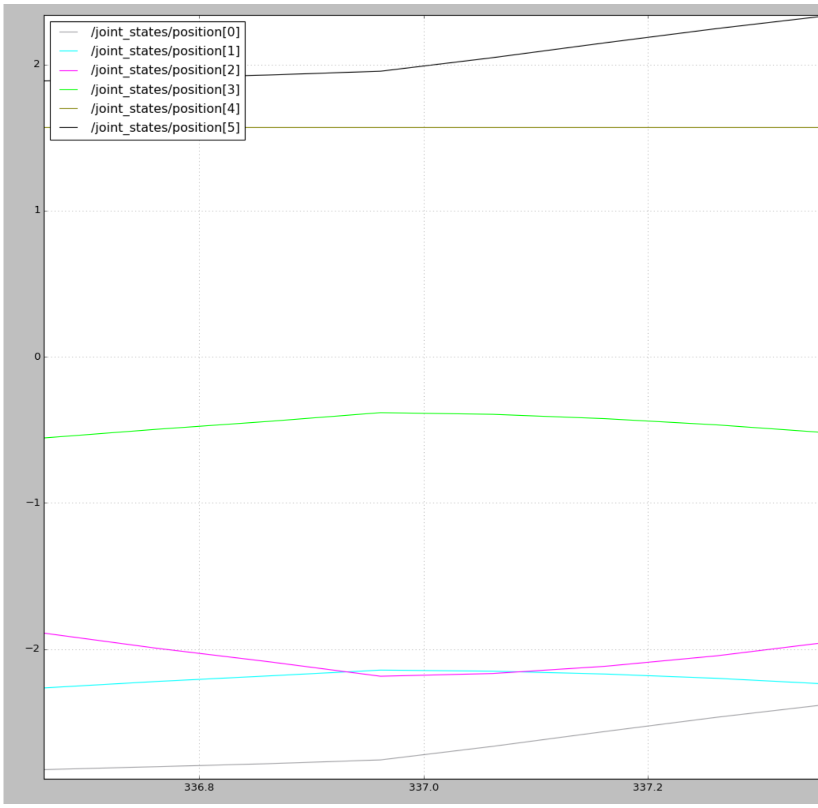
1. In the Topic field add the following topics:

```
/joint_states/position[0]
/joint_states/position[1]
/joint_states/position[2]
/joint_states/position[3]
/joint_states/position[4]
/joint_states/position[5]
```

1. Then run the path planner:

```
rosrun myworkcell_core myworkcell_node
```

1. We can see the joint positions streaming in real-time:



4.2.4 ROS Style Guide and ros_lint

Motivation

The ROS Scan-N-Plan application is complete, tested and documented. Now we want to clean up the code according to the style guide so other developers can easily understand our work.

Information and Resources

The Official ROS C++ Style Guide

Automated Style Guide Enforcement

Scan-N-Plan Application: Problem Statement

We have completed and tested our Scan-N-Plan program and we need to release the code to the public. Your goal is to ensure the code we have created conforms to the ROS C++ Style Guide.

Scan-N-Plan Application: Guidance

Configure Package

1. Add a build dependency on roslint to your package's package.xml:

```
<build_depend>roslint</build_depend>
```

1. Add roslint to catkin REQUIRED COMPONENTS in CMakeLists.txt:

```
find_package(catkin REQUIRED COMPONENTS
  ...
  roslint
)
```

1. Invoke roslint function from CMakeLists.txt

```
roslint_cpp()
```

Run roslint

1. To run roslint:

```
roscd myworkcell_core
catkin_make --make-args roslint
```

4.2.5 Docker AWS

Demo #1 - Run front-end Gazebo host and back-end in Docker

Setup workspace

Front-end (run on host and only contains gui)

in terminal 1

```
mkdir -p ./training/front_ws/src
cd ./training/front_ws/src
gazebo -v
git clone -b gazebo7 https://github.com/fetchrobotics/fetch_gazebo.git
git clone https://github.com/fetchrobotics/robot_controllers.git
git clone https://github.com/fetchrobotics/fetch_ros.git
cd ..
catkin build fetch_gazebo fetch_description
```

Back-end (run in container)

In this step, we will create a docker image that has the executables we need:

- run /bin/bash in the rosindustrial/core:indigo image then apt-get the package, commiting the result.
- run /bin/bash in the rosindustrial/core:indigo image then build the package from source, commiting the result.
- create a docker container using the fetch Dockerfile, which we will perform. https://gist.github.com/AustinDeric/242c1edf1c934406f59dfd078a0ce7fa

```
cd ../fetch-Dockerfile/
docker build --network=host -t rosindustrial/fetch:indigo .
```

Running the Demo

Run the front-end

Run the front end in terminal 1:

```
source devel/setup.bash
roslaunch fetch_gazebo playground.launch
```

Run the backend

There are multiple ways to perform this:

- run /bin/bash in the fetch container and manually run the demo node.
- run the demo node directly in the container, which is the method we will perform

Run the back end in terminal 2:

```
docker run --network=host rosindustrial/fetch:indigo roslaunch fetch_gazebo_demo demo.
↪launch
```

Demo #2 - Run front-end on a web-server and back-end in docker

start the environment

```
docker run --network=host rosindustrial/fetch:indigo roslaunch fetch_gazebo␣
↪playground.launch headless:=true gui:=false
```

run the gazebo web server:

```
docker run -v "/home/aderic/roscloud/training/front_ws/src/fetch_gazebo/fetch_gazebo/
↪models/test_zone/meshes/:/root/gzweb/http/client/assets/test_zone/meshes/" -v "/
↪home/aderic/roscloud/training/front_ws/src/fetch_ros/fetch_description/meshes:/root/
↪gzweb/http/client/assets/fetch_description/meshes" -it --network=host giodegas/
↪gzweb /bin/bash
```

then run the server:

```
/root/gzweb/start_gzweb.sh && gzserver
```

run the demo in terminal 3:

```
docker run --network=host fetch roslaunch fetch_gazebo_demo demo.launch
```

Demo #3 Robot Web Tools

In this demo we will run an industrial robot URDF viewable in a browser In terminal 1 we will load a robot to the parameter server

```
mkdir -p abb_ws/src
git clone -b kinetic-devel https://github.com/ros-industrial/abb.git
docker run -v "/home/aderic/roscloud/training/abb_ws:/abb_ws" --network=host -it␣
↪rosindustrial/core:kinetic /bin/bash
cd abb_ws
catkin build
source devel/setup.bash
roslaunch abb_irb5400_support load_irb5400.launch
```

in terminal 2 we will start the robot web tools:

```
docker run --network=host rosindustrial/viz:kinetic roslaunch viz.launch
```

in terminal 3 we will launch the webserver first we need to start a www folder

```
cp -r abb_ws/src/abb/abb_irb5400_support/ www/
```

```
docker run -v "/home/aderic/roscloud/training/www:/data/www" -v "/home/aderic/
↪roscloud/training/nginx_conf/:/etc/nginx/local/" -it --network=host rosindustrial/
↪nginx:latest /bin/bash
nginx -c /etc/nginx/local/nginx.conf
```