Welcome to the Duckietown Developer Manual

Contents

Basics - Terminal

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What you will get	• Know how to use a terminal

Working over the terminal is a skill that every roboticist-to-be needs to acquire. It enables you to work on remote agents or computers without the need for a graphical user interface (GUI) and lets you work very efficiently. Once you get the hang of it, you will find out for yourself how it can make your life easier.

Using a terminal

It makes sense to learn how to use the terminal very well, as it will save you a lot of time along the way. If you are completely new to working with a terminal, often also called “console” or “command line”, an official beginners tutorial can be found on the Ubuntu website.

If you are looking for an extensive list of commands that can be used from the terminal, this is the place to look at.

TODO write section on how to pimp up the terminal and provide some best practices for development

Using the Duckietown Shell

The Duckietown Shell, or `dts` for short, is a pure Python, easily distributable (few dependencies) utility for Duckietown.

The idea is that most of the functionalities are implemented as Docker containers, and `dts` provides a nice interface for that, so that users should not type a very long docker run command line. These functionalities range from calibrating your Duckiebot and running demos to building this Duckumentation and submitting agents to open challenges and monitoring your evaluations and leaderboard positioning.

If you followed all the steps in the laptop setup, you already installed `dts`. If not, now is the time to go back and do it.

Basics - Development

This section of the book will introduce the basics of software development in Duckietown. The arguments presented in this section are very general and should be clear to any developer (not just in Duckietown).

ISO/IEC 9126

ISO/IEC 9126 is a international standard for product quality in Software Engineering. It was officially replaced by the new ISO/IEC 25010 in 2011 that introduces a few minor changes.

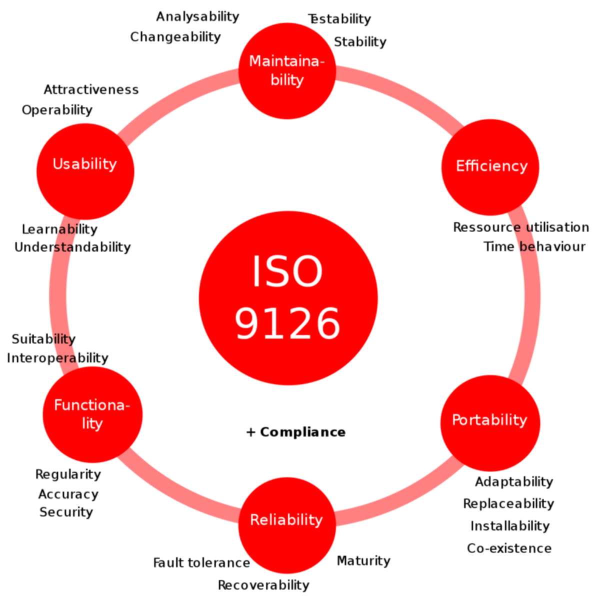


Fig. 1 ISO/IEC 9126 Standard (source: Wikipedia)

Software development, as any other activities carried out by human beings is subject to human biases. The ISO/IEC 9126 standard’s objective is that of aknowledging the most common biases and addressing them by definining clear guidelines about what properties a **good** software product should have.

In this section, we are not going to dive into this standard, but we strongly believe that such standard (and its successor ISO/IEC 25010) should be the best friend of any developer.

Throughout this book, we will mention some of these qualities as we motivate some of the decisions made while creating the Duckietown Development Workflow.

Hands on

We suggest the reader to get familiar with such standard by using these resources:

- Wikipedia - ISO/IEC 9126
- Official ISO/IEC 9126 (by ISO.org)
- Official ISO/IEC 25010 (by ISO.org)

Ask the community

If you have any questions about good practices in software development, join the Duckietown Slack.

Linux

This section of the book will introduce Linux distributions and specifically the Ubuntu distribution. We will provide guides for installing Ubuntu in *dual-boot* mode or inside a *virtual machine*.

Linux

Linux is a group of free and open-source software operating systems built around the Linux kernel first released in 1991. Typically, Linux is packaged in a form known as a Linux distribution such as Fedora or Ubuntu.

Ubuntu is the Linux distribution officially supported by the Duckietown community.

Ubuntu

As of this writing, the most recent version of Ubuntu is 22.04 LTS (Long Term Service) which will be supported until April 2032.

Installation

It is highly recommended to install Ubuntu directly on your laptop or as a dual boot operating system alongside your existing OS. However we also provide some guidance on installing Ubuntu within a Virtual Environment on your laptop.

Dual Boot

- First you need to download a `.iso` image file which contains the version of Ubuntu you want. Here is 22.04 LTS make sure to download the desktop image.
- Next, you need a free USB drive with at least 2GB of space. The drive will be completely written over.
- You need some software to write the .iso to the USB. If on Windows you can use Rufus
- Create the bootable USB drive, disconnect the USB then reconnect to your computer.
- Restart your computer
  - If your computer simply boots into the existing operating system you need to change the boot order in your BIOS.
  - Restart your computer again and press the button during startup which lets you into the BIOS. It may say on your computer what this button is but you may need to Google depending on your laptop model. For example Lenovo might be F1 or F2.
  - Look for an option to change boot order and put priority on your USB drive.
- Your computer should now boot into Ubuntu installation and you can follow the instructions for dual boot.

Virtual Machine

- First you need to download a .iso image file which contains the version of Ubuntu you want. Here is 22.04 LTS make sure to download the desktop image.
- Download your desired Virtual Machine platform (popular choices are Virtual Box and VMWare).

Note: Using a Virtual Machine might require some particular settings for you networking settings. The virtual machine should appear as a device on your local network. For example, in VirtualBox, you need to set up a *Bridged Network*. This might differ in other hypervisors.

Terminal

Some pointers:

- Open a terminal with Ctrl + Alt + T

- `/` is the top level root directoy which contains your
- `~` refers to your home folder located in `/home/[username]`

Hands on

We suggest that you install a Linux distribution on your computer and get familiar with it before proceeding to the next sections.

Ask the community

If you have any questions about good practices in installing Ubuntu on your computer or other questions about Ubuntu, join and ask on the Duckietown Slack!

Git

Every time there is a large project, with many contributors and the need for code versioning and history, developers rely on VCS (Version Control Systems) tools. Duckietown uses Git as VCS and GitHub.com as a service provider for it. The Duckietown organization page on GitHub is github.com/duckietown.

Monolithicity VS Modularity

Whether a software project should be monolithic or modular is one of the most debated decisions that a group of developers faces at the beginning of a software project. Books have been written about it. Duckietown started as a monolithic project, and some of us still remember the infamous Software repository, and only later transitioned to a full modular approach.

There are two levels of modularity in Duckietown. We distinguish between **Modules** and **Nodes**. Modules form our first and highest level of modularity, with each module being a collection of nodes. Nodes constitute the smallest software entities, and each node is usually responsible for a very specific task. Nodes are not allowed to exist outside modules. We will revisit these concepts later in the book, but in a nutshell, modules represent high level concepts, like *autonomous driving capability* for a vehicle, while nodes within a module tackle more granular tasks, like *traffic signs detection*.

In Duckietown, code is separated so that each module has its own repository. All official repositories are hosted under the same GitHub organization github.com/duckietown. Be brave, (as of April 2020) we have more than 220 repositories there. You can also have your own modules hosted as repositories on your own GitHub account.

Git

This section goes through the most common operations you can perform on a git project and a git project hosted on GitHub.com.

Terminology

A non-exhaustive list of terms commonly used in git follow.

Repository

A repo (short for repository), or git project, encompasses the entire collection of files and folders associated with a project, along with each file’s revision history.

Branch

Branches constitute threads of changes within a repository. Though we call them branches, do not try to force an analogy with tree branches, they are similar in spirit but quite different in how they work.

A repository is not allowed to exist without a branch, and every operation inside a repository only makes sense in the context of a branch (the *active* branch). Inside a repository, you can have as many branches as you want, but you always work on one branch at a time. Every git project has at least one main branch, usually called the `master` branch.

Use the command `git branch` to see the list of branches present in your repository and which branch you are currently working on.

Though, branches are used in different scenarios, they simply allow groups of developpers to work on their own task without having their work affect or be affected by other groups' work. For example, after a project is released with version `1.0.0`, one team is tasked to develop a new feature for the version `1.1.0` milestone while another team is asked to fix a bug that a user reported and whose patch will be released in the version `1.0.1`.

Branch operations are performed through the command `git branch`.

Commit

A commit is an atomic change in a repository. A commit is a set of changes to one or more files within your repository. Each commit is uniquely identified within a repository by the hash (SHA-1) of the changes it contains ("plus" a header).

When you create/delete/edit one or more files in a git repository and you are confident enough about those changes, you can commit them using the command `git commit`.

Note: A commit is not a snapshot (or a copy) of the entire repository at a given point in time. Each commit contains only the incremental difference from the previous commit, called *delta* in git.

A chain of commits in which all the ancestors are included makes a branch. Since every commit is linked to its parent, a branch is simply a *pointer* to a commit (the full chain of commits can always be reconstructed from the commit). In other words, you can think of branches as human friendly labels for commits. Every time you create a new commit, the pointer of the current branch advances to the newly created commit.

Tag

A tag is a human friendly name for a commit but unlike branches, tags are read-only. Once created, they cannot be modified to point to a different commit.

Tags are commonly used for labeling commits that constitute milestones in the project development timeline, for example a release.

Fork

A fork is basically a copy of someone else's repository. Usually, you cannot create branches or change code in other people's repositories, that's why you create your own copy of it. This is called `forking`.

Remote

A git *remote* is a copy of your repository hosted by a git service provider, e.g. GitHub. Remotes allow you to share your commits and branches so that other developers can fetch them. Technically speaking, remotes are exactly the same as local repositories, but unlike your local repository, they are reachable over the internet.

You can use the commands `git fetch` and `git push` to bring your local copy of the repository in sync with a remote, by downloading commits or uploading new commits respectively.

Merging branches

Merging is the dual operation of creating a new branch. Imaigne you have branched out a new branch (e.g. *new-feature*) from the some branch (e.g. *master*), made some improvements and tested them out. Now you want to incorporate these changes in the *master* branch which hosts your main code. The **merge** operation does exactly that. It takes the changes done in *new-feature* and applies them to *master*.

Often git will manage to apply these changes by itself. However, sometimes if both *new-feature* and *master* changed the same part of the code, git cannot determine by itself which of the two changes should be kept. Such a case is called *merge conflict* and you will have to manually select what should be kept after the merge.

Pull Requests

If you are working on a secondary branch or if you forked a repository and want to submit your changes for integration into the mainstream branch or repository, you can open a so-called Pull Request (in short **PR**).

A pull request can be seen as a three-step merge operation between two branches where the changes are first *proposed*, then *discussed and adapted* (if requested), and finally *merged*.

Common operations

Fork a repository on GitHub

To fork (creating a copy of a repository, that does not belong to you), you simply have to go to the repository's webpage and click fork on the upper right corner.

Clone a repository

Cloning a repository is the act of creating a local copy of a remote repository. A repo is cloned only at the very beginning, when you still don't have a local copy of it.

To clone a repository, either copy the HTTPS or SSH link given on the repository's webpage. Use the following command to create a local copy of the remote git repository identified by the given URL.

```
git clone [REPOSITORY-URL]
```

This will create a directory in the current working path with the same name of the repository and the entire history of commits will be downloaded onto your computer.

Create a new branch

The command for creating a new branch is a little bit counter-intuitive, but you will get use to it. Use the following command to create a new branch:

```
git checkout -b [NEW-BRANCH-NAME]
```

This creates a new branch pointing at the same commit your currently active branch is pointing at. In other words, you will end up with two branches pointing at the same commit. Note that after you issue this command, the newly created branch becomes your active branch.

Working tree

In git, we use the term *working tree* to indicate all the changes that are not committed yet. You can think of it as your workspace. When you create a new commit, the hash for the current working tree is computed and assigned to the new commit together with the changes since the last commit. The working tree clears as you commit changes.

Remark: You cannot create commits from a clean working tree.

Use the command `git status` to inspect the status of your working tree.

Create a new commit

Unlike many git operations, a commit is not created by a single git command. There are two steps to follow. First, we mark all the changes that we want to be part of our new commit, second, we create the commit. From your working tree, mark changes to include in the new commit using the command:

```
git add [FILE]
```

The command `git status` will always show you which changes are marked to be used for a new commit and which changes are not. Use the command

```
git commit -m "[COMMIT-MESSAGE]"
```

to create a new commit. Replace `[COMMIT-MESSAGE]` with your notes about what changes this commit includes.

Note: Do not underestimate the value of good commit messages, the moment you will go back to your history of commits looking for a change of interest, having good commit messages will be a game changer.

Push changes

Use the following command to *push* your local changes to the remote repository so that the two repositories can get in sync.

```
git push origin [BRANCH-NAME]
```

Fetch changes

If you suspect that new changes might be available on the remote repository, you can use the command

```
git fetch origin [BRANCH-NAME]
```

to download the new commits available on the remote (if any). These new changes will be appended to the branch called `origin/[BRANCH-NAME]` in your local repository. If you want to apply them to your current branch, use the command

```
git merge origin/[BRANCH-NAME]
```

Use the command `git pull origin/[BRANCH-NAME]` to perform *fetch* and then *merge*.

Delete branches

Unlike the vast majority of git commands, git delete does not work on the current branch. You can delete other branches by running the command

```
git branch -d [BRANCH-NAME]
```

If you want to delete your current branch, you will need to checkout another branch first. This prevents ending up with a repository with no branches.

To propagate the deletion of a branch to the remote repository, run the command:

```
git push origin --delete [BRANCH-NAME]
```

Open a GitHub Issue

If you are experiencing issues with any code or content of a repository (such as this operating manual you are reading right now), you can submit issues. For doing so go to the dashboard of the corresponding repository and press the `Issues` tab where you can open a new request.

For example you encounter a bug or a mistake in this operating manual, please visit this repository's Issues page to report an issue.

GitHub Issues are a crucial part of the life cycle of a software product, as they constitute a feedback loop that goes directly from the end-user to the product developers. You don't have to be a developer or an expert in software engineering to open an Issue.

Hands on

Git

It is strongly suggested to all git beginners to follow the awesome tutorial Learn Git Branching.

Further reading material can be found at the following links:

- Git Handbook
- Basic Branching and Merging

GitHub

You can gain access to GitHub by creating an account on github.com (if you don't have one already).

A short GitHub tutorial is available at this link.

It is higly suggested that you setup an SSH key for secure passwordless access to GitHub by following these steps:

1. Generate a new SSH key
2. Add SSH key to your GitHub account.

Ask the community

If you have any questions about how to use of Git in Duckietown, join and ask on the Duckietown Slack!

Docker

This section will introduce Docker and the features of Docker that the Duckietown community employs. For a more general introduction to Docker, we suggest reading the official Docker overview page.

What is Docker?

Docker is used to perform operating-system-level virtualization, something often referred to as "containerization". While Docker is not the only software that does this, it is by far the most popular one.

Containerization refers to an operating system paradigm in which the kernel allows the existence of multiple isolated user space instances called containers. These containers may look like real computers from the point of view of programs running in them.

A computer program running on an ordinary operating system can see all resources available to the system, e.g. network devices, CPU, RAM; However, programs running inside of a container can only see the container's resources. Resources assigned to the container become thus available to all processes that live inside that container.

Containers VS. Virtual Machine

Containers are often compared to virtual machines (VMs). The main difference is that VMs require a host operating system (OS) with a hypervisor and a number of guest OSs, each with their own libraries and application code. This can result in a significant overhead.

Imagine running a simple Ubuntu server in a VM on Ubuntu: you will have most of the kernel libraries and binaries twice and a lot of the processes will be duplicated on the host and on the guest OS. Containerization, on the other hand, leverages the existing kernel and OS and adds only the additional binaries, libraries and code necessary to run a given application. See the illustration bellow.

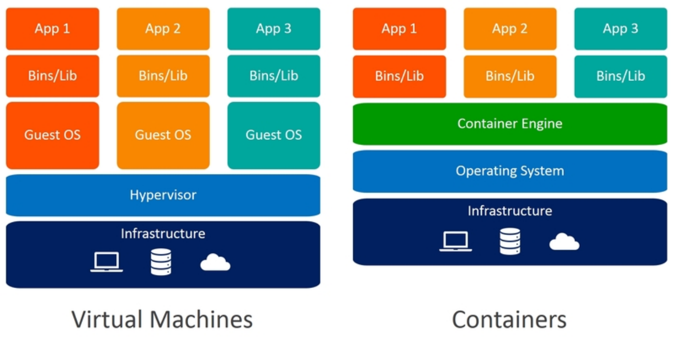


Fig. 2 Differences between Virtual Machines and Containers (source: Weaveworks)

Because containers don't need a separate OS to run they are much more lightweight than VMs. This makes them perfect to use in cases where one needs to deploy a lot of independent services on the same hardware or to deploy on not-especially powerful platforms, such as Raspberry Pi - the platform the Duckietown community uses.

Containers allow for reuse of resources and code, but are also very easy to work with in the context of version control. If one uses a VM, they would need to get into the VM and update all the code they are using there. With a Docker container, the same process is as easy as pulling the container image again.

How does Docker work?

You can think that Docker containers are build from Docker images which in turn are build up of Docker layers. So what are these?

Docker images are build-time artifacts while Docker containers are run-time constructs. That means that a Docker image is static, like a `.zip` or `.iso` file. A container is like a running VM instance: it starts from a static image but as you use it, files and configurations might change.

Docker images are build up from layers. The initial layer is the *base layer*, typically an official stripped-down version of an OS. For example, a lot of the Docker images we run in Duckietown have `ubuntu:18.04` as a base.

Each layer on top of the base layer constitutes a change to the layers below. The Docker internal mechanisms translate this sequence of changes to a file system that the container can then use. If one makes a small change to a file, then typically only a single layer will be changed and when Docker attempts to pull the new version, it will need to download and store only the changed layer, saving space, time and bandwidth.

In the Docker world, images get organized by their repository name, image name and tags. As with Git and GitHub, Docker images are stored in image registers. The most popular Docker register is called DockerHub and it is what we use in Duckietown.

An image stored on DockerHub has a name of the form:

```
[repository/]image[:tag]
```

The parts `repository` and `tag` are optional and they default to `library` (indicating Docker official images) and `latest` (special tag always pointing to the *latest* version of an image). For example, the Duckietown Docker image

```
duckietown/dt-core:ente-arm64v8
```

has the repository name `duckietown`, the image name `dt-core`, and the tag `ente-arm64v8`, which carries both the name of the Duckietown software distribution that the image contains, i.e., `ente`, and the CPU architecture that this image is targeting, i.e., `arm64v8`. We will talk about different CPU architectures and why they need to be part of the Docker image tag in the section .

All Duckietown-related images are in the `duckietown` repository. Though images can be very different from each other and for various applications.

Different CPU architectures

Since Docker images contain binaries, they are not portable across different CPU architectures. In particular, binaries are executable files that are compiled to the level of CPU instructions. Different CPU architectures present different instructions sets.

Many modern computers use the `amd64` architecture, used by almost all modern Intel and AMD processors. This means that it is very likely that you can find a Docker image online and run it on your computer without having to worry about CPU architectures.

In Duckietown, we use low-end computers like the Raspberry Pi (officially used on any Duckietown device) and Nvidia Jetson. These low-cost computers employ Arm processors that are based on the `arm32v7` instructions set.

Note: Full disclosure, while all devices officially supported in Duckietown are based on 64-bit capable Arm processors, thus using the `arm64v8` instructions set, the Raspbian OS only supports 32-bit, which is the reason why we use `arm32v7` images.

Working with images

If you want to get a new image from a Docker registry (e.g. DockerHub), you have to *pull* it. For example, you can get an Ubuntu image by running the command:

```
docker pull ubuntu
```

According to , this will pull the image with full name `library/ubuntu:latest` which, as of May 2020, corresponds to Ubuntu 20.04.

You will now be able to see the new image pulled by running:

```
docker image list
```

If you don’t need it anymore or you are running out of storage space, you can remove an image with,

```
docker image rm ubuntu
```

You can also remove images by their `IMAGE ID` as printed by the `list` command above. A shortcut for `docker image rm` is `docker rmi`.

Sometimes you might have a lot of images you are not using anymore. You can easily remove them all with:

```
docker image prune
```

This will remove all images that are not supporting any container. In fact, you cannot remove images that are being used by one or more containers. To do so, you will have to remove those containers first.

If you want to look into the heart and soul of your images, you can use the commands `docker image history` and `docker image inspect` to get a detailed view.

Working with containers

Containers are the run-time equivalent of images. When you want to start a container, Docker picks up the image you specify, creates a file system from its layers, attaches all devices and directories you want, “boots” it up, sets up the environment up and starts a pre-determined process in this container. All that magic happens with you running a single command: `docker run`. You don’t even need to have pulled the image beforehand, if Docker can’t find it locally, it will look for it on DockerHub.

Here’s a simple example:

```
docker run ubuntu
```

This will take the `ubuntu` image with `latest` tag and will start a container from it.

The above won’t do much. In fact, the container will immediately exit as it has nothing to execute. When the main process of a container exits, the container exits as well. By default the `ubuntu` image runs `bash` and as you don’t pass any commands to it, it exits immediately. This is no fun, though.

Let’s try to keep this container alive for some time by using the `-it` flags. This tells Docker to create an interactive session.

```
docker run -it ubuntu
```

Now you should see something like:

```
root@73335ebd3355:/#
```

Keep in mind that the part after `@` will be different — that is your container ID.

In this manual, we will use the following icon to show that the command should be run in the container:

```
command to be run inside the container
```

You are now in your new `ubuntu` container! Try to play around, you can try to use some basic `bash` commands like `ls`, `cd`, `cat` to make sure that you are not in your host machine.

You can check which containers you are running using the `docker ps` command — analogous to the `ps` command. Open a new terminal window (don't close the other one yet) and type:

```
docker ps
```

An alternative (more explicit) syntax is

```
docker container list
```

These commands list all running containers.

Now you can go back to your `ubuntu` container and type `exit`. This will bring you back to you host shell and will stop the container. If you again run the `docker ps` command you will see nothing running. So does this mean that this container and all changes you might have made in it are gone? Not at all, `docker ps` and `docker container list` only list the *currently running* containers.

You can see all containers, including the stopped ones with:

```
docker container list -a
```

Here `-a` stands for *all*. You will see you have two `ubuntu` containers here. There are two containers because every time you use `docker run`, a new container is created. Note that their names seem strangely random. We could have added custom, more descriptive names—more on this later.

We don't really need these containers, so let's get rid of them:

```
docker container rm ![container name 1] ![container name 2]
```

You need to put your container names after `rm`. Using the containr IDs instead is also possible. Note that if the container you are trying to remove is still running you will be asked to stop it first.

You might need to do some other operations with containers. For example, sometimes you want to start or stop an existing container. You can simply do that with:

```
docker container start ![container name]
docker container stop ![container name]
docker container restart ![container name]
```

Imagine you are running a container in the background. The main process is running but you have no shell attached. How can you interact with the container? You can open a terminal in the container with:

```
docker attach ![container name]
```

Running images

Often we will ask you to run containers with more sophisticated options than what we saw before. Look at the following example: (don't try to run this, it will not do much).

```
docker -H hostname.local run -dit --privileged --name joystick --network=host -v
/data:/data duckietown/rpi-duckiebot-joystick-demo:master18
```

shows a summary of the options we use most often in Duckietown. Below, we give some examples

Short command	Full command	Explanation
`-i`	`--interactive`	Keep STDIN open even if not attached, typically used together with `-t`.
`-t`	`--tty`	Allocate a pseudo-TTY, gives you terminal access to the container, typically used together with `-i`.
`-d`	`--detach`	Run container in background and print container ID.
	`--name`	Sets a name for the container. If you don't specify one, a random name will be generated.
`-v`	`--volume`	Bind mount a volume, exposes a folder on your host as a folder in your container. Be very careful when using this.
`-p`	`--publish`	Publish a container's port(s) to the host, necessary when you need a port to communicate with a program in your container.
`-d`	`--device`	Similar to `-v` but for devices. This grants the container access to a device you specify. Be very careful when using this.
	`--privileged`	Give extended privileges to this container. That includes access to **all** devices. Be **extremely** careful when using this.
	`--rm`	Automatically remove the container when it exits.
`-H`	`--hostname`	Specifies remote host name, for example when you want to execute the command on your Duckiebot, not on your computer.
	`--help`	Prints information about these and other options.

Table 1 `docker run` Options

Examples

Set the container name to `joystick`:

```
--name joystick
```

Mount the host's path `/home/myuser/data` to `/data` inside the container:

```
-v /home/myuser/data:/data
```

Publish port 8080 in the container as 8082 on the host:

```
-p 8082:8080
```

Allow the container to use the device `/dev/mmcblk0`:

```
-d /dev/mmcblk0
```

Run a container on the Duckiebot:

```
-H duckiebot.local
```

Other useful commands

Pruning images

Sometimes your docker system will be clogged with images, containers, networks, etc. You can use `docker system prune` to clean it up.

```
docker system prune
```

Keep in mind that this command will delete **all** containers that are not currently running and **all** images not used by running containers. So be extremely careful when using it.

Portainer

Often, for simple operations and basic commands, one can use Portainer.

Portainer is itself a Docker container that allows you to control the Docker daemon through your web browser. You can install it by running:

```
docker volume create portainer_data
docker run -d -p 9000:9000 --name portainer --restart always -v
/var/run/docker.sock:/var/run/docker.sock -v portainer_data:/data
portainer/portainer
```

Note that Portainer comes pre-installed on your Duckiebot, so you don't need to run the above command to access the images and containers on your robot. You still might want to set it up for your computer.

Hands on

Before you can do any software development in Duckietown, you need to get comfortable with Docker and its tools.

Complete the following steps before proceeding to the next section:

1. Install Docker
2. Orientation and Setup
3. Build and run your image
4. Share images on Docker Hub

If you still feel like there is something that you are missing about Docker, you might want to spend some time going through this guide as well.

Ask the community

If you need help with Docker basics or the use of Docker in Duckietown, join the Slack channel #help-docker.

Duckietown Shell

This section of the book will introduce the Duckietown Shell (`dts` in short) and the reason behind its creation. In this book, we will use dts commands quite often, make sure you don't miss this section.

Brief History

The Duckietown Shell is indeed a shell. It was created in July 2018 to help Duckietown users launch Duckietown demos on a Duckiebot. It became clear pretty soon that having a dedicated shell for Duckietown was a game changer for the whole community. In fact, since the very beginning, the shell had a built-in system for auto-update, which allowed developers to develop new commands or improve old ones and deploy the changes in no time.

Duckietown has a history of using `Makefiles` as a way to simplify complex and operations involving many (usually very long) bash commands. Other developers, instead, preferred bash scripts over Makefiles. And finally, our CI system (based on Jenkins), used `Jenkinsfiles` to define automated jobs.

The Duckietown Shell came to the rescue and unified everything, while Makefiles, bash scripts and Jenkinsfiles slowly started disappearing from our repositories. Today, Docker images to run on Duckiebots, Python libraries published on PyPi and even the book you are reading right now are built through dts.

Get Started

The Duckietown Shell is released as a Python3 package through the PyPi package store. You can install the Duckietown Shell on your computer by running,

```
pip3 install duckietown-shell
```

This will install the `dts` command. The Duckietown Shell is distribution independent, so the first time you launch it you have to specify the distribution of Duckietown software you are working on by following the setup prompts.

Use the command,

```
(Cmd) commands
```

to list all the commands available to the chosen distribution.

You don't really need to run the shell before you can type in your command, for example, you can achieve the same result as above by running,

```
dts commands
```

> **Note**
>
> The nice thing about opening the shell before typing your command is that then you can use the `Tab` key to auto-complete.

Installable commands

Some commands come **not** pre-installed. These are usually commands that are either very specific to an application, thus not useful to the majority of Duckietown users, or commands that can only be used during a short time window, like commands that let you participate to competitions periodically organized at international AI and Robotics conferences, e.g. AIDO.

Hands on

Install the Duckietown Shell as instructed in . Make sure everything works as expected by running the command `dts update` successfully.

Ask the community

If you have any questions about the Duckietown Shell, join and ask on the Duckietown Slack!

Beginner - The **DTProject**

What you will need	• Working environment setup • Accounts setup • Basic knowledge of Python
What you will get	• Learn how to use DTProjects, the most important building block in Duckietown

Table of contents

New project

What you will need	• Working environment setup

	• Accounts setup • Basic knowledge of Python
What you will get	• Learn how to use DTProjects, the most important building block in Duckietown • Learn how to create a new DTProject from a template

Duckietown-compliant Docker images are built out of Duckietown Projects, in short `DTProjects`. A boilerplate for the simplest DTProject is provided by the duckietown/template-basic repository.

Create project from a template

Visit the template repository page duckietown/template-basic. Click on the button that reads “Use this template” and then choose “Create a new repository” from the dropdown menu.

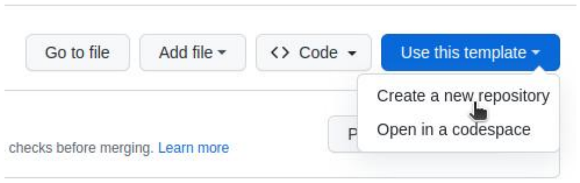
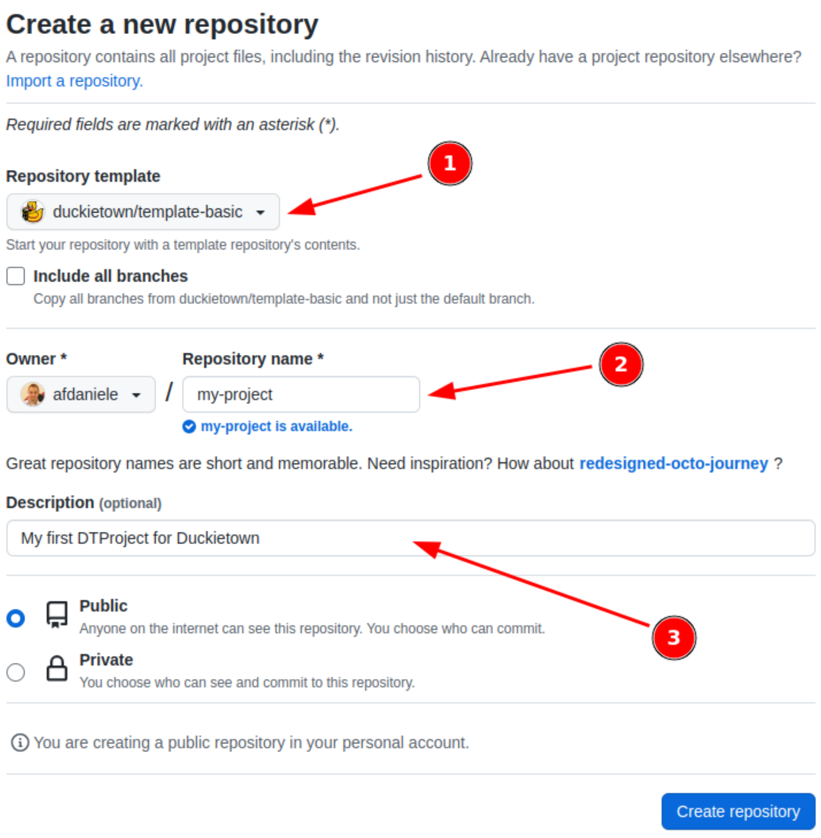


Fig. 3 Use template repository on GitHub.

This will take you to a page that looks like the following:


Create a new repository

A repository contains all project files, including the revision history. Already have a project repository elsewhere? Import a repository.

Required fields are marked with an asterisk (*).

Repository template: duckietown/template-basic

Start your repository with a template repository's contents.

☐ Include all branches
Copy all branches from duckietown/template-basic and not just the default branch.

Owner *: afdaniele / Repository name *: my-project

my-project is available.

Great repository names are short and memorable. Need inspiration? How about redesigned-octo-journey ?

Description (optional): My first DTProject for Duckietown

● Public
Anyone on the internet can see this repository. You choose who can commit.

○ Private
You choose who can see and commit to this repository.

You are creating a public repository in your personal account.

Fig. 4 Creating a repository from template.

Pick a name for your repository (say `my-project`) and press the button *Create repository from template*. Note, you can replace `my-project` with the name of the repository that you prefer, if you do change it, make sure you use the right name in the instructions going forward.

This will create a new repository and copy everything from the repository `template-basic` to your new repository. You can now open a terminal and clone your newly created repository.

```
git clone https://github.com/YOUR_NAME/my-project
cd my-project
```

> **Note**
>
> Replace `YOUR_NAME` in the link above with your GitHub username.

Edit placeholders

The repository contains already everything you need to create a Duckietown-compliant Docker image for your program. Before doing anything else, we need to head over to the `Dockerfile` and edit the following lines using a text editor:

```
ARG REPO_NAME="<REPO_NAME_HERE>"
ARG DESCRIPTION="<DESCRIPTION_HERE>"
ARG MAINTAINER="<YOUR_FULL_NAME> (<YOUR_EMAIL_ADDRESS>)"
```

Replace the placeholders strings with, respectively,

- the name of the repository (i.e., `my-project`);
- a brief description of the functionalities of the module
- your name and email address to claim the role of maintainer;

For example,

```
ARG REPO_NAME="my-project"
ARG DESCRIPTION="My first Duckietown project"
ARG MAINTAINER="Duckie (duckie@duckietown.com)"
```

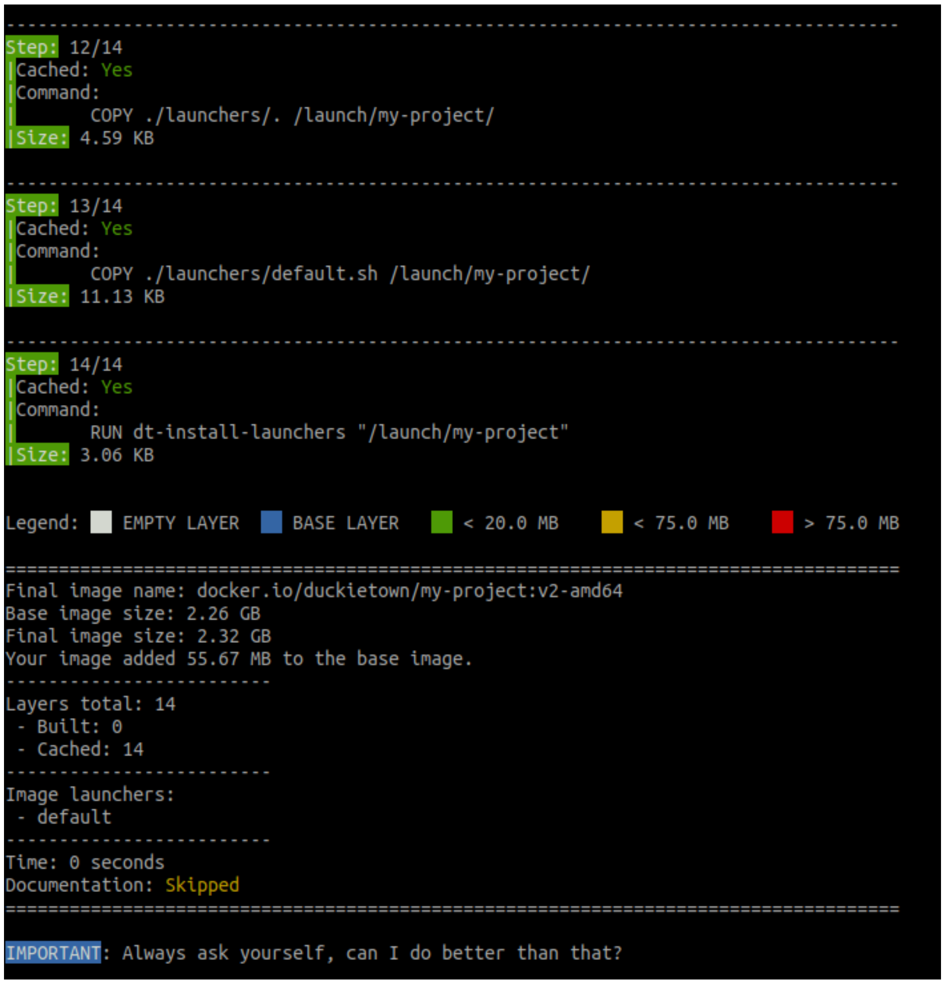
Save the changes. We can now build the image, even though there is not going to be much going on inside it until we place our code in it.

Build the project

Now, in a terminal, move to the directory created by the `git clone` instruction above and run the following command (beware that it might take some time):

```
dts devel build -f
```

The flag `-f` (short for `--force`) is needed in order to allow `dts` to build a module out of a non-clean repository. A repository is not clean when there are changes that are not committed (and in fact our changes to `Dockerfile` are not). This check is in place to prevent developers from forgetting to push local changes. If the build is successful, you will see something like the following:



```
--------------------------------------------------------------------------------------
Step: 12/14
|Cached: Yes
|Command:
|       COPY ./launchers/. /launch/my-project/
|Size: 4.59 KB

--------------------------------------------------------------------------------------
Step: 13/14
|Cached: Yes
|Command:
|       COPY ./launchers/default.sh /launch/my-project/
|Size: 11.13 KB

--------------------------------------------------------------------------------------
Step: 14/14
|Cached: Yes
|Command:
|       RUN dt-install-launchers "/launch/my-project"
|Size: 3.06 KB

Legend: ⬜ EMPTY LAYER 🟦 BASE LAYER 🟩 < 20.0 MB 🟨 < 75.0 MB 🟥 > 75.0 MB

======================================================================================
Final image name: docker.io/duckietown/my-project:v2-amd64
Base image size: 2.26 GB
Final image size: 2.32 GB
Your image added 55.67 MB to the base image.
-------------------------
Layers total: 14
 - Built: 0
 - Cached: 14
-------------------------
Image launchers:
 - default
-------------------------
Time: 0 seconds
Documentation: Skipped
======================================================================================

IMPORTANT: Always ask yourself, can I do better than that?
```

Fig. 5 Building a container through the development command in the Duckietown shell.

As discussed above, building a project produces a Docker image. This image is the *compiled* version of your source project. You can find the name of the resulting image at the end of the output of the `dts devel build` command. In the example above, look for the line:

```
Final image name: docker.io/duckietown/my-project:v2-amd64
```

Run the project

You can now run your container by executing the following command.

```
dts devel run
```

This will show the following message:

```
...
==> Launching app...
This is an empty launch script. Update it to launch your application.
<== App terminated!
```

Congratulations

You just built and run your first Duckietown-compliant Docker image.

Add your code

Now that we know how to build Docker images for Duckietown, let’s build one with a simple Python program inside.

Open a terminal and go to the directory `my-project` created in the previous page. In Duckietown, Python code must belong to a Python package. Python packages are placed inside the directory `packages/` you can find at the root of `my-project`. Let us go ahead and create a directory called `my_package` inside `packages/`.

```
mkdir -p ./packages/my_package
```

A Python package is simply a directory containing a special file called `__init__.py`. So, let us turn that `my_package` into a Python package.

```
touch ./packages/my_package/__init__.py
```

Now that we have a Python package, we can create a Python script in it. Use your favorite text editor or IDE to create the file `./packages/my_package/my_script.py` and place the following code inside it.

```
message = "\nHello World!\n"
print(message)
```

We now need to tell Docker we want this script to be the one executed when we run the command `dts devel run`. In order to do so, open the file `./launchers/default.sh` and replace the line

```
echo "This is an empty launch script. Update it to launch your application."
```

with the line

```
dt-exec python3 -m "my_package.my_script"
```

Note

Always prepend `dt-exec` to the main command in `./launchers/default.sh`.

Using `dt-exec` helps us deal with an interesting problem called “The zombie reaping problem” (more about this in this article).

You can also create more launcher scripts. To know more about that, check out the page Launchers.

Let us now re-build the image:

```
dts devel build -f
```

and run it:

```
dts devel run
```

This will show the following message:

```
...
==> Launching app...

Hello World!

<== App terminated!
```

Congratulations 🎉

You just built and run your own Duckietown-compliant Docker image.

Define dependencies

It is quite common that our programs need to import libraries, thus we need a way to install them. Since our programs reside in Docker images, we need a way to install libraries inside the image when the image is built.

All the project templates provided by Duckietown support two package managers out of the box:

- Advanced Package Tool (`apt`)
- Pip Installs Packages for Python3 (`pip3`)

List your apt packages or pip3 packages in the files `dependencies-apt.txt`. As for `pip3` dependencies, we make a distinction between Duckietown-owned and third-party libraries. List all the Duckietown-owned libraries you want to install in the file `dependencies-py3.dt.txt` and third-party libraries in the file `dependencies-py3.txt`.

> **Note**
>
> Dependencies files support comments (lines starting with `#`) and empty lines. Use them to group dependencies together and make dependencies lists easier to read and maintain.

Running `dts devel build` after editing these files will rebuild the image with the new dependencies installed.

That's it! Now you know how to customize dependencies as well!

Exercise: Basic NumPy program

Write a program that performs the sum of two numbers using NumPy. Add `numpy` to the file `dependencies-py3.txt` to have it installed in the Docker image.

Run on your Duckiebot

Now that we know how to package a piece of software into a Docker image for Duckietown using DTProjects, we can go one step further and write code that will run on the robot instead of our local computer.

This part assumes that you have a Duckiebot up and running with hostname `ROBOT_NAME`. Of course, you don't need to change the hostname to `ROBOT_NAME`, just replace it with your robot name in the instructions below. You can make sure that your robot is ready by executing the command

```
ping ROBOT_NAME.local
```

If we can ping the robot, we are good to go.

Let us go back to our script file `my_script.py` we created in Add your code and change it to:

```
import os

vehicle_name = os.environ['VEHICLE_NAME']
message = f"\nHello from {vehicle_name}!\n"
print(message)
```

We can now modify slightly the instructions for building the image so that the image gets built directly on the robot instead of our computer. Run the command

```
dts devel build -f -H ROBOT_NAME
```

As you can see, we added `-H ROBOT_NAME` to the build command. This new option tells `dts` where to build the image.

Once the image is built, we can run it on the robot by running the command

```
dts devel run -H ROBOT_NAME
```

If everything worked as expected, you should see the following output,

```
...
==> Launching app...

Hello from ROBOT_NAME!

<== App terminated!
```

Note

Some WARNING and INFO messages from `dts` and from the container's entrypoint are expected. Here are some examples:

From `dts`

- `WARNING:dts:Forced!`
- `INFO:dts:Running an image for arm64v8 on aarch64.`

Among entrypoint logs of the container:

- `INFO: The environment variable VEHICLE_NAME is not set. Using 'myduckiebot'.`

Congratulations

You just built and run your first Duckietown-compliant and Duckiebot-compatible Docker image. We are sure this is just the first of many!

Launchers

As we discussed earlier, the directory `launchers/` contains scripts that can serve as entry scripts to the Docker containers that are spawned out of a DTProject Docker image.

Attention

If you are familiar with Docker.

We purposefully refer to these scripts as **entry scripts** as not to confuse them with **entrypoints** as they are defined by Docker. In fact, launcher scripts **will not** be directly used as container entrypoints. A generic entrypoint is defined in all Duckietown images and is used to configure the containers' network, environment, etc.

The default launcher

Every project template comes with a launcher file called `default.sh`. This is the launcher that runs by default inside the container when we run the command `dts devel run`. This launcher should be modified and set to launch the main behavior of our project. For example, when making a DTProject that implements autonomous lane following in Duckietown, we want our default launcher to run the lane following pipeline.

While the default launcher is great, you will quickly realize that, for some projects, having only one entry behavior is quite limiting. For example, let us imagine that we are working on an autonomous lane following behavior DTProject. In this case, apart from running the full behavior (we will use the default launcher for that), it might be useful to have entry scripts that allow us to run single components of our multi-component lane follower pipeline, say, so that we can test single components one at a time.

In some cases, we will use additional launchers as test scripts. In other cases, it might make sense to leave the default launcher untouched and only implement additional launchers. This might be useful, for example, when a DTProject implements a collection of sensor calibrations. In this case, we might want to leave the default launcher untouched as there is no “default calibration”, and then have the additional launchers `camera-intrinsic-calibration.sh`, `camera-extrinsic-calibration.sh`, etc.

Add new launcher

In order to add a new launcher, you can simply make a new file inside the `launchers/` directory. The only rule is that such file must either have extension `.sh`, or, have a shebang declaration on its first line.

For example, we can make a launcher out of a Python script file `launchers/my-launcher.py` with the content,

```
#!/usr/bin/env python3

message = "This is a Python launcher"
print(message)
```

Note

The output from the command `dts devel build` shows the list of launchers installed in the image we just built. For example,

```
...
------------------------
Image launchers:
 - default
 - test-agent
 - test-lens-distortion
------------------------
```

Launchers inside the container

Launchers inside the container appear as shell commands named as `dt-launcher-<LAUNCHER_NAME>`. For example, the launcher file `launchers/my-launcher.sh` will be available as the shell command `dt-launcher-my-launcher`.

A typical example launcher script explained

In this section, we take a look at a simple and typical launcher script. In particular, let’s try to understand these utilities:

- `dt-launchfile-init`
- `dt-exec`
- `dt-launchfile-join`

Here is an example launcher script in dt-commons:

```
#!/bin/bash
source /environment.sh

dt-launchfile-init
dt-exec echo "This is an empty launch script. Update it to launch your application."
dt-launchfile-join
```

Let’s take a look at the file line by line, after the *shebang* (`#!/bin/bash`) line .

```
source /environment.sh
```

The above line loads our custom wrappers/functions facilitating launching programs. They are defined in this file, among which the reader in most cases only need to care about the use of the following 3 utilities.

```
dt-launchfile-init
```

The above makes sure the terminating signals are registered correctly for the programs that are run in this script. And it prints the line that goes `"==> Launching app..."`.

Here is what's meant by "register terminating signals": It is common to press `[Ctrl+C]` to stop a terminal program. What happens under the hood is a signal is sent to the foreground process that runs in the terminal. The process then decides what to do upon receiving one. And with `dt-launchfile-init`, it is setup such that the `SIGINT` signal will be passed to all child processes of the launcher script. In particular, when `[Ctrl+C]` is captured from the terminal, or when one performs `docker stop ...` to kill a container that runs a launcher script, this utility helps "broadcast" `SIGINT` for its child processes to shutdown properly.

It is common to have some clean-up handling when `SIGINT` is received, e.g. `on_shutdown` function of classes inheriting from DTROS. That is why it is important to ensure this signal gets through to all the child processes.

```
dt-exec ...
```

The `dt-exec` function allows us to make new child processes and have them run in the background. You can have as many child processes as you want (i.e., have multiple commands of the form `dt-exec ...`). They all be kept running in the background and warned by `dt-launchfile-init` when a signal is received. Use `dt-exec` only for long running processes, i.e., processes that run until the container is stopped.

```
dt-launchfile-join
```

The above utility waits for any child processes to finish and return. The child processes should be shutdown properly with the help from `dt-launchfile-init`. And once they all exited, the following will be printed in the console: `"<== App terminated!"`.

In summary, these 3 utilities help better manage the signals and processes within the launcher script, and should be used for your launcher scripts as well.

Project Templates

While DTProjects are open to all sorts of customizations to accommodate for virtually any need, Duckietown provides a set of templated projects that cover the most common use cases. For each project template we provide a templated repository.

Coding project templates

These project templates are designed for projects implementing robot behaviors (e.g., lane following), back-end systems (e.g., REST APIs), etc.

Name	Features	Link
basic	• Ubuntu 20.04 base image • Support for Python packages in `packages/`	duckietown/template-basic
ros	• Same as **basic** • Support for ROS • Support for catkin packages in `packages/`	duckietown/template-ros
core	• Same as **ros** • Duckietown autonomous driving modules baked in	duckietown/template-core

Table 2 Coding project templates

Documentation project templates

These project templates are designed for projects implementing documentation books and manuals such as the one you are looking at right now.

Name	Features	Link
book	• Based on Jupyter Book • Compiles into HTML and PDF • Easy cross-reference with Duckietown books library	duckietown/template-book

Table 3 Documentation project templates

Duckietown Learning Experiences (LXs) project templates

These project templates are designed for the development of web-based dashboards based on `\compose\`. A project based on this template is the robot dashboard.

Name	Link
lx	duckietown/template-lx
lx-recipe	duckietown/template-lx-recipe

Table 4 Duckietown Learning Experiences (LXs) project templates

Dashboard project templates

These project templates are designed for the development of web-based dashboards based on `\compose\`. A project based on this template is the robot dashboard.

Name	Link
compose	duckietown/template-compose

Table 5 Dashboard project templates

In Duckietown, everything runs in Docker containers. All you need in order to run a piece of software in Duckietown is a Duckietown-compliant Docker image with your software in it.

Duckietown-compliant Docker images are built out of Duckietown Projects, in short `DTProjects`. A DTProject is a git repository with an agreed-upon structure that our automated tools can parse. Everybody can use existing DTProjects and everybody can create new ones and distribute them freely over the internet. Agreeing on a structure for our code is crucial for the creation of a community of developers who can easily share their solutions.

High level robot behaviors in Duckietown, such as autonomous driving (in Duckiebots) or autonomous flight (in Duckiedrones), are implemented collectively by a set of DTProjects. Breaking down a complex problem into smaller problems that are tackled independently is very common in software development and is inspired by a military strategy called “divide and conquer” (latin: *divide et impera*) commonly used by the Roman Empire.

By implementing complex behaviors as the union of smaller and simpler DTProjects, we can drastically improve the **usability**, **mantainability**, and **modularity** of our software solutions. Moreover, DTProjects can be exchanged, shared, extended, and improved with and by the community.

Each DTProject produces a Docker Image

As we will see in the next sections, a DTProject needs to be built into its corresponding executable Docker image before it can be executed.

Understanding the pros and cons of forcing code to only run inside Docker containers right now is crucial.

Bad news first! The biggest downside of using Docker to isolate the execution of our code is that by doing so, we are wrapping our source code inside a Docker image. This makes it harder for us to do development, since our code will not be easily accessible through our local file system. This is what scares/frustrates people away from Docker the most. Keep it in mind, if it happens to you, you are not the only one. The Duckietown development workflow explained in this book aims, among other things, at reducing the effect of this code isolation. We will get back to this topic later in the book.

As for the good news, i.e., why using Docker to isolate our code makes sense and our life easier, we could write a book about it, but it is better if we discover those benefits as we go.

Structure of a DTProject

DTProjects have an agreed-upon files structure with known locations for source code, configuration files, dependencies lists, etc.

Meta-files

- `.dtproject`: Signals that this directory contains a Duckietown Project;
- `.gitignore`: List of files and directories ignore by `git`;
- `.dockerignore`: List of files and directories ignore by `docker`;
- `.bumpversion.cfg`: Configuration for bumpversion, used to perform semantic versioning on the project;

Docker

- `Dockerfile`: Dockerfile building the project's Docker image;
- `configurations.yaml`: Collection of Docker container configurations that can be used on this project;

Source code

- `packages/`: This directory can contain both Python and Catkin packages;
- `launchers/`: Scripts that can be used as entry scripts inside the project's Docker container;

Dependencies

- `dependencies-apt.txt`: List of dependency packages that can be installed via `apt`;
- `dependencies-py3.dt.txt`: List of Duckietown-owned dependency packages that can be installed via `pip`;
- `dependencies-py3.txt`: List of third-party dependency packages that can be installed via `pip`;

Assets and Documentation

- `assets/`: Store static assets in this directory. For example, configuration files you need to bake into the image;
- `docs/`: Contains a book project that can be used to write documentation about this project;
- `html/`: Hosts the HTML of the compiled documentation in `docs/`;

Other

- `LICENSE.pdf`: The Duckietown Software Terms of Use;
- `README.md`: Brief description of the DTProject;

Project Templates

While a DTProject exposes a lot of parameters that the final user can tune, e.g., base Docker image, support for ROS, etc., it helps to have a set of predefined presets covering the most common use cases. We call these **Project Templates**. Project templates are stored on GitHub as **Template Repositories**. These are of a special kind of repositories and their main characteristic is that one can use them to initialize new repositories.

The simplest module template is called `basic` and its template repository is duckietown/template-basic. Since understanding the differences between different templates is outside the scope of this section, we can use any template for the remainder of this section, we suggest using the one above. For a list of predefined project templates, check out the Project Templates

In the next sections of this chapter we will learn how to customize, build, and run our own DTProjects both locally and on a Duckietown robot.

Beginner - Use ROS

What you will need	• A computer set up with the Duckietown software requirements • An initialized Duckiebot • Completed tutorial on DTProject
What you will get	• A working knowledge of ROS development in Duckietown • A custom ROS node with a publisher and a subscriber running on your Duckiebot

Table of contents

New ROS DTProject

What you will need	• Working environment setup • Accounts setup
What you will get	• Learn how to create a new ROS-compatible DTProject from a template

Create project from a template

Visit the template repository page duckietown/template-ros. Click on the button that reads “Use this template” and then choose “Create a new repository” from the dropdown menu.

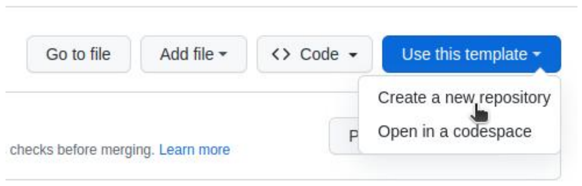
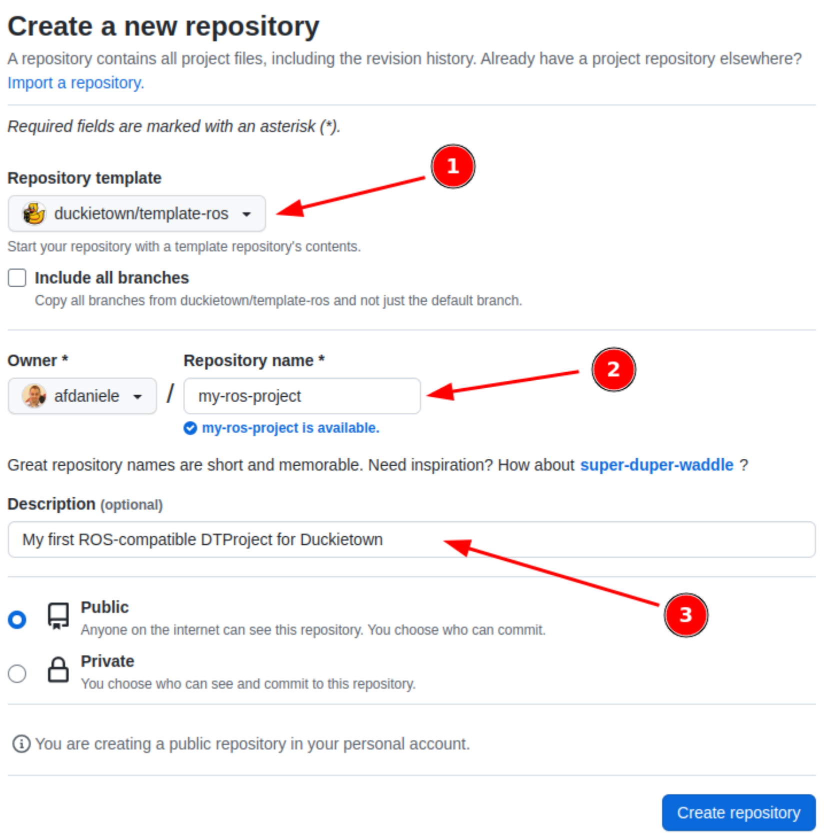


Fig. 6 Use template repository on GitHub.

This will take you to a page that looks like the following:


Create a new repository

A repository contains all project files, including the revision history. Already have a project repository elsewhere? Import a repository.

Required fields are marked with an asterisk (*).

Repository template: duckietown/template-ros

Start your repository with a template repository's contents.

Include all branches

Copy all branches from duckietown/template-ros and not just the default branch.

Owner *: afdaniele / Repository name *: my-ros-project

my-ros-project is available.

Great repository names are short and memorable. Need inspiration? How about super-duper-waddle ?

Description (optional): My first ROS-compatible DTProject for Duckietown

[✓ Public] Anyone on the internet can see this repository. You choose who can commit.

Private: You choose who can see and commit to this repository.

You are creating a public repository in your personal account.

Fig. 7 Creating a repository from template.

Make sure the selected template is `duckietown/template-ros`, pick a name for our repository (e.g., `my-ros-project`), and add a description for the new repository.

Click on the button *Create repository*.

Note

You can replace `my-ros-project` with the name of the repository that you prefer. If you do change it, make sure you use the right name in the instructions going forward.

This will create a new repository starting from the content of the template `template-ros`. You can now open a terminal and clone your newly created repository.

```
git clone https://github.com/YOUR_NAME/my-ros-project
cd my-ros-project
```

Note

Replace `YOUR_NAME` in the link above with your GitHub username.

Edit placeholders

As we learned in Edit placeholders, we now need to edit the placeholders left by the template. Head over to the `Dockerfile` and edit the following lines using any text editor:

```
ARG REPO_NAME="<REPO_NAME_HERE>"
ARG DESCRIPTION="<DESCRIPTION_HERE>"
ARG MAINTAINER="<YOUR_FULL_NAME> (<YOUR_EMAIL_ADDRESS>)"
```

Replace the placeholders strings with, respectively,

- the name of the repository (i.e., `my-ros-project`);
- a brief description of the functionalities implemented in this project;
- your name and email address to claim the role of maintainer;

Save the changes. We can now compile this project into a Docker image.

Build the project

Exactly as in Build the project, we can now move to the project root and run the following command to build our project (beware that it might take some time):

```
dts devel build -f
```

Again, building a project produces a Docker image. This image is the *compiled* version of your source project. You can find the name of the resulting image at the end of the output of the `dts devel build` command. In this case, look for the line:

```
Final image name: duckietown/my-ros-project:v2-amd64
```

Run the project

Again, as in Run the project, we can run our project by executing the command,

```
dts devel run
```

This will show the following message:

```
...
==> Launching app...
This is an empty launch script. Update it to launch your application.
<== App terminated!
```

> **Congratulations**
>
> You just built and run your first ROS-based Duckietown-compliant Docker image.

Catkin Packages

What you will need	• New ROS DTProject as described here
What you will get	• Learn how to create a new catkin package inside a DTProject

ROS uses the catkin build system to organize and build its software. If you are not familiar with the catkin build system, you can learn about it by following the official tutorials.

In a nutshell, catkin organizes entire projects in the so-called *catkin workspaces*. A catkin workspace is nothing more than a directory containing a bunch of software modules called *catkin packages*. Each software module can contain a set of executables (e.g., binaries, script files) called *ROS nodes*. ROS nodes interact with one another using two of the most common communication patterns, called **`publish-subscribe`** and **`request-reply`**.

ROS implements the `publish-subscribe` pattern using **ROS Publishers** and **ROS Subscribers**, and the `request-reply` pattern using **ROS Services**. More on these later.

Let us now take a step back and review catkin workspaces, packages, and nodes more in details.

Catkin workspace

The directory `packages/` you find at the root of a DTProject is a catkin workspace.

Advanced: the real story behind the *packages* directory

In reality, `packages/` is more of a sub-workspace, as it is internally joined with other `packages/` directories from other projects (the ancestor projects) to form a full catkin workspace.

Create a new Catkin package

Open a terminal at the root of the DTProject `my-ros-project` created earlier. Again, Catkin packages are directories inside the directory `packages/` of `my-ros-project`. Let us go ahead and create a new directory called `my_package` inside `packages/`.

```
mkdir -p ./packages/my_package
```

A Catkin package (also known as a *ROS package*) is simply a directory containing two special files, `package.xml` and `CMakeLists.txt`. So, let us turn the `my_package` folder into a ROS package by creating these two files.

Create the file `package.xml` inside `my_package` using your favorite text editor and place/adjust the following content inside it:

```
<package>
  <name>my_package</name>
  <version>0.0.1</version>
  <description>
  My first Catkin package in Duckietown.
  </description>
  <maintainer email="YOUR_EMAIL@EXAMPLE.COM">YOUR_FULL_NAME</maintainer>
  <license>None</license>

  <buildtool_depend>catkin</buildtool_depend>
</package>
```

Replace `YOUR_FULL_NAME` with your first and last name and `YOUR_EMAIL@EXAMPLE.COM` with your email address.

Now, create the file `CMakeLists.txt` inside `my_package` using your favorite text editor and place/adjust the following content inside it:

```
cmake_minimum_required(VERSION 2.8.3)
project(my_package)

find_package(catkin REQUIRED COMPONENTS
  rospy
)

catkin_package()
```

We now have a catkin package inside a catkin workspace in a ROS-capable DTProject. We will now add our code by adding ROS nodes to our catkin package.

ROS Publisher

What you will need	• A Duckietown robot turned ON and visible on `dts fleet discover`
What you will get	• Learn how to create a new **ROS Node** publishing messages using a **ROS Publisher**

The most common communication pattern in Robotics is known as **`publish-subscribe`**. ROS implements the `publish-subscribe` pattern using **ROS Publishers** and **ROS Subscribers**. In this section, we will learn to create a **ROS Publisher**.

The general concept is simple, a publisher has the job of publishing messages from a ROS node into the ROS network for other nodes to receive (using **ROS Subscribers**).

Create Publisher ROS Node

We will see how to write a simple ROS program with Python, but any language supported by ROS should do it. In Create a new Catkin package, we learned how to make a new Catkin package, we will now populate that package with a ROS node hosting a ROS Publisher.

Nodes are placed inside the directory `src/` of a Catkin package. Let us go ahead and create the directory `src` inside `my_package`. We can do so by running the following command from the root of our DTProject.

```
mkdir -p ./packages/my_package/src
```

We now use our favorite text editor to create the file `my_publisher_node.py` inside the `src/` directory we just created and place the following code in it:

```
#!/usr/bin/env python3

import os
import rospy
from std_msgs.msg import String
from duckietown.dtros import DTROS, NodeType


class MyPublisherNode(DTROS):

    def __init__(self, node_name):
        # initialize the DTROS parent class
        super(MyPublisherNode, self).__init__(node_name=node_name,
node_type=NodeType.GENERIC)
        # static parameters
        self._vehicle_name = os.environ['VEHICLE_NAME']
        # construct publisher
        self._publisher = rospy.Publisher('chatter', String, queue_size=10)

    def run(self):
        # publish message every 1 second (1 Hz)
        rate = rospy.Rate(1)
        message = f"Hello from {self._vehicle_name}!"
        while not rospy.is_shutdown():
            rospy.loginfo("Publishing message: '%s'" % message)
            self._publisher.publish(message)
            rate.sleep()

if __name__ == '__main__':
    # create the node
    node = MyPublisherNode(node_name='my_publisher_node')
    # run node
    node.run()
    # keep the process from terminating
    rospy.spin()
```

Note

Using the super class `DTROS` provided by the Python module `duckietown.dtros` is not mandatory but it is highly suggested as it provides a lot of useful features that plain ROS does not. More on these later.

We now need to the tell our file system that we want our file `my_publisher_node.py` be treated as an executable file. We do so by running the following command from the root of our DTProject:

```
chmod +x ./packages/my_package/src/my_publisher_node.py
```

Define launcher

As we discussed above, everything in Duckietown runs inside Docker containers. This means that we also need to tell Docker what to run when the container is started. In this case, we want our new ROS publisher node to run.

Each DTProject compiles into a single Docker image, but we can declare multiple start "behaviors" for the same project/image so that the same project can serve multiple (though related) purposes. As we learned in Launchers, we can use **launchers** to accomplish this. As we learned in Add new launcher, we create a new launcher to allow for this new start behavior.

In order to do so, we create the file `./launchers/my-publisher.sh` and add the following content,

```
#!/bin/bash

source /environment.sh

# initialize launch file
dt-launchfile-init

# launch publisher
rosrun my_package my_publisher_node.py

# wait for app to end
dt-launchfile-join
```

Launch the Publisher node

This part assumes that you have a Duckiebot up and running with a known hostname, e.g., `ROBOT_NAME`. Let us make sure that our robot is ready by executing the command,

```
ping ROBOT_NAME.local
```

If you can ping the robot, you are good to go.

Let us now re-compile our project using the command

```
dts devel build -H ROBOT_NAME -f
```

and run it using the newly defined launcher (we use the flag `-L/--launcher` to achieve this):

```
dts devel run -H ROBOT_NAME -L my-publisher
```

This will show the following message:

```
...
==> Launching app...
[INFO] [1693000564.020676]: [/my_publisher_node] Initializing...
[INFO] [1693000564.028260]: [/my_publisher_node] Node starting with switch=True
[INFO] [1693000564.029052]: [/my_publisher_node] Found 0 user configuration files in
'/data/config/nodes/generic'
[INFO] [1693000564.029608]: [/my_publisher_node] Found 0 user configuration files in
'/data/config/nodes/my_publisher_node'
[INFO] [1693000564.034693]: [/my_publisher_node] Health status changed [STARTING] ->
[STARTED]
[INFO] [1693000564.035819]: Publishing message: 'Hello from vbot!'
[INFO] [1693000565.036489]: Publishing message: 'Hello from vbot!'
[INFO] [1693000566.036378]: Publishing message: 'Hello from vbot!'
...
```

Congratulations □

You just built and run your first Duckietown-compliant and Duckiebot-compatible ROS publisher.

If you want to stop it, just use `Ctrl+C`.

ROS Subscriber

What you will need	• A Duckietown robot turned ON and visible on `dts fleet discover`
What you will get	• Learn how to create a new **ROS Node** receiving messages

using a **ROS Subscriber**

The most common communication pattern in Robotics is known as `publish-subscribe`. ROS implements the `publish-subscribe` pattern using **ROS Publishers** and **ROS Subscribers**. In this section, we will learn to create a **ROS Subscriber**.

The general concept is simple: a subscriber has the job of listening for messages about a specific *topic* that are published by other ROS nodes (using **ROS Publishers**) over a ROS network.

Create Subscriber ROS Node

In Create a new Catkin package, we learned how to make a new Catkin package, we will now populate that package with a ROS node hosting a ROS Subscriber.

Again, nodes are placed inside the directory `src/` of a Catkin package. If we followed the tutorial Create Publisher ROS Node we should already have this directory.

We now use our favorite text editor to create the file `my_subscriber_node.py` inside the `src/` directory we just created and place the following code in it:

```
#!/usr/bin/env python3

import rospy
from duckietown.dtros import DTROS, NodeType
from std_msgs.msg import String

class MySubscriberNode(DTROS):

    def __init__(self, node_name):
        # initialize the DTROS parent class
        super(MySubscriberNode, self).__init__(node_name=node_name,
node_type=NodeType.GENERIC)
        # construct subscriber
        self.sub = rospy.Subscriber('chatter', String, self.callback)

    def callback(self, data):
        rospy.loginfo("I heard '%s'", data.data)

if __name__ == '__main__':
    # create the node
    node = MySubscriberNode(node_name='my_subscriber_node')
    # keep spinning
    rospy.spin()
```

Note

Using the super class `DTROS` provided by the Python module `duckietown.dtros` is not mandatory but it is highly suggested as it provides a lot of useful features that plain ROS does not. More on these later.

We now need to the tell our file system that we want our file `my_subscriber_node.py` be treated as an executable file. We do so by running the following command from the root of our DTProject:

```
chmod +x ./packages/my_package/src/my_subscriber_node.py
```

Define launcher

We now create a new launcher file `./launchers/my-subscriber.sh` with the following content inside,

```
#!/bin/bash

source /environment.sh

# initialize launch file
dt-launchfile-init

# launch subscriber
rosrun my_package my_subscriber_node.py

# wait for app to end
dt-launchfile-join
```

Launch the Subscriber node

This part assumes that you have a Duckiebot up and running with a known hostname, e.g., `ROBOT_NAME`. Let us make sure that our robot is ready by executing the command,

```
ping ROBOT_NAME.local
```

If you can ping the robot, you are good to go.

Let us now re-compile our project using the command

```
dts devel build -H ROBOT_NAME -f
```

and run it using the newly defined launcher (we use the flag `-L/--launcher` to achieve this):

```
dts devel run -H ROBOT_NAME -L my-subscriber
```

This will show the following messages before hanging,

```
...
==> Launching app...
[INFO] [1693000997.289437]: [/my_subscriber_node] Initializing...
[INFO] [1693000997.296816]: [/my_subscriber_node] Node starting with switch=True
[INFO] [1693000997.297660]: [/my_subscriber_node] Found 0 user configuration files
in '/data/config/nodes/generic'
[INFO] [1693000997.298273]: [/my_subscriber_node] Found 0 user configuration files
in '/data/config/nodes/my_subscriber_node'
[INFO] [1693000997.303460]: [/my_subscriber_node] Health status changed [STARTING] -
> [STARTED]
...
```

This is because the ROS Subscriber is now waiting for messages to come in. Let us open a new terminal at the root of the project and launch an instance of the publisher we built previously. We can do so by running the following command,

```
dts devel run -H ROBOT_NAME -L my-publisher -n publisher
```

Note

We need to add the option `-n publisher` to tell `dts` to allow multiple instances of the same project to run simultaneously.

You should notice that messages will start to appear on the subscriber side. The expected output is the following,

```
...
==> Launching app...
[INFO] [1693000997.289437]: [/my_subscriber_node] Initializing...
[INFO] [1693000997.296816]: [/my_subscriber_node] Node starting with switch=True
[INFO] [1693000997.297660]: [/my_subscriber_node] Found 0 user configuration files
in '/data/config/nodes/generic'
[INFO] [1693000997.298273]: [/my_subscriber_node] Found 0 user configuration files
in '/data/config/nodes/my_subscriber_node'
[INFO] [1693000997.303460]: [/my_subscriber_node] Health status changed [STARTING] -
> [STARTED]
[INFO] [1693001092.577549]: I heard 'Hello from ROBOT_NAME!'
[INFO] [1693001093.557725]: I heard 'Hello from ROBOT_NAME!'
...
```

Congratulations ▯

You just built and run your first Duckietown-compliant and Duckiebot-compatible ROS subscriber.

If you want to stop it, just use `Ctrl+C`.

Faster Development Workflow

In this section we will learn some tricks that enable a much faster development workflow in `dts`.

Run locally

As we have seen so far, we can add new code to a DTProject or make a change to existing code and then build and run either locally or directly on a Duckiebot. While working with ROS, we only have seen examples in which all the nodes were run on the Duckiebot. This is because ROS sets up all the nodes to defaultly look for a ROS network on the *local* machine, and given that our ROS network originates on the Duckiebot, we can leverage the default configuration of ROS by running the nodes directly on the Duckiebot. Unfortunately, building and running on the Duckiebot is not the best option when it comes to speed, though having a responsive development workflow is crucial in software development.

There are two major issues with the current workflow,

1. our source code always resides on our local computer, so Docker needs to transfer it over to the Duckiebot for the image to be built;
2. the Duckiebot's on-board computer is too slow to be used as a development testbed (while it is fine for final deployments);

Ideally, we would like to be able to build and run ROS nodes on our local computer in a way that is transparent to all other ROS nodes. This can be done very easily with `dts`, and we will now see how.

Let us go back to the example in ROS Subscriber. A block diagram showing the ROS nodes and their location in the network would be the following,

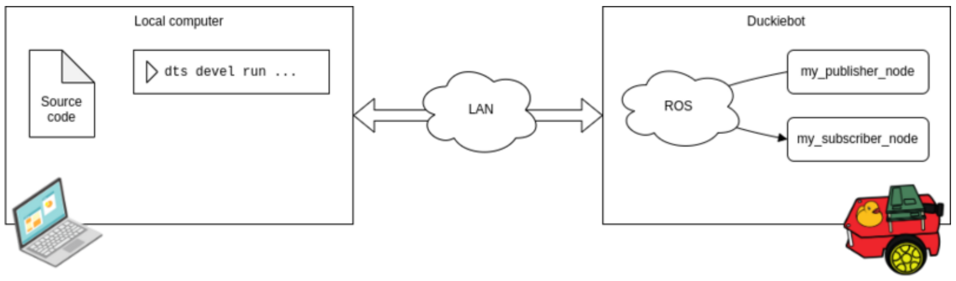


Fig. 8 Block diagram for a Pub-Sub setup with both nodes running on the Duckiebot.

Let us now keep everything as is for the Publisher and slightly change the commands we use to build and run the Subscriber. In particular, we use the following commands instead,

```
dts devel build -f
dts devel run -R ROBOT_NAME -L my-subscriber
```

We are now telling `dts` to build the project locally (we removed `-H ROBOT_NAME` from the `build` command). We are also telling `dts` to run the subscriber node locally (we removed `-H ROBOT_NAME` from the `run` command) but to connect it to the ROS network of the Duckiebot (using the `--ros/-R ROBOT_NAME` option on the `run` command). A block diagram showing the new configuration of ROS nodes and their location in the network would be the following,

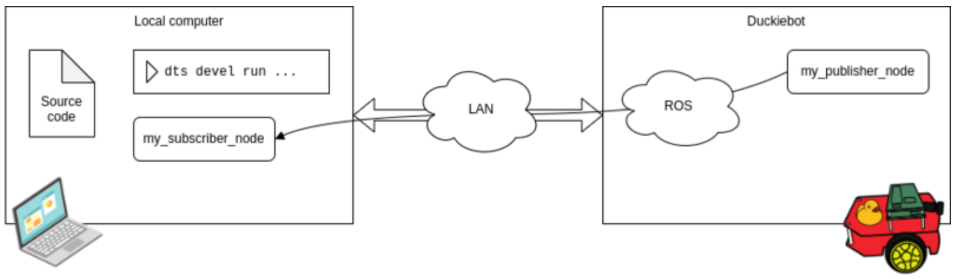


Fig. 9 Block diagram for a Pub-Sub setup with the Subscriber node running on the local computer.

Subscribe to camera

What you will need	• A Duckietown robot turned ON and visible on `dts fleet discover`
What you will get	• Learn how to receive camera images from your robot using a **ROS Subscriber**

Topic and message type of interest

As you should know by now, ROS allows different processes to communicate with one another by exchanging *messages* over *topics*. In order for two ROS nodes to be able to talk, they need to agree on a topic name (e.g., camera images), and a message type (e.g., each message is a JPEG image).

In ROS, a topic is identified by a string (e.g., `camera/image`), while message types are defined using the official messages description language.

In the case of the camera sensor, the topic used by the Duckiebot to publish camera frames is `/ROBOT_NAME/camera_node/image/compressed`, while the message type used over this topic is the standard sensor_msgs/CompressedImage, and contains the following fields.

```
std_msgs/Header header
string format
uint8[] data
```

where,

- `header`: is the standard ROS header object;
- `format`: specifies the format of the data, for example, `png` or `jpeg`;
- `data`: is an array of bytes containing the actual image in the format specified;

Create Subscriber ROS Node

In Create a new Catkin package, we learned how to make a new Catkin package. We will assume that a catkin package already exists, i.e., `packages/my_package/`. You can reuse the one we created earlier.

We now use our favorite text editor to create the file `camera_reader_node.py` inside the `src/` directory of our catkin package and add the following content,

```
#!/usr/bin/env python3

import os
import rospy
from duckietown.dtros import DTROS, NodeType
from sensor_msgs.msg import CompressedImage

import cv2
from cv_bridge import CvBridge

class CameraReaderNode(DTROS):

    def __init__(self, node_name):
        # initialize the DTROS parent class
        super(CameraReaderNode, self).__init__(node_name=node_name,
node_type=NodeType.VISUALIZATION)
        # static parameters
        self._vehicle_name = os.environ['VEHICLE_NAME']
        self._camera_topic = f"/{self._vehicle_name}/camera_node/image/compressed"
        # bridge between OpenCV and ROS
        self._bridge = CvBridge()
        # create window
        self._window = "camera-reader"
        cv2.namedWindow(self._window, cv2.WINDOW_AUTOSIZE)
        # construct subscriber
        self.sub = rospy.Subscriber(self._camera_topic, CompressedImage,
self.callback)

    def callback(self, msg):
        # convert JPEG bytes to CV image
        image = self._bridge.compressed_imgmsg_to_cv2(msg)
        # display frame
        cv2.imshow(self._window, image)
        cv2.waitKey(1)

if __name__ == '__main__':
    # create the node
    node = CameraReaderNode(node_name='camera_reader_node')
    # keep spinning
    rospy.spin()
```

Again, we make our node executable,

```
chmod +x ./packages/my_package/src/camera_reader_node.py
```

Define launcher

Similarly to what we did in the section Define launcher, we create a new launcher file `./launchers/camera-reader.sh` with the content,

```
#!/bin/bash

source /environment.sh

# initialize launch file
dt-launchfile-init

# launch subscriber
rosrun my_package camera_reader_node.py

# wait for app to end
dt-launchfile-join
```

Let us now re-compile our project using the command

```
dts devel build -f
```

Launch the node

We are now ready to run our camera reader node,

```
dts devel run -R ROBOT_NAME -L camera-reader -X
```

This will open a new window like the following,

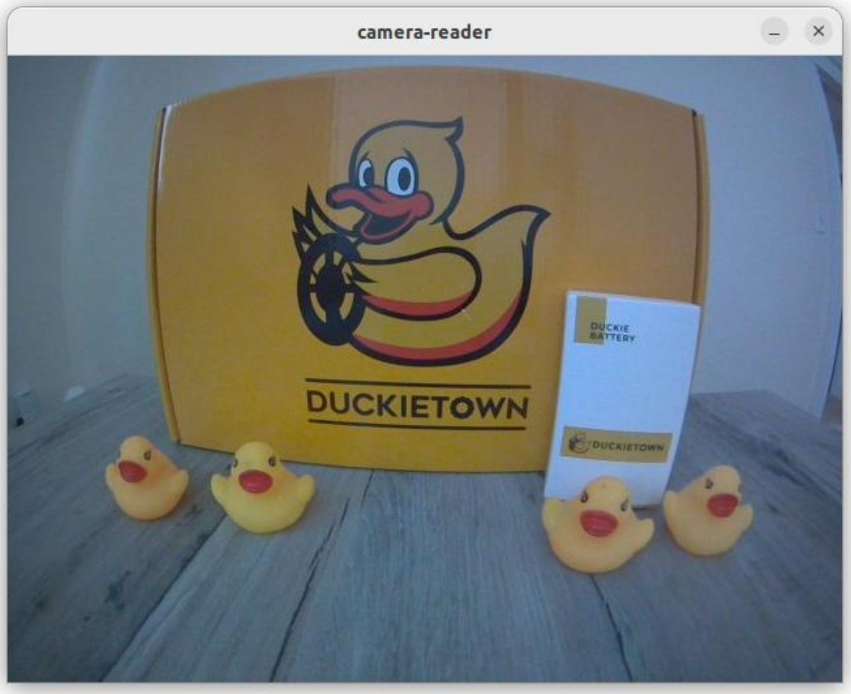


Fig. 10 Camera feed window.

If you want to stop the node, just use `Ctrl+C` in the terminal.

Note

We used the flag `-X` to instruct `dts` to allow this project to create new windows on this computer's screen.

Attention

The trick we learned in [Run locally]() to speed up our development workflow becomes mandatory here. In fact, this particular node needs access to a screen to be able to open the window showing the camera feed, hence the need to run it locally as the Duckiebot is not connected to a monitor. You can put this to the test by attempting to build and run this node on the Duckiebot (using the `-H ROBOT_NAME`) flag, you will be presented the error `cannot open display`.

TODO	Add section back in the Basic part of this book where we explain what the `-X` flag does in `dts devel run`. Once done, update NOTE above to recall where we learned this.

Congratulations

You just built and run your first ROS node connected to the existing ROS network exposed by the Duckiebot.

Subscribe to wheel encoders

What you will need	• A Duckietown robot turned ON and visible on `dts fleet`

	`discover`
What you will get	• Learn how to receive wheel encoder data from your robot using a **ROS Subscriber**

Topic and message type of interest

For the wheel encoders, the topics used by the Duckiebot to publish the encoder ticks are

- `/ROBOT_NAME/left_wheel_encoder_node/tick`
- `/ROBOT_NAME/right_wheel_encoder_node/tick`

And the message type used over these topics is **duckietown_msgs/WheelEncoderStamped** and contains the following fields.

```
uint8 ENCODER_TYPE_ABSOLUTE=0
uint8 ENCODER_TYPE_INCREMENTAL=1
std_msgs/Header header
int32 data
uint16 resolution
uint8 type
```

where,

- `header`: is the standard ROS header object;
- `data`: is the current accumulated number of ticks on that motor;
- `resolution`: is how many ticks will be recorded when the motor spins for a full revolution (360 degrees);
- `type`: indicates the type of the encoder, `absolute` or `incremental`, and it takes the values from the constants `ENCODER_TYPE_ABSOLUTE` and `ENCODER_TYPE_INCREMENTAL` defined in the message itself. For a detailed explanation of the difference between the two types of encoders, we direct the reader to this page;

For example, on the *DB21* series robot, the resolution is `135` and the type is `1` (`ENCODER_TYPE_INCREMENTAL`). This means that each motor records `135` ticks per full revolution, and that `data=0` at whatever the initial position of the wheel was when the robot was turned ON.

Note

If the wheels are spun by hand, the ticks only increase. The robot can only sense direction (hence decrease the counter) when the wheels are spun by the motors.

Create Subscriber ROS Node

We now use our favorite text editor to create the file `wheel_encoder_reader_node.py` inside the `src/` directory of our catkin package and add the following content,

```
#!/usr/bin/env python3

import os
import rospy
from duckietown.dtros import DTROS, NodeType
from duckietown_msgs.msg import WheelEncoderStamped


class WheelEncoderReaderNode(DTROS):

    def __init__(self, node_name):
        # initialize the DTROS parent class
        super(WheelEncoderReaderNode, self).__init__(node_name=node_name,
node_type=NodeType.PERCEPTION)
        # static parameters
        self._vehicle_name = os.environ['VEHICLE_NAME']
        self._left_encoder_topic =
f"/{self._vehicle_name}/left_wheel_encoder_node/tick"
        self._right_encoder_topic =
f"/{self._vehicle_name}/right_wheel_encoder_node/tick"
        # temporary data storage
        self._ticks_left = None
        self._ticks_right = None
        # construct subscriber
        self.sub_left = rospy.Subscriber(self._left_encoder_topic,
WheelEncoderStamped, self.callback_left)
        self.sub_right = rospy.Subscriber(self._right_encoder_topic,
WheelEncoderStamped, self.callback_right)

    def callback_left(self, data):
        # log general information once at the beginning
        rospy.loginfo_once(f"Left encoder resolution: {data.resolution}")
        rospy.loginfo_once(f"Left encoder type: {data.type}")
        # store data value
        self._ticks_left = data.data

    def callback_right(self, data):
        # log general information once at the beginning
        rospy.loginfo_once(f"Right encoder resolution: {data.resolution}")
        rospy.loginfo_once(f"Right encoder type: {data.type}")
        # store data value
        self._ticks_right = data.data

    def run(self):
        # publish received tick messages every 0.05 second (20 Hz)
        rate = rospy.Rate(20)
        while not rospy.is_shutdown():
            if self._ticks_right is not None and self._ticks_left is not None:
                # start printing values when received from both encoders
                msg = f"Wheel encoder ticks [LEFT, RIGHT]: {self._ticks_left},
{self._ticks_right}"
                rospy.loginfo(msg)
            rate.sleep()

if __name__ == '__main__':
    # create the node
    node = WheelEncoderReaderNode(node_name='wheel_encoder_reader_node')
    # run the timer in node
    node.run()
    # keep spinning
    rospy.spin()
```

Again, we make our node executable,

```
chmod +x ./packages/my_package/src/wheel_encoder_reader_node.py
```

Define launcher

Similarly to what we did in the section Define launcher, we create a new launcher file `./launchers/wheel-encoder-reader.sh` with the content,

```
#!/bin/bash

source /environment.sh

# initialize launch file
dt-launchfile-init

# launch subscriber
rosrun my_package wheel_encoder_reader_node.py

# wait for app to end
dt-launchfile-join
```

Let us now re-compile our project using the command

```
dts devel build -f
```

Launch the node

We are now ready to run our reader node,

```
dts devel run -R ROBOT_NAME -L wheel-encoder-reader
```

The `resolution` and `type` values will be printed at the top of the logs once.

Then in the console, the received left and right encoder data will be printed. Try:

- spinning the left/right wheel, in both directions
- driving the robot back and forth with the virtual joystick

Observe how the values change in both cases.

If you want to stop the node, just use `Ctrl+C` in the terminal.

Congratulations

You just built and run a ROS node capable of reading information from the wheel encoder sensors on the Duckiebot.

Publish to wheels

What you will need	• A Duckietown robot turned ON and visible on `dts fleet discover`
What you will get	• Learn how to control the Duckiebot's wheels using a **ROS Publisher**

Topic and message type of interest

The topic used by the Duckiebot to receive wheel commands is `/ROBOT_NAME/wheels_driver_node/wheels_cmd`, while the message type used over this topic is **duckietown_msgs/WheelsCmdStamped** which contains the following fields.

```
std_msgs/Header header
float32 vel_left
float32 vel_right
```

where,

- `header`: is the standard ROS header object;
- `vel_left`: is the signed duty cycle for the *left* wheel (-1.0: full throttle backwards; 0.0: still; 1.0: full throttle forward)
- `vel_right`: is the signed duty cycle for the *right* wheel (-1.0: full throttle backwards; 0.0: still; 1.0: full throttle forward)

Note

There is no physical interpretation of these values, as in velocity or angular velocity, because the commands are PWM duty cycles. Therefore, the term throttle (0% - 100%) is used. And even given with the same throttle commands, the physical velocities would vary with different motors and wheels, which could be then measured by sensors like encoders.

Create Publisher ROS Node

We now use our favorite text editor to create the file `wheel_control_node.py` inside the `src/` directory of our catkin package and add the following content,

```
#!/usr/bin/env python3

import os
import rospy
from duckietown.dtros import DTROS, NodeType
from duckietown_msgs.msg import WheelsCmdStamped


# throttle and direction for each wheel
THROTTLE_LEFT = 0.5        # 50% throttle
DIRECTION_LEFT = 1         # forward
THROTTLE_RIGHT = 0.3       # 30% throttle
DIRECTION_RIGHT = -1       # backward


class WheelControlNode(DTROS):

    def __init__(self, node_name):
        # initialize the DTROS parent class
        super(WheelControlNode, self).__init__(node_name=node_name,
node_type=NodeType.GENERIC)
        # static parameters
        vehicle_name = os.environ['VEHICLE_NAME']
        wheels_topic = f"/{vehicle_name}/wheels_driver_node/wheels_cmd"
        # form the message
        self._vel_left = THROTTLE_LEFT * DIRECTION_LEFT
        self._vel_right = THROTTLE_RIGHT * DIRECTION_RIGHT
        # construct publisher
        self._publisher = rospy.Publisher(wheels_topic, WheelsCmdStamped,
queue_size=1)

    def run(self):
        # publish 10 messages every second (10 Hz)
        rate = rospy.Rate(0.1)
        message = WheelsCmdStamped(vel_left=self._vel_left,
vel_right=self._vel_right)
        while not rospy.is_shutdown():
            self._publisher.publish(message)
            rate.sleep()

    def on_shutdown(self):
        stop = WheelsCmdStamped(vel_left=0, vel_right=0)
        self._publisher.publish(stop)

if __name__ == '__main__':
    # create the node
    node = WheelControlNode(node_name='wheel_control_node')
    # run node
    node.run()
    # keep the process from terminating
    rospy.spin()
```

Again, we make our node executable,

```
chmod +x ./packages/my_package/src/wheel_control_node.py
```

Define launcher

We create a new launcher file `./launchers/wheel-control.sh` with the content,

```
#!/bin/bash

source /environment.sh

# initialize launch file
dt-launchfile-init

# launch subscriber
rosrun my_package wheel_control_node.py

# wait for app to end
dt-launchfile-join
```

Let us now re-compile our project using the command

```
dts devel build -f
```

Launch the node

Danger

The robot's wheels will start spinning as soon as the node is launched. Please, make sure that your robot has enough space to drive around without the risk of harming somebody or himself (e.g., by falling off a desk).

We run the node,

```
dts devel run -R ROBOT_NAME -L wheel-control
```

And observe the wheels rotate as instructed. If you want to stop it, just use `Ctrl+C`, and the wheels should stop spinning as per the behavior defined in the function `on_shutdown()` above.

Congratulations

You just built and run your first ROS node capable of interacting with the Duckiebot and control one of its actuators.

Publish chassis-level commands

What you will need	• A Duckietown robot turned ON and visible on `dts fleet discover`
What you will get	• Learn how to control the Duckiebot's chassis linear and angular velocities using a **ROS Publisher**

Topic and message type of interest

The topic used by the Duckiebot to receive Twist commands and compute inverse kinematics to obtain lower level wheel commands is `/ROBOT_NAME/car_cmd_switch_node/cmd`, while the message type used over this topic is **duckietown_msgs/Twist2DStamped** which contains the following fields.

```
std_msgs/Header header
float32 v
float32 omega
```

where,

- `header`: is the standard ROS header object;
- `v`: is the linear velocity in `m/s` with positive signs in the forward driving direction;
- `omega`: is the angular velocity in `rad/s` with positive signs in counter-clockwise direction when looking down to the Duckiebot;

Note

The commanded expected `v` and `omega` relies on good kinematic calibration and car model to function.

Create Publisher ROS Node

We now use our favorite text editor to create the file `twist_control_node.py` inside the `src/` directory of our catkin package and add the following content,

```python
#!/usr/bin/env python3

import os
import rospy
from duckietown.dtros import DTROS, NodeType
from duckietown_msgs.msg import Twist2DStamped


# Twist command for controlling the linear and angular velocity of the frame
VELOCITY = 0.3  # linear vel    , in m/s    , forward (+)
OMEGA = 4.0     # angular vel   , rad/s     , counter clock wise (+)


class TwistControlNode(DTROS):

    def __init__(self, node_name):
        # initialize the DTROS parent class
        super(TwistControlNode, self).__init__(node_name=node_name, 
node_type=NodeType.GENERIC)
        # static parameters
        vehicle_name = os.environ['VEHICLE_NAME']
        twist_topic = f"/{vehicle_name}/car_cmd_switch_node/cmd"
        # form the message
        self._v = VELOCITY
        self._omega = OMEGA
        # construct publisher
        self._publisher = rospy.Publisher(twist_topic, Twist2DStamped, queue_size=1)

    def run(self):
        # publish 10 messages every second (10 Hz)
        rate = rospy.Rate(10)
        message = Twist2DStamped(v=self._v, omega=self._omega)
        while not rospy.is_shutdown():
            self._publisher.publish(message)
            rate.sleep()

    def on_shutdown(self):
        stop = Twist2DStamped(v=0.0, omega=0.0)
        self._publisher.publish(stop)

if __name__ == '__main__':
    # create the node
    node = TwistControlNode(node_name='twist_control_node')
    # run node
    node.run()
    # keep the process from terminating
    rospy.spin()
```

Again, we make our node executable,

```
chmod +x ./packages/my_package/src/twist_control_node.py
```

Define launcher

We create a new launcher file `./launchers/twist-control.sh` with the content,

```bash
#!/bin/bash

source /environment.sh

# initialize launch file
dt-launchfile-init

# launch subscriber
rosrun my_package twist_control_node.py

# wait for app to end
dt-launchfile-join
```

Let us now re-compile our project using the command

```
dts devel build -f
```

Launch the node

Danger

The robot’s wheels will start moving and spinning as soon as the node is launched. Please, make sure that your robot has enough space to drive around without the risk of harming somebody or himself (e.g., by falling off a desk).

We run the node,

```
dts devel run -R ROBOT_NAME -L twist-control
```

And observe the wheels rotate as instructed. If you want to stop it, just use `Ctrl+C`, and the wheels should stop spinning as per the behavior defined in the function `on_shutdown()` above.

Congratulations ▯

You just built and run a ROS node capable of interacting with the Duckiebot and control the wheels by leveraging existing functionalities exposed by the Duckiebot (e.g., inverse kinematics, wheel calibration).

Basic Project Structure

In Duckietown, everything runs in Docker containers. All you need in order to run a piece of software that uses ROS in Duckietown is a Duckietown-compliant Docker image with your software in it.

A boilerplate is provided here. If you have completed the Tutorial on DTProject (as you should have), you will recognize the content of this repository as being a DTProject template.

Similarly to what we learned in New project, we will instantiate a new project repository by using the template repository available on GitHub.

The procedure for building and executing a ROS-compatible DTProject is the same we learned in the Tutorial on DTProject section.

Let’s get started!

Beginner - Python Library

In this section, you will create your own Python library following the Duckietown template.

Step 1: Get the Duckietown library template

A boilerplate is provided by the library template repository.

The repository contains a lot of files, but do not worry, we will analyze them one by one. Click on the button that reads “Use this template” and then choose “Create a new repository” from the dropdown menu.

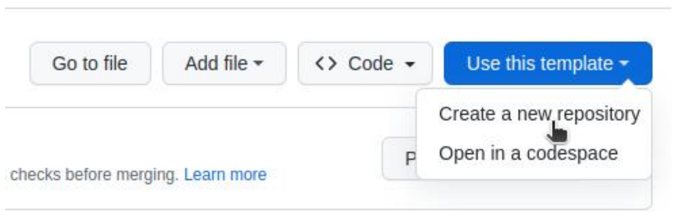
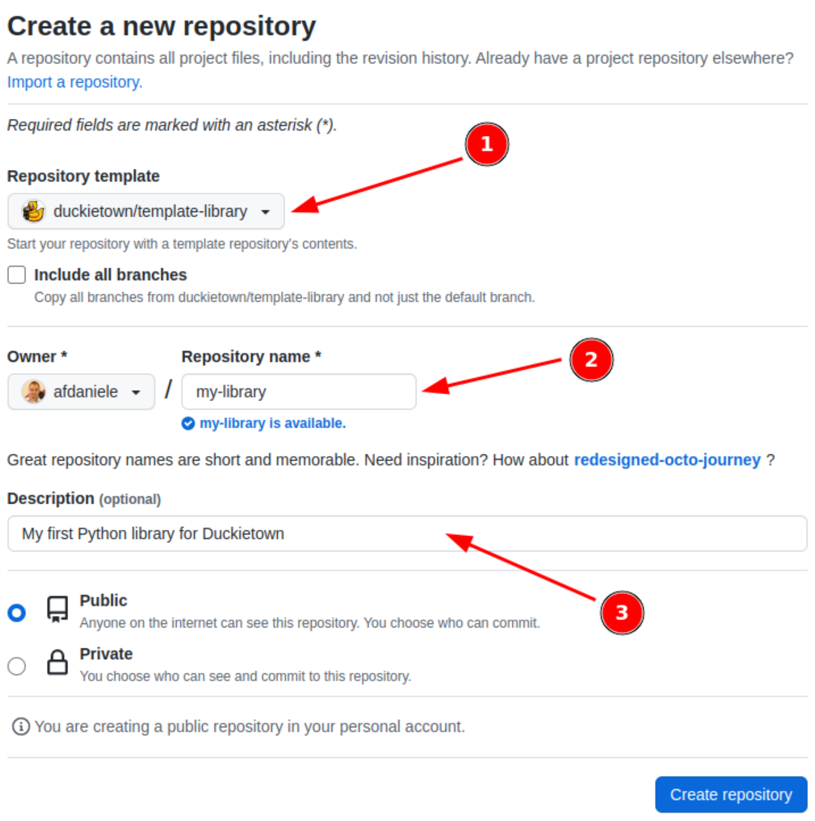


Fig. 11 Use template repository on GitHub.

This will take you to a page that looks like the following:



Create a new repository

A repository contains all project files, including the revision history. Already have a project repository elsewhere? Import a repository.

Required fields are marked with an asterisk (*).

Repository template: duckietown/template-library

Start your repository with a template repository's contents.

Include all branches

Copy all branches from duckietown/template-library and not just the default branch.

Owner *: afdaniele / Repository name *: my-library

my-library is available.

Great repository names are short and memorable. Need inspiration? How about redesigned-octo-journey ?

Description (optional): My first Python library for Duckietown

Public — Anyone on the internet can see this repository. You choose who can commit.

Private — You choose who can see and commit to this repository.

You are creating a public repository in your personal account.

Fig. 12 Creating a repository from template.

Pick a name for your repository (say `my-library`) and press the button *Create repository from template*.

Note

You can replace `my-library` with the name of the repository that you prefer.

This will create a new repository and copy everything from the repository `template-library` to your new repository. You can now open a terminal and clone your newly created repository.

```
git clone https://github.com/YOUR_USERNAME/my-library
cd my-library
```

Attention

Replace `YOUR_USERNAME` in the link above with your GitHub username.

Features of the library template

We have the following features in our new library:

- Unit-tests using Nose.
- Building/testing in Docker environment locally.
- Integration with CircleCI for automated testing.

- Integration with CodeCov for displaying coverage result.
- Integration with Sphinx to build code docs. (So far, only built locally.)
- Jupyter notebooks, which are run also in CircleCI as tests.
- Version bump using Bumpversion.
- Code formatting using Black.
- Command-line program for using the library.

Anatomy of the library template

This repository describes a library called "`duckietown_pondcleaner`" and there is one command-line tool called `dt-pc-demo.`

Meta-files

- `.gitignore`: Files ignore by Git.
- `.dtproject`: Enables the project to be built and used by `dts devel` tools
- `.bumpversion.cfg`: Configuration for bumpversion
- `Makefile`: Build tools configuration with Make

Python packaging

- `requirements.txt`: Contains the *pinned* versions of your requirement that are used to run tests.
- `MANIFEST.in`: Deselects the tests to be included in the egg.
- `setup.py`: Contains meta information, definition of the scripts, and the dependencies information.

Python code

- `src/` - This is the path that you should set as "sources root" in your tool
- `src/duckietown_pondcleaner`: Contains the code.
- `src/duckietown_pondcleaner/__init__.py`: Contains the `__version__` library.
- `src/duckietown_pondcleaner_tests`: Contains the tests - not included in the egg.

Docker testing

These are files to build and run a testing container.

- `.dockerignore`: Describes what files go in the docker container.
- `Dockerfile`: The build configuration for the software image

Sphinx

- `src/conf.py`: Sphinx settings
- `src/index.rst`: Sphinx main file
- `src/duckietown_pondcleaner/index.rst`: Documentation for the package

Coverage

- `.coveragerc`: Options for code coverage.

Notebooks

- `notebooks`: Notebooks that are run also as a test.
- `notebooks-extra`: Other notebooks (not run as test)
- `notebooks/*.ipynb`: The notebooks themselves.

Step 2: Creating your Library

Using the repo you have already created:

- Clone the newly created repository;
- Place your Python packages inside `src/`;
- List the python dependencies in the file `dependencies.txt`;
- Update the appropriate section in the file `setup.py`;

Make sure that there are no other remains:

```
grep -r . pondcleaner
```

Update the branch names in `README.md`.

Other set up (for admins)

The following are necessary steps for admins to do:

1. Activate on CircleCI. Make one build successful.
2. Activate on CodeCov. Get the `CODECOV_TOKEN`. Put this token in CircleCI environment.

Step 3: Using the library template utilities

Test the code

Test the code using Docker by:

```
make test-docker
```

This runs the test using a Docker container built from scratch with the pinned dependencies in `requirements.txt`. This is equivalent to what is run on CircleCI.

To run the tests natively on your pc, use:

```
make test
```

Note

To run the tests you will need to have installed the libraries listed in the file `requirements.txt` on your computer.

For that we assume you have already set up a Python virtual environment.

To use a Python virtual environment you will need to `pip install virtualenv` then `virtualenv duckietown` then `source duckietown/bin/activate`. In order to install the requirements to run the test do `pip install -r requirements.txt`.

Development

In the same virtual environment as above run:

```
python setup.py develop
```

This will install the library in an editable way (rather than copying the sources somewhere else).

If you don’t want to install the deps, do:

```
python setup.py develop  --no-deps
```

For example, this is done in the Dockerfile so that we know we are only using the dependencies in `requirements.txt` with the exact pinned version.

Adding tests

To add another tests, add files with the name `test_*py` in the package `duckietown_podcleaner_tests`. The name is important.

Tip

Make sure that the tests are actually run by looking at the coverage results.

Using the notebooks

Always clean the notebooks before committing them:

```
make -C notebooks cleanup
```

Warning

If you don't think you can be diligent about this, then add the notebooks using Git LFS.

Step 4: Releasing a new version of your library

Updating the version

The first step is to change the version and tag the repo. **DO NOT** change the version manually; use the CLI tool `bumpversion` instead.

The tool can be called by:

```
make bump    # bump the version, tag the tree
```

If you need to include the version in a new file, list it inside the file `.bumpversion.cfg` using the syntax `[bumpversion:file: &lt;FILE_PATH &gt;]`.

Releasing the package

The next step is to upload the package to PyPy. We use twine. Invoke it using:

```
make upload  # upload to PyPI
```

For this step, you need to have admin permissions on PyPy.

Beginner - Code Hierarchy

What you will need	• An understanding of the basics of Docker • An initialized Duckiebot
What you will get	• Knowledge of the software architecture on a Duckiebot

In order to develop new functionality within the Duckietown ecosystem, you need to understand how the existing code is structured. This module will introduce you to the top-level structure as well as the references that can help you delve deeper.

While on the outside Duckietown seems to be all about a simple toy car with some duckies on top, once you dive deeper you will find out that it is much bigger on the inside. It's not only about cars, but also boats and drones. And you can run the same code on a real Duckiebot, in simulation, or in a competitive AI Driving Olympics environment. You can also use some of the dozens of projects done before. As we clearly cannot cover everything in a concise way, this module will instead focus only on the code that runs on a Duckiebot during the standard demos, e.g. Lane Following and Indefinite Navigation.

Main images and repositories

You probably noticed three container and image names popping up when you were running the demos, calibrating your Duckiebot, or developing some of the previous exercises: `dt-duckiebot-interface`, `dt-car-interface`, and `dt-core`. In this section, we'll discuss what each image provides and how they interact.

Let's first look at the bigger picture: the container hierarchy in Duckietown.

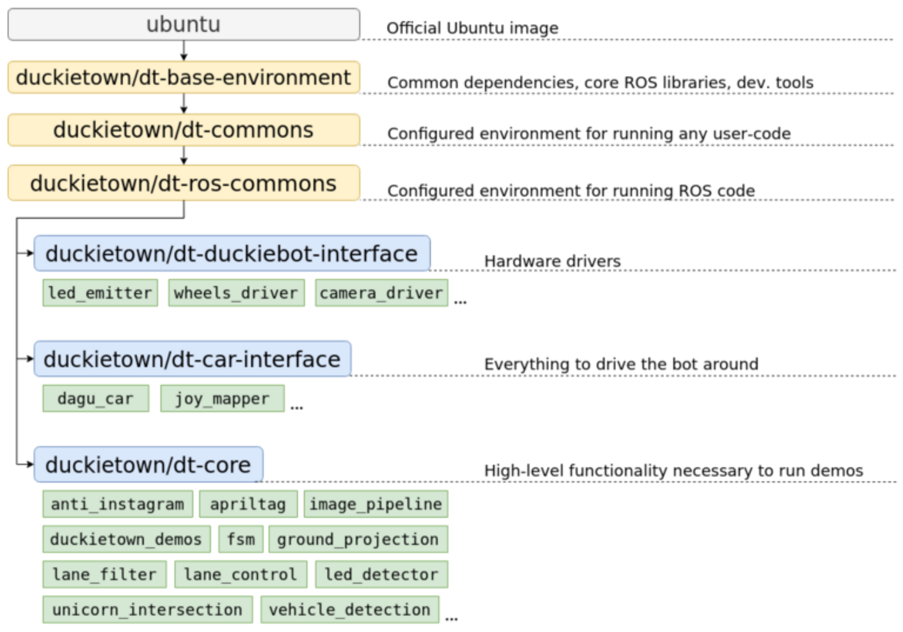

ubuntu
Official Ubuntu image
duckietown/dt-base-environment
Common dependencies, core ROS libraries, dev. tools
duckietown/dt-commons
Configured environment for running any user-code
duckietown/dt-ros-commons
Configured environment for running ROS code
duckietown/dt-duckiebot-interface
Hardware drivers
led_emitter
wheels_driver
camera_driver
...
duckietown/dt-car-interface
Everything to drive the bot around
dagu_car
joy_mapper
...
duckietown/dt-core
High-level functionality necessary to run demos
anti_instagram
apriltag
image_pipeline
duckietown_demos
fsm
ground_projection
lane_filter
lane_control
led_detector
unicorn_intersection
vehicle_detection
...

Fig. 13 The Docker image hierarchy

As you can see in the above image, all three of the containers actually inherit the same container. Recall that 'inheritance' in a Docker images means that the 'child' image has a `FROM` statement with the 'parent' image in its Dockerfile. We typically say that the 'child' *is based on* 'the parent'.

The image on which everything is based is `ubuntu`. It is simply the official Ubuntu image, with no added perks. Ubuntu 22.04 (Jammy Jellyfish) is used for the `ente` distribution of the Duckietown stack. Of course, as you can imagine, it is missing many key features that we would need. Also, it needs to be properly configured in order to work correctly with our software.

The `duckietown/dt-base-environment` adds many of the core libraries and configurations that we need. It installs development tools such as `vim`, `git`, `nano` and libraries for handling `i2c` devices, processing images, and efficiently doing linear algebra. It adds compilers, linkers, and libraries necessary for the compiling/building of software from source. Furthermore, we add `pip` and a bunch of handy `python3` libraries, such as `numpy`, `scipy`, `matplotlib`, and `smbus` (used to communicate with motors, LEDs, etc). Finally, `duckietown/dt-base-environment` also provides the core ROS libraries, including `rospy`: ROS's Python bindings. The version of `ROS` used is ROS Noetic Ninjemys.

Then, `duckietown/dt-commons` builds on top of `duckietown/dt-base-environment`. We provide a number of Duckietown libraries here that deal with files handling, infrastructure communication, and everything else that makes our development tools run smoothly. This image configures the environment so that the hostname resolution is correctly performed also, and ensures that the environment variables pertaining to the type of the robot, its hardware, and its configuration are all properly set. It also makes sure that all Python libraries are discoverable, and that ROS is setup correctly.

Building on top of it we have `duckietown/dt-ros-commons`, which has everything you need in order to start developing code that directly works on your Duckiebot. However, as there are a few components that all Duckietown ROS nodes share, it is convenient to package them in an image. These are `duckietown-utils` (a library with a number of useful functions), `duckietown_msgs` (a ROS package that contains all the ROS message types used in Duckietown), and `DTROS`. `DTROS` is a 'mother' node for all other nodes in Duckietown. You have already seen it while working with ROS publishers and subscribers, but we will look at it in more detail soon.

The `duckietown/dt-ros-commons` is also the place where we keep protocols that are key for the communication between nodes found in different repositories. By placing them here, we ensure that all repositories work with the exact same protocol, and hence we prevent communication issues.

Currently, the only protocol there is `LED_protocol`, which is used by the `led_emitter_node` in `dt-duckiebot-interface`, which emits LED-encoded messages, and by the `led_detector_node` in `dt-core`, which interprets the messages encoded in the LED flashing of other robots.

Finally, `duckietown/dt-ros-commons` packs another handy node: the `ros_http_api_node`. It exposes the ROS environment as an HTTP API. The ROS HTTP API runs by default on any Duckietown device and allows access to ROS topics, parameters, services, nodes, etc, over HTTP, which is an extremely portable interface. This is the technology behind our web-based interfaces that communicate with ROS, such as the Duckietown Dashboard.

We finally can focus on `dt-duckiebot-interface`, `dt-car-interface`, and `dt-core`. The first, `dt-duckiebot-interface`, contains all the hardware drivers you need to operate your Duckiebot. In particular these are the drivers for the camera (in the `camera_driver` package), the ones for the motors (`wheels_driver`), and the LED drivers (`led_emitter`). Thanks to these nodes, you don't need to interact with low level code to control your Duckiebot. Instead, you can simply use the convenient ROS topics and services provided by these nodes.

The `dt-car-interface` image provides additional basic functionality that is not on hardware level. It is all you need to be able to drive your Duckiebot around, in particular the parts that handle the commands sent by a (virtual) joystick (the `joy_mapper` package) and the forward and inverse kinematics that convert the desired robot movement to wheel commands (`dagu_car` package). It might not be immediately clear at first why these are not part of `dt-duckiebot-interface` or `dt-core`. In some use cases, e.g. for the demos or controlling a robot via a joystick, it is beneficial to have these two packages. For others, e.g. when deploying a completely different pipeline, e.g. end-to-end reinforcement learning, one would prefer to interact directly with the drivers. We will see more examples of use cases shortly.

The `dt-core` image provides all the high level robot behavior that you observe when running a demo. The image processing pipeline, decision-making modules, lane and intersection contollers, and many others reside there.

If you are curious to see all the ROS packages available in each of these images, you can check out the corresponding GitHub repositories:

- `dt-base-environment`
- `dt-commons`
- `dt-ros-commons`
- `dt-duckiebot-interface`
- `dt-car-interface`
- `dt-core`

Note

Make sure to look at the `ente` branches of these repositories! This is the most current release of the Duckietown software.

As you will see in the nodes, there's a lot of inline documentation provided.

Warning

Unfortunately, for the moment only `dt-ros-commons`, `dt-duckiebot-interface`, and `dt-car-interface` are documented. We are working on providing similar level of documentation for `dt-core` as well.

Various configurations of the Duckietown codebase

As we already mentioned, the Duckietown codebase can be used in various configurations: on a physical robot, in simulation, as an AI Driving Olympics submission, etc. Depending on how you want to deploy or use your code, you will be using different Docker images. Here we will take a look at a some of the most common use cases.

Driving with a (virtual) joystick

If you only want to drive your Duckiebot around, you need the `joy_mapper` node that translates the joystick `Joy` messages to car command messages, the `kinematics` node that in turn converts these to wheel command messages, and the `wheels_driver` node that controls the motors. So the `dt-duckiebot-interface` and `dt-car-interface` images are enough.

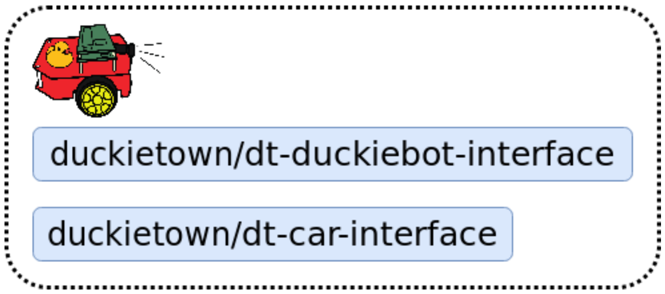

duckietown/dt-duckiebot-interface
duckietown/dt-car-interface

Fig. 14 Driving with a virtual joystick.

Driving through the Dashboard

As you saw when setting up your Duckiebot, the Dashboard and the Compose interface also provide manual driving functionality. For this, one needs the same images as before, of course together with the Dashboard image itself:

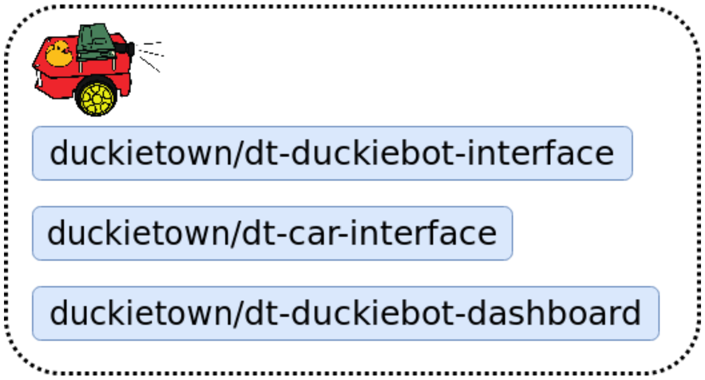

duckietown/dt-duckiebot-interface
duckietown/dt-car-interface
duckietown/dt-duckiebot-dashboard

Fig. 15 Driving through the Dashboard.

Running a demo on a Duckiebot

Running a demo requires to drive around together with the high-level processing and logic that reside in the `dt-core` image:

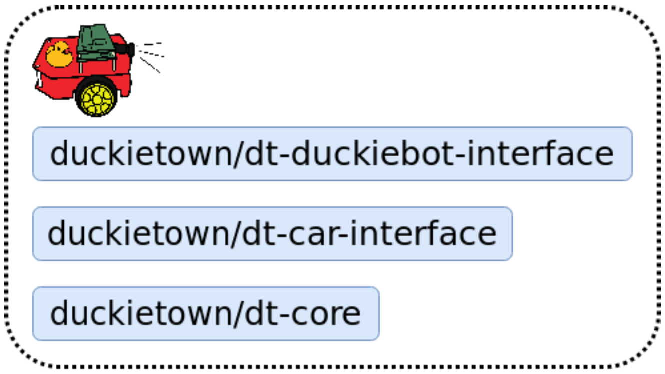

duckietown/dt-duckiebot-interface
duckietown/dt-car-interface
duckietown/dt-core

Fig. 16 Running a demo on a Duckiebot.

Running a demo in simulation

A demo can also be executed in simulation. In this case, instead of using the hardware drivers `dt-duckiebot-interface` provides, we substitute them with the simulator interface:

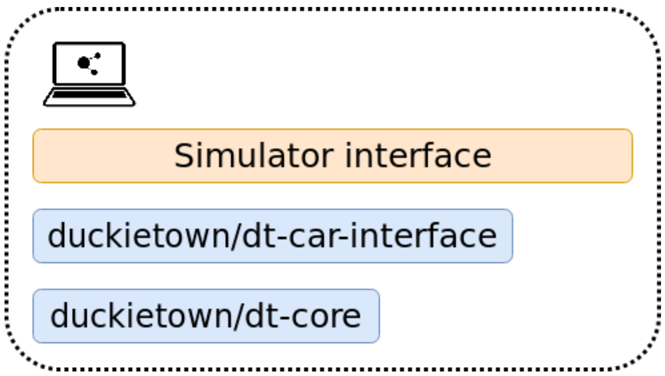


Fig. 17 Running a demo in simulation.

Evaluating AIDO submissions in simulation

An AI Driving Olympics submission is essentially a container that receives image data and outputs wheel commands. Therefore, it can replace the `dt-car-interface` and `dt-core` images and still use the same simulator framework. This can also be done in the cloud, and that is exactly how AIDO submissions get evaluated in simulation on the challenges server.

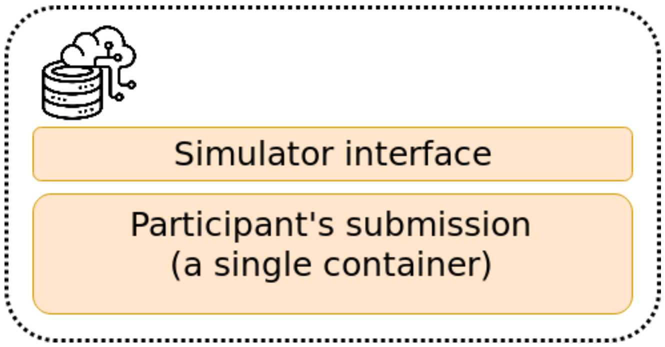


Fig. 18 Evaluating an AIDO submission in simulation.

Evaluating AIDO submissions on a Duckiebot

The same submission image, with not a single change, can be also tested on a real Duckiebot! Simply substitute the simulator with the `dt-duckiebot-interface`. As the containers don't need to run on the same device, we can also use much powerful computers (also state-of-the-art GPUs) when testing submissions. This is the way that AIDO submissions get evaluated in Autolabs. In this way, even if you don't have a Duckiebot, you can develop your submission in simulation, then submit it to be evaluated in simulations on the challenges server, and if it performs well, you can request remote evaluation on a real Duckiebot in a Duckietown Autolab!

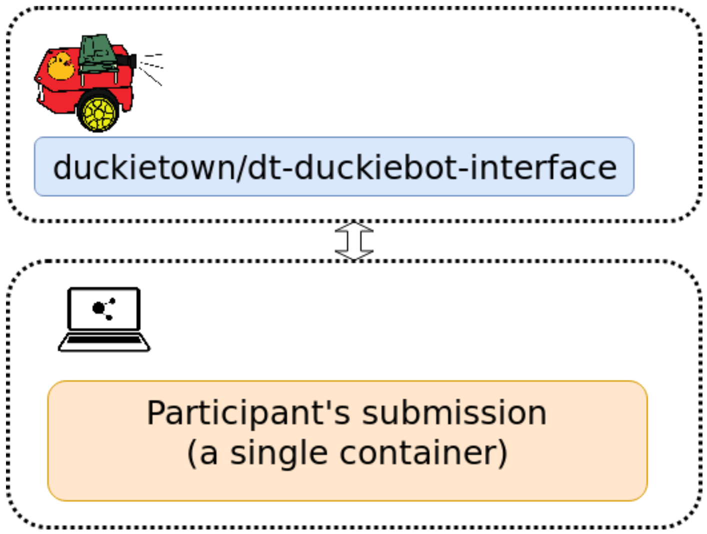


Fig. 19 Evaluating an AIDO submission on a Duckiebot.

Beginner - Documentation

This section provides a comprehensive guide to writing inline documentation to your ROS nodes and libraries. We will discuss both *what* should be documented and *how* it should be documented. Head to for the details about how to then create a human-friendly webpage showing the documentation.

Table of contents

Write documentation

Basics about inline code documentation

Documentation is a must-do in any software project. As harsh as it sounds, you can write an absolutely revolutionary and beautiful software package that can save anyone who uses it years of their time while simultaneously solving all of humanity's greatest problems. But if people do not know that your code exists, have no idea how to use it, or understanding its intricacies takes too much effort, then you will neither save anyone any time, nor solve any problem. In fact, as far as the world beyond you is concerned, all your work is as good as if never done. Therefore, if you wish your code to be ever used, **document** it as extensively as possible!

Inline documentation is a pretty handy way of helping people use your software. On one hand, it is right in the place where it is needed: next to the classes and methods that you are documenting. On the hand, it is also much easier to update when you change something in the code: the documentation of your function is typically no more than 20 lines above your change. On the third hand (should you have one) documentation written in this way inherits the structure of your software project, which is a very natural way of organizing it. On the fourth hand (you can borrow someone else's), there are some really nice packages that take your documentation and make it into a beautiful webpage.

Note

The documentation that you are currently reading is called *a book* and exists independent of any code repository.

In Duckietown we use Sphinx for building our code documentation. Sphinx is the most popular way of creating code documentation for Python projects. You can find out more on their webpage and there are a lot of interesting things to read there. Documenting your code is as simple as writing docstrings and the occasional comment. Then, Sphinx takes care of parsing all your docstrings and making a nice webpage for it. However, in order for all this to work nicely, you need to format your documentation in a particular way. We will discuss this later in this page.

What should be documented and where?

The short answer to this question is “everything and in the right place”. The long answer is the same.

Every ROS node should be documented, meaning a general description of what it is for, what it does, and how it does it. Additionally, all its parameters, publishers, subscribers, and services need to be described. The default values for the parameters should be also added in the documentation. Every method that your node’s class has should also be documented, including the arguments to the method and the returned object (if there is such), as well as their types.

Every library in your `include` directory should also be documented. That again means, every class, every method, every function. Additionally, the library itself, and its modules should have a short description too.

Finally, your whole repository, and every single package should also be documented.

Let’s start from a node. Here is a sample for the camera node:

```python
class CameraNode(DTROS):
    """

    The node handles the image stream, initializing it, publishing frames
    according to the required frequency and stops it at shutdown.
    `Picamera <https://picamera.readthedocs.io/>`_ is used for handling
    the image stream.

    Note that only one :obj:`PiCamera` object should be used at a time.
    If another node tries to start an instance while this node is running,
    it will likely fail with an `Out of resource` exception.

    Args:
        node_name (:obj:`str`): a unique, descriptive name for the node that ROS
will use

    Configuration:
        ~framerate (:obj:`float`): The camera image acquisition framerate, default
is 30.0 fps
        ~res_w (:obj:`int`): The desired width of the acquired image, default is
640px
        ~res_h (:obj:`int`): The desired height of the acquired image, default is
480px
        ~exposure_mode (:obj:`str`): PiCamera exposure mode

    Publisher:
        ~image/compressed (:obj:`CompressedImage`): The acquired camera images

    Service:
        ~set_camera_info:
            Saves a provided camera info to
`/data/config/calibrations/camera_intrinsic/HOSTNAME.yaml`.

            input:
                camera_info (obj:`CameraInfo`): The camera information to save

            outputs:
                success (:obj:`bool`): `True` if the call succeeded
                status_message (:obj:`str`): Used to give details about success

    """

    def __init__(self, node_name):

        # Initialize the DTROS parent class
        super(CameraNode, self).__init__(node_name=node_name,
                                         node_type=NodeType.PERCEPTION)

    [...]

    def save_camera_info(self, camera_info_msg, filename):
        """Saves intrinsic calibration to file.

            Args:
                camera_info_msg (:obj:`CameraInfo`): Camera Info containing
calibration
                filename (:obj:`str`): filename where to save calibration

            Returns:
                :obj:`bool`: whether the camera info was successfully written
        """
        # Convert camera_info_msg and save to a yaml file
        self.log("[saveCameraInfo] filename: %s" % (filename))

        # Converted from camera_info_manager.py
        calib = {'image_width': camera_info_msg.width,
        [...]

        self.log("[saveCameraInfo] calib %s" % (calib))

        try:
            f = open(filename, 'w')
            yaml.safe_dump(calib, f)
            return True
        except IOError:
            return False
```

The documentation of the node itself should *always* be as a docstring after the class definition. *Do not* put it, or anything else as a docstring for the `__init__` method. This will not be rendered in the final output.

The documentation of the node should start with a general description about the node, its purpose, where it fits in the bigger picture of the package and repository, etc. Feel generous with the description here. Then there is a section with the arguments needed for initializing the node (the arguments of the `__init__` method) which will almost always be exactly the same as shown. After that there is a configuration section where you should put all the parameters for the node, their type, a short description, and their default value, as shown.

This is then followed by Subscribers, Publishers and Services, in this order. If the node has no Subscribers, for example as the camera node, then you don't need to add this section. Note the specific way of structuring the documentation of the service!

Then, every method should be documented as a docstring immediately after the function definition (as the `save_camera_info` example). Again, add a short description of the method, as well as the arguments it expects and the return value (should such exist).

Libraries should be documented in a similar way. However, when documenting libraries, it is important to actually invoke the Sphinx commands for documenting particular objects in the `__init__.py` file. Furthermore, this file should contain a description of the package itself. Here's an example from the `line_detector` library's `__init__.py` file:

```
"""

    line_detector
    -------------

    The ``line_detector`` library packages classes and tools for handling line
section extraction from images. The
    main functionality is in the :py:class:`LineDetector` class.
:py:class:`Detections` is the output data class for
    the results of a call to :py:class:`LineDetector`, and :py:class:`ColorRange` is
used to specify the colour ranges
    in which :py:class:`LineDetector` is looking for line segments.

    There are two plotting utilities also included: :py:func:`plotMaps` and
:py:func:`plotSegments`

    .. autoclass:: line_detector.Detections

    .. autoclass:: line_detector.ColorRange

    .. autoclass:: line_detector.LineDetector

    .. autofunction:: line_detector.plotMaps

    .. autofunction:: line_detector.plotSegments


"""
```

You can see that it describes the library and its elements, and then uses the Sphinx commands which will parse these classes and functions and will add their documentation to this page. You can find more details about these functions in .

Similarly, every ROS package needs a documentation file. This should go in the `docs/packages` directory of your repository and should be named `package_name.rst`. It should describe the package and then should invoke the Sphinx commands for building the documentation for the individual nodes and libraries. See the following example:

```
ROS Package: ground\_projection
===============================

.. contents::

The ``ground_projection`` package provides the tools for projecting line segments
from an image reference frame to the ground reference frame, as well as a ROS node
that implements this functionality. It has been designed to be a part of the lane
localization pipeline. Consists of the ROS node
:py:class:`nodes.GroundProjectionNode` and the :py:mod:`ground_projection` library.


GroundProjectionNode
--------------------

.. autoclass:: nodes.GroundProjectionNode

Included libraries
------------------

.. automodule:: ground_projection
```

Style guide

You probably noticed the plethora of funky commands in the above examples. These are called *directives*, and we'll now take a closer look at them. The basic style of the documentation comes from reStructuredText, which is the default plaintext markup language used by Sphinx. The rest are Sphinx directives which Sphinx then replaces with markup which it creates from your docstrings.

Basic styles

- You can use `*text*` to italicize the text.
- You can use `**text**` to make it in boldface.
- Values, names of variables, errors, messages, etc. should be in grave accent quotes:

```
``like that``
```

- Section are created by underlying section title with a punctuation character, at least as long as the text:

```
What a cool heading
===================

Nice subsection
---------------

A neat subsubsection
^^^^^^^^^^^^^^^^^^^^
```

- External links can be added like this:

```
    For this, we use `Picamera <https://picamera.readthedocs.io/>`_ which is an
external library.
```

- When describing standard types (like `int`, `float`, etc.) use

```
:obj:`int`
```

- If the type is an object of one of the libraries in the repository, then use the referencing directives from the next section in order to create hyperlinks. If it is a message, use the message type. If a list, a dictionary, or a tuple, you can use expressions like `:obj:`list` of :obj:`float``
- Attributes of a class can also be documented. We recommend that you do that for all important attributes and for constants. Here are examples of the various ways you can document attributes:

```
class Foo:
    """Docstring for class Foo."""

    #: Doc comment for class attribute Foo.bar.
    #: It can have multiple lines.
    bar = 1

    flox = 1.5   #: Doc comment for Foo.flox. One line only.

    baz = 2
    """Docstring for class attribute Foo.baz."""

    def __init__(self):
        #: Doc comment for instance attribute qux.
        self.qux = 3

        self.spam = 4
        """Docstring for instance attribute spam."""
```

See also

You can find more examples with reStructuredText here and here, and detailed specification here.

Referencing other objects

You can add a link to a different package, node, method, or object like that:

```
    :py:mod:`duckietown`
    :py:class:`duckietown.DTROS`
    :py:meth:`duckietown.DTROS.publisher`
    :py:attr:`duckietown.DTROS.switch`
```

All of these refer to the `duckietown` Python package. When dealing will nodes, things are a bit trickier, because they are not a part of a package. However, in order to make Sphinx work nicely with ROS nodes, we create a fake package that has them all as classes. Hence, if you want to refer to the `CameraNode`, you can do it like that:

```
    :py:class:`nodes.CameraNode`
```

Warning

We are considering replacing `nodes` with the repository name, so keep in mind this might change soon.

Custom sections

When documenting a node, you can (and you should) make use of the following ROS-specific sections: `Examples`, `Raises`, `Configuration`, `Subscribers`, `Subscriber`, `Publishers`, `Publisher`, `Services`, `Service`, `Fields`, `inputs`, `input`, `outputs`, `output`. If you need other custom sections you can add them in the `docs/config.yaml` file in your repository.

Using autodoc

We use the autodoc extension of Sphinx in order to automatically create the markup from the docstrings in our Python code. In particular, you can use the following directives:

```
.. automodule:: ground_projection

.. autoclass:: line_detector.ColorRange

.. autofunction:: line_detector.plotMaps

.. automethod:: nodes.CameraNode.save_camera_info
```

You can find more details here.

Build documentation

You can write a Jupyter Book to document your project. The book source code is located in `/docs/src` and you can refer to the Book Writer Manual for details on the supported features and a syntax cheat sheet.

To build the book you can simply run from the root of your project:

```
dts docs build
```

Including reStructuredText in Markdown

To insert rST into Markdown, you can use the eval-rst directive:

~~~
```{eval-rst}
.. note::

   A note written in reStructuredText.

.. include:: ./include-rst.rst
```
~~~

Note

A note written in reStructuredText.

Automatic API generation (advanced)

It is also possible to automatically generate the API documentation from docstrings written in your source code. You can refer to the official guide for how to do this.

The **DTROS** class

This section deals with how you should write the code in a ROS node. In particular, how to structure it. Writing the code of a node goes hand-in-hand with documenting it, but this will be discussed in more detail in Beginner - Documentation.

General structure

All ROS nodes should be in the `src` directory of the respective package. If the node is called `some_name`, then the file that has its implementation should be called `some_name_node.py`. This file should always be executable. Furthermore, all the logic of the node should be implemented in a Python class called `SomeNameNode`.

The structure of the `some_name_node.py` should generally look like the following example (without the comments):

```python
#!/usr/bin/env python

# import external libraries
import rospy

# import libraries which are part of the package (i.e. in the include dir)
import library

# import DTROS-related classes
from duckietown.dtros import \
    DTROS, \
    NodeType, \
    TopicType, \
    DTReminder,\
    DTParam, \
    ParamType

# import messages and services
from std_msgs.msg import Float32
from duckietown_msgs.msg import \
    SegmentList, \
    Segment, \
    BoolStamped

class SomeNameNode(DTROS):
    def __init__(self, node_name):
        # class implementation

if __name__ == '__main__':
    some_name_node = SomeNameNode(node_name='same_name_node')
    rospy.spin()
```

Observe that all nodes in Duckietown should inherit from the super class `DTROS`. This is a hard requirement. `DTROS` provides a lot of functionalities on top of the standard ROS nodes which make writing and debugging your node easier, and also sometimes comes with performance improvements.

In Python code, never ever do universal imports like `from somepackage import *`. This is a terrible practice. Instead, specify exactly what you are importing, i.e. `from somepackage import somefunction`. It is fine if you do it in `__init__.py` files but even there try to avoid it if possible.

When using a package that has a common practice alias, use it, e.g. `import numpy as np`, `import matplotlib.pyplot as plt`, etc. However, refrain from defining your own aliases.

The code in this node definition should be restricted as much as possible to ROS-related functionalities. If your node is performing some complex computation or has any logic that can be separated from the node itself, implement it as a separate library and put it in the `include` directory of the package.

Node initialization

There are a lot of details regarding the initialization of the node so let’s take a look at an example structure of the `__init__` method of our sample node.

```python
class SomeNameNode(DTROS):
    def __init__(self, node_name):
        super(SomeNameNode, self).__init__(
            node_name=node_name,
            node_type=NodeType.PERCEPTION
        )

        # Setting up parameters
        self.detection_freq = DTParam(
            '~detection_freq',
            param_type=ParamType.INT,
            min_value=-1,
            max_value=30
        )
        # ...

        # Generic attributes
        self.something_happened = None
        self.arbitrary_counter = 0
        # ...

        # Subscribers
        self.sub_img = rospy.Subscriber(
            'image_rect',
            Image,
            self.cb_img
        )
        self.sub_cinfo = rospy.Subscriber(
            'camera_info',
            CameraInfo,
            self.cb_cinfo
        )
        # ...

        # Publishers
        self.pub_img = rospy.Publisher(
            'tag_detections_image/compressed',
            CompressedImage,
            queue_size=1,
            dt_topic_type=TopicType.VISUALIZATION
        )
        self.pub_tag = rospy.Publisher(
            'tag_detections',
            AprilTagDetectionArray,
            queue_size=1,
            dt_topic_type=TopicType.PERCEPTION
        )
        # ...
```

Now, let's take a look at it section by section.

Node Creation

In classic ROS nodes, you would initialize a ROS node with the function `rospy.init_node(...)`. DTROS does that for you, you simply need to pass the node name that you want to the super constructor as shown above.

DTROS supports node categorization, this is useful when you want to visualize the ROS network as a graph, where graph nodes represent ROS nodes and graph edges represent ROS topics. In such a graph, you might want to group all the nodes working on the `PERCEPTION` problem together, say, to clear the clutter and make the graph easier to read. Use the parameter `node_type` in the super constructor of your node to do so. Use the values from the `NodeType` enumeration.

Possible node types are the following:

```
GENERIC
DRIVER
PERCEPTION
CONTROL
PLANNING
LOCALIZATION
MAPPING
SWARM
BEHAVIOR
VISUALIZATION
INFRASTRUCTURE
COMMUNICATION
DIAGNOSTICS
DEBUG
```

Node Parameters

All parameters should have names relative to the namespace of the node, i.e. they should start with `~`. Also, all parameters should be in the scope of the instance, not the method, so they should always be declared inside the constructor and start with `self.` .

Attention

The parameters should never have default values set in the code. All default values should be in the configuration file!

This makes sure that we don't end up in a situation where there are two different default values in two different files related to the node.

In classic ROS, you get the value of a parameter with `rospy.get_param(...)`. One of the issues of the ROS implementation of parameters is that a node cannot request to be notified when a parameter's value changes at runtime. Common solutions to this problem employ a polling strategy (which consists of querying the parameter server for changes in value at regular intervals). This is highly inefficient and does not scale. The `dtros` library provides a solution to this. Alternatively to using `rospy.get_param(...)` which simply returns you the current value of a paramter, you can create a `DTParam` object that automatically updates when a new value is set. Use `self.my_param = DTParam("~my_param")` to create a `DTParam` object and `self.my_param.value` to read its value.

Generic attributes

Then we initialize all the non-ROS attributes that we will need for this class. Note that this is done *before* initializing the Publishers and Subscribers. The reason is that if a subscriber's callback depends on one of these attributes, we need to define it before we use it. Here's an example that might fail:

```
class CoolNode(DTROS):
   def __init__(...):
       self.sub_a = rospy.Subscriber(..., callback=cb_sth, ...)
       self.important_variable = 3.1415

   def cb_sth(self):
       self.important_variable *= 1.0
```

And something that is better:

```
class CoolNode(DTROS):
   def __init__(...):
       self.important_variable = 3.1415
       sub_a = rospy.Subscriber(..., callback=cb_sth, ...)

   def cb_sth(self):
       self.important_variable *= 1.0
```

Publishers and Subscribers

Finally, we initialize all the Subscribers and Publishers as shown above. The `dtros` library automatically decorates the methods `rospy.Publisher` and `rospy.Subscriber`. By doing so, new parameters are added. All the parameters added by `dtros` have the prefix `dt_` (e.g., `dt_topic_type`). Use the values from the `TopicType` enumeration. Possible types list is identical to the node types list above.

Note

Only declare a topic type in a `rospy.Publisher` call.

Naming of variables and functions

All functions, methods, and variables in Duckietown code should be named using `snake_case`. In other words, only lowercase letters with spaces replaced by underscored. Do **not** use `CamelCase`. This is to be used **only** for class names.

The names of all subscribers should start with `sub_` as in the example above. Similarly, names of publishers should start with `pub_` and names of callback functions should start with `cb_`.

Initalizing publishers and subscribers should again always be in the scope of the instance, hence starting with `self.`.

Switching nodes on and off

Custom behavior on shutdown

If you need to take care of something before when ROS tries to shut down the node, but before it actually shuts it down, you can implement the `on_shutdown` method. This is useful if you are running threads in the background, there are some files that you need to close, resources to release, or to put the robot into a safe state (e.g. to stop the wheels).

Handling debug topics

Often we want to publish some information which helps us analyze the behavior and performance of the node but which does not contribute to the behavior itself. For example, in order to check how well the lane filter works, you might want to plot all the detected segments on a map of the road. However, this can be quite computationally expensive and is needed only on the rare occasion that someone wants to take a look at it.

A frequent (**but bad design**) way of handling that is to have a topic, to which one can publish a message, which when received will induce the node to start building a publishing the debug message. A much better way, and the one that **should be used** in Duckietown is to create and publish the debug message *only if* someone has subscribed to the debug topic. This is very easy to achieve with the help of `dtros`. Publishers created within a DTROS node exports the utility function `anybody_listening()`. Here’s an example:

```
if self.pub_debug_img.anybody_listening():
    debug_img = self.very_expensive_function()
    debug_image_msg = self.bridge.cv2_to_compressed_imgmsg(debug_img)
    self.pub_debug_img.publish(debug_image_msg)
```

Note also that all debug topics should be in the `debug` namespace of the node, i.e. `~debug/debug_topic_name`.

Similarly, a Subscriber created within a DTROS node exports the utility function `anybody_publishing()` that checks whether there are nodes that are currently publishing messages.

Timed sections

If you have operations that might take non-trivial amount of computational time, you can profile them in order to be able to analyze the performance of your node. `DTROS` has a special context for that which uses the same mechanism as the debug topics. Hence, if you do not subscribe to the topic with the timing information, there would be no overhead to your performance. Therefore, be generous with the use of timed sections.

The syntax looks like that:

```
with self.time_phase("Step 1"):
    run_step_1()

...

with self.time_phase("Step 2"):
    run_step_2()
```

Then, if you subscribe to `~debug/phase_times` you will be able to see for each separate section detailed information about the frequency of executing it, the average time it takes, and also the exact lines of code and the file in which this section appears.

Config files

If your node has at least one parameter, then it should have a configuration file. If there is a single configuration (as is the case with most nodes) this file should be called `default.yaml`. Assuming that our node is called `some_node`, the configuration files for the node should be in the `config/some_node/` directory.

Every parameter used in the implementation of the node should have a default value in the configuration file. Furthermore, there should be no default values in the code. The only place where they should be defined is the configuration file.

Launch files

Assuming that our node is called `some_node` then in the `launch` directory of the package there should be an atomic launch file with the name `some_node.launch` which launches the node in the correct namespace and loads its configuration parameters.

The launch file content of most node will be identical to the following, with only the node name and package name being changed.

```
<launch>
  <arg name="veh"/>
  <arg name="pkg_name" value="some_package"/>
  <arg name="node_name" default="some_node"/>
  <arg name="param_file_name" default="default" doc="Specify a param file"/>

  <group ns="$(arg veh)">
    <node  name="$(arg node_name)" pkg="$(arg pkg_name)" type="$(arg node_name).py"
output="screen">
      <rosparam command="load" file="$(find some_package)/config/$(arg
node_name)/$(arg param_file_name).yaml"/>
    </node>
  </group>

</launch>
```

Intermediate - Diagnostics

One of the strengths of Duckietown is that of allowing complex (sometimes state-of-the-art) algorithms to run on low-end computing devices like the Raspberry Pi. Unfortunately, low-end devices are not famous for their computational power, so we developers have to be smart about the way we use the resources available.

The Duckietown Diagnostics tool provides a simple way of *recording* the status of a system during an *experiment*. The easiest way to think about it is that of an observer taking snapshots of the status of our system at regular temporal intervals.

Introduction

Running example

Throughout this section we will refer to the toy example of a robot with a single camera (just like our Duckiebots) in which camera drivers produce image frames at a frequency of `20Hz` and we are interested in pushing the camera to its limit, i.e., `30Hz`.

When do I need it?

You need to run the diagnostics tool every time you have made changes to a piece of code and you want to test how these changes affect the footprint of your code on the system resources and the system as a whole.

Considering our toy example above, we expect that changing the drivers frequency will likely result in higher usage of resources in order to cope with the increase in images that need to be processed. Sometimes these changes have a direct and expected effect on the system’s resources, e.g., CPU cycles, RAM, etc. Others, they have effects that are legitimate from a theoretical point of view but hard to exhaustively enumerate a priori, e.g., increase in CPU temperature due to higher clock frequencies, increase in network traffic if the images are transferred over the network.

The diagnostics tool provides a standard way of analyzing the response of a system to a change.

When do I run it?

The diagnostics tool is commonly used for two use cases:

- analysis of *steady states* (long-term effects) of a system;
- analysis of *transient states* (short-term effects) of a system;

The *steady state* analysis consists of measuring the activity of a system in the long run and in the absence of anomaly or changes. For example, if we want to check for memory leaks in a system, we would run a *steady state* analysis and look at the RAM usage in a long period of time. In this case, we would run the diagnostics tool only after the system reached a stable (steady) state and we don't expect significant events to happen.

The *transient state* analysis consists of measuring how a system reacts to a change in the short run. For example, you have a process that receives point clouds from a sensor and stores them in memory to perform ICP alignment on them every `T` seconds. In this case, we expect that this process will be fairly inactive in terms of CPU usage for most of the time with periodical spikes every `T` seconds. Clearly, small values of `T` mean fewer point clouds to align every time ICP fires but more frequent alignments while large values of `T` mean longer queues of point clouds to align every time ICP fires. We might be interested in tuning the value of `T` so that those spikes do not starve other processes of resources while still maximizing `T`. In this case, we would monitor the system around those ICP events for different values of `T`. In this case, we would run the diagnostics tool at any point in time for a duration of `t > T` seconds so that at least one event of interest (e.g., ICP event) is captured.

Get Started

In this section, we will see how to perform a diagnostics experiment.

NOTE: At the end of each diagnostics test, the resulting log is automatically transferred to a remote server. If the diagnostics tool fails to transfer the log to the server, the tests data will be lost and the test need to be run again.

Run a (single test) diagnostics experiment

You can run a diagnostics test for `60` seconds on the target device `[ROBOT]` with the command

```
dts diagnostics run -H [ROBOT] -G my_experiment -d 60
```

Let the diagnostics tool run until it finishes. A successful experiment concludes with a log similar to the following:

```
. . .
[system-monitor 00h:00m:55s] [healthy] [8/8 jobs] [13 queued] [0 failed] ...
[system-monitor 00h:00m:58s] [healthy] [8/8 jobs] [13 queued] [0 failed] ...
INFO:system-monitor:The monitor timed out. Clearing jobs...
INFO:system-monitor:Jobs cleared
INFO:system-monitor:Collecting logged data
INFO:system-monitor:Pushing data to the cloud
INFO:system-monitor:Pushing to the server [trial 1/3]...
INFO:system-monitor:The server says: [200] OK
INFO:system-monitor:Data transferred successfully!
INFO:system-monitor:Stopping workers...
INFO:system-monitor:Workers stopped!
INFO:system-monitor:Done!
```

The most important thing to look for is the line

```
INFO:system-monitor:The server says: [200] OK
```

which indicates that the diagnostics log was successfully transferred to the remote diagnostics server.

Visualize the results

The diagnostics server collects diagnostics logs and organizes them according to the given group, subgroup and hostname of the target machine of each test.

To check the outcome of a diagnostics test, open your browser and navigate to https://dashboard.duckietown.org/diagnostics. Tests will be available on this page a few seconds after the upload is complete.

Use the dropdowns `Group` and `Subgroup` to find your experiment and test. Remember, when the subgroup is not explicitly specified with the argument `-S/--subgroup`, `default` is used.

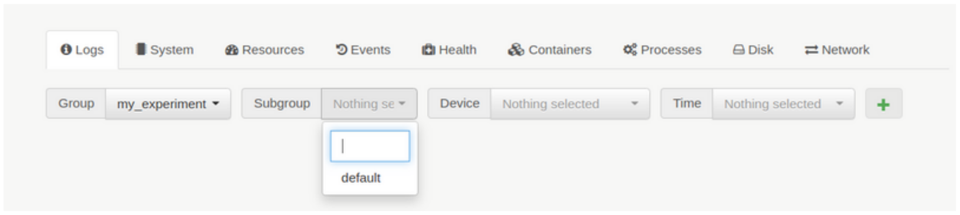


Fig. 20 Selecting diagnostics test on dashboard.duckietown.org

Use the tabs `System`, `Resources`, etc. to see the content of the diagnostics log.

One experiment, many tests

In many cases, your experiment is that of comparing two or more configurations or implementations of part of your system. In these cases, you need to run multiple tests as part of a single experiment. The diagnostics tool allows you to declare a group (`-G/--group`) and a subgroup (`-S/--subgroup`) when you run a test. Use the group argument to name your experiment and the subgroup to name the single tests.

Let us recall the example of Running example. We want to measure the effects of changing the drivers frequency on the system, so we run (and monitor) the system twice, a first time with the frequency tuned at `20Hz`, and a second time with the frequency at `30Hz`. We call the overall **experiment** `camera_frequency` and the two **tests**, `20hz` and `30hz` respectively. We can use the following commands to run the two tests described above, one before and the other after applying the change to the camera drivers code.

```
dts diagnostics run -H [ROBOT] -G camera_frequency -S 20hz -d 60
dts diagnostics run -H [ROBOT] -G camera_frequency -S 30hz -d 60
```

We can now use the Diagnostics page available at https://dashboard.duckietown.org/diagnostics. to visualize both tests side by side. Similarly to what we have done in Visualize the results, we will use the dropdown buttons to select our tests and add them to the list. Once we have both on the list, we can move to the other tabs to see how the results of the two tests compare.

Reference

In this section, we will describe the various arguments that the diagnostics tool accepts. Use them to configure the diagnostics tool to fit your needs.

Usage

You can run a diagnostics test using the command:

```
dts diagnostics run \
    -H/--machine [ROBOT] \
    -G/--group [EXPERIMENT] \
    -d/--duration [SECONDS] \
    [OPTIONS]
```

Options

The following table describes the **options** available to the diagnostics tool.

Argument	Type	Description
`-H` `--machine`	-	Machine where the diagnostics tool will run. This can be any machine with a network connection to the target machine.
`-T` `--target`	localhost	Machine target of the diagnostics. This is the machine about which the log is created.
`--type`	auto	Specify a device type (e.g., duckiebot, watchtower). Use `--help` to see the list of allowed values.
`--app-id`	-	ID of the API App used to authenticate the push to the server. Must have access to the 'data/set' API endpoint
`--app-secret`	-	Secret of the API App used to authenticate the push to the server
`-D` `--database`	-	Name of the logging database. Must be an existing database.
`-G` `--group`	-	Name of the experiment (e.g., new_fan)
`-S` `--subgroup`	"default"	Name of the test within the experiment (e.g., fan_model_X)
`-D` `--duration`	-	Length of the analysis in seconds, (-1: indefinite)
`-F` `--filter`	"*"	Specify regexes used to filter the monitored containers
`-m` `--notes`	"empty"	Custom notes to attach to the log
`--no-pull`	False	Whether we do not try to pull the diagnostics image before running the experiment
`--debug`	False	Run in debug mode
`--vv` `--verbose`	False	Run in debug mode

Table 6 Options available to the command `dts diagnostics run`

Simulation in Duckietown

What you will need	• [Implementing Basic Robot Behaviors]()
What you will get	• Results: Experience with running and testing on the Duckietown simulator

_images/simplesim_free.png

Why simulation?

Daphne is an avid Duckietowner who loves Duckies. In her mission to "save the Duckies" from bugs in her code she used to spend a large portion of her time writing unit tests for her algorithms and ROS nodes. Some of these tests would check that the accuracy of her object detection pipeline was above a certain threshold, that the estimated offset of the Duckiebot from the lane given several input images was correct or that the output of the controller given several offsets gave sensible results. She noticed that this way of testing would fall short in several aspects:

- The number of hand-crafted edge cases was not representative of the number of situations the Duckiebot would encounter in a single drive
- Issues at the interface of these algorithms would not be caught
- To increase code coverage and maintain it, a lot of time would need to go into writing tests, mock ups, gathering and labelling test data, etc

- Quantifying controller performance was hard without having access to a model of the vehicle used to propagate the state forward in time

Daphne also found that having to charge her robot's battery, setting up her Duckietown loop, placing her Duckiebot on the loop, connecting to it, and running the part of the pipeline that had to be tested everytime she or someone in her team wanted to merge new changes into the codebase was extremely time consuming.

More over, Daphne and her real Duckiebot only have access to a small Duckietown loop. But she wants to ensure that her algorithms work in the most complicated and busy environments of Duckietown.

All of the above were compelling reasons for Daphne to start looking at full-stack simulators that would allow her to simultaneously address the shortcomings of unit testing, the inconvenience of manual testing and the ability to test scenarios that are not possible or too risky in real life.

Luckily, she found just the right thing at the Duckietown gym.

Daphne's story is the story of every autonomous driving company, whose mission is instead to "save the humans" and which cannot afford to make mistakes on the real roads, and which require automated integration testing tools that can be run faster-than-real-time under challenging conditions. As an example, Waymo has driven around 20 million miles on real roads, but around 15 billion miles in simulation!

Introduction to the Duckietown Simulator

Gym-Duckietown is a simulator for the Duckietown universe, written in pure Python/OpenGL (Pyglet). It places your agent, a Duckiebot, inside an instance of a Duckietown: a loop of roads with turns, intersections, obstacles, Duckie pedestrians, and other Duckiebots.

Gym-Duckietown is fast, open, and incredibly customizable. What started as a lane-following simulator has evolved into a fully-functioning autonomous driving simulator that you can use to train and test your Machine Learning, Reinforcement Learning, Imitation Learning, or even classical robotics algorithms. Gym-Duckietown offers a wide range of tasks, from simple lane-following to full city navigation with dynamic obstacles. Gym-Duckietown also ships with features, wrappers, and tools that can help you bring your algorithms to the real robot, including domain-randomization, accurate camera distortion, and differential-drive physics (and most importantly, realistic waddling).

_images/finalmain.gif

Quickstart Guide

To run a minimal demo of the simulator, you simply need a (virtual) environment with the gym_duckietown pip3 package installed.

To set up such an environment, the safest way is to run the following (you could also skip the virtual environment but you may have clashing packages installed):

```
$ cd ~ && virtualenv dt-sim
$ source dt-sim/bin/activate
$ pip3 install duckietown-gym-daffy
```

TODO reference to daffy library above

Now you need to create a simple python script with uses the gym-duckietown API to connect to the simulator, the API is very simple as you will see.

Create and run the following file, from within the environment you have set up above:

```
#!/usr/bin/env python3
import gym_duckietown
from gym_duckietown.simulator import Simulator
env = Simulator(
        seed=123, # random seed
        map_name="loop_empty",
        max_steps=500001, # we don't want the gym to reset itself
        domain_rand=0,
        camera_width=640,
        camera_height=480,
        accept_start_angle_deg=4, # start close to straight
        full_transparency=True,
        distortion=True,
    )
while True:
    action = [0.1,0.1]
    observation, reward, done, misc = env.step(action)
    env.render()
    if done:
        env.reset()
```

What do you observe? Does this make sense? Why is it driving straight? Can you make it drive backwards or turn? When is `done = True`? What is `observation`?

Driving around in the simulator

If you want to drive the robot around in simulation you might have read about the utility script `manual_control.py`. This is located in the root of the gym_duckietown repository and can be run after making sure that all the dependencies are met. Clone the repository and in the root of it run:

```
$ ./manual_control.py --env-name Duckietown-udem1-v0
```

You should be able to drive around with the arrow keys. If you are experiencing large delays and low frame rate, please replace the lines

```

pyglet.clock.schedule_interval(update, 1.0 / 30)

# Enter main event loop
pyglet.app.run()

```

by

```
import time

...

dt = 0.01
while True:
    update(dt)
    time.sleep(dt)

```

Environments

There are multiple registered gym environments, each corresponding to a different map file:

- `Duckietown-straight_road-v0`
- `Duckietown-4way-v0`
- `Duckietown-udem1-v0`
- `Duckietown-small_loop-v0`
- `Duckietown-small_loop_cw-v0`
- `Duckietown-zigzag_dists-v0`
- `Duckietown-loop_obstacles-v0` (static obstacles in the road)
- `Duckietown-loop_pedestrians-v0` (moving obstacles in the road)

The `MultiMap-v0` environment is essentially a wrapper for the simulator which will automatically cycle through all available map files. This makes it possible to train on a variety of different maps at the same time, with the idea that training on a variety of different scenarios will make for a more robust policy/model.

`gym-duckietown` is an *accompanying* simulator to real Duckiebots, which allow you to run your code on the real robot. We provide a domain randomization API, which can help you transfer your trained policies from simulation to real world. Without using a domain transfer method, your learned models will likely overfit to various aspects of the simulator, which won't transfer to the real world. When you deploy, you and your Duckiebot will be running around in circles trying to figure out what's going on.

_images/domainrand-sim.gif

Installation

We have covered the basic installation in the quickstart guide.

Alternative Installation Instructions (Alternative Method)

Alternatively, you can find further installation instructions here

Docker Image

There is a pre-built Docker image available on Docker Hub, which also contains an installation of PyTorch.

Note

In order to get GPU acceleration, you should install and use nvidia-docker.

Design

Map File Format

The simulator supports a YAML-based file format which is designed to be easy to hand edit. See the maps subdirectory for examples. Each map file has two main sections: a two-dimensional array of tiles, and a listing of objects to be placed around the map. The tiles are based on the Duckietown appearance specification.

TODO absolute URL here

The available tile types are:

- empty
- straight
- curve_left
- curve_right
- 3way_left (3-way intersection)
- 3way_right
- 4way (4-way intersection)
- asphalt
- grass
- floor (office floor)

The available object types are:

- barrier
- cone (traffic cone)
- duckie
- duckiebot (model of a Duckietown robot)
- tree
- house
- truck (delivery-style truck)
- bus

- building (multi-floor building)
- sign_stop, sign_T_intersect, sign_yield, etc. (see meshes subdirectory)

Although the environment is rendered in 3D, the map is essentially two-dimensional. As such, objects coordinates are specified along two axes. The coordinates are rescaled based on the tile size, such that coordinates [0.5, 1.5] would mean middle of the first column of tiles, middle of the second row. Objects can have an `optional` flag set, which means that they randomly may or may not appear during training, as a form of domain randomization.

Observations

The observations are single camera images, as numpy arrays of size (120, 160, 3). These arrays contain unsigned 8-bit integer values in the [0, 255] range. This image size was chosen because it is exactly one quarter of the 640x480 image resolution provided by the camera, which makes it fast and easy to scale down the images. The choice of 8-bit integer values over floating-point values was made because the resulting images are smaller if stored on disk and faster to send over a networked connection.

Actions

The simulator uses continuous actions by default. Actions passed to the `step()` function should be numpy arrays containining two numbers between -1 and 1. These two numbers correspond to the left and right wheel input respectively. A positive value makes the wheel go forward, a negative value makes it go backwards. There is also a Gym wrapper class named `DiscreteWrapper` which allows you to use discrete actions (turn left, move forward, turn right) instead of continuous actions if you prefer.

Reward Function

The default reward function tries to encourage the agent to drive forward along the right lane in each tile. Each tile has an associated Bezier curve defining the path the agent is expected to follow. The agent is rewarded for being as close to the curve as possible, and also for facing the same direction as the curve's tangent. The episode is terminated if the agent gets too far outside of a drivable tile, or if the `max_steps` parameter is exceeded. See the `step` function in this source file.

Customizing the Simulator

You can modify the parameters of the simulator. Simply modify the parameters sent to the `Simulator` constructor:

```
from gym_duckietown.simulator import Simulator
env = Simulator(
    seed=123, # random seed
    map_name="loop_empty",
    max_steps=500001, # we don't want the gym to reset itself
    domain_rand=0,
    camera_width=640,
    camera_height=480,
    accept_start_angle_deg=4, # start close to straight
    full_transparency=True,
    distortion=True,
)
```

When we take a look at the constructor, you'll notice that we aren't using all of the parameters listed. In particular, the three you should focus on are:

- `map_name`: What map to use;
- `domain_rand`: Applies domain randomization, a popular, black-box, sim2real technique
- `randomized_maps_on_reset`: Slows training time, but increases training variety.
- `camera_rand`: Randomizes the camera calibration to increase variety.
- `dynamics_rand`: Simulates a miscalibrated Duckiebot, to better represent reality.

Running headless

The simulator uses the OpenGL API to produce graphics. This requires an X11 display to be running, which can be problematic if you are trying to run training code through on SSH, or on a cluster. You can create a virtual display using Xvfb. The instructions shown below illustrate this. Note, however, that these instructions are specific to MILA, look further down for instructions on an Ubuntu box:

```
# Reserve a Debian 9 machine with 12GB ram, 2 cores and a GPU on the cluster
sinter --reservation=res_stretch --mem=12000 -c2 --gres=gpu

# Activate the gym-duckietown Conda environment
source activate gym-duckietown

cd gym-duckietown

# Add the gym_duckietown package to your Python path
export PYTHONPATH="&#36;{PYTHONPATH}:`pwd`"

# Load the GLX library
# This has to be done before starting Xvfb
export LD_LIBRARY_PATH=/Tmp/glx:&#36;LD_LIBRARY_PATH

# Create a virtual display with OpenGL support
Xvfb :&#36;SLURM_JOB_ID -screen 0 1024x768x24 -ac +extension GLX +render -noreset
&#38;<code>&gt;</code> xvfb.log &#36;
export DISPLAY=:&#36;SLURM_JOB_ID
```

Troubleshooting

If you run into problems of any kind, don't hesitate to open an issue on this repository. It's quite possible that you've run into some bug we aren't aware of. Please make sure to give some details about your system configuration (ie: PC or Max, operating system), and to paste the command you used to run the simulator, as well as the complete error message that was produced, if any.

Troubleshooting

SYMPTOM ImportError: Library "GLU" not found

RESOLUTION You may need to manually install packaged needed by Pyglet or OpenAI Gym on your system. The command you need to use will vary depending which OS you are running. For example, to install the glut package on Ubuntu:

```
$ sudo apt-get install freeglut3-dev
```

And on Fedora:

```
$ sudo dnf install freeglut-devel
```

Troubleshooting

SYMPTOM NoSuchDisplayException: Cannot connect to "None"

RESOLUTION If you are connected through SSH, or running the simulator in a Docker image, you will need to use xvfb to create a virtual display in order to run the simulator. See the Running Headless subsection.

Troubleshooting

SYMPTOM Poor performance, low frame rate

RESOLUTION It's possible to improve the performance of the simulator by disabling Pyglet error-checking code. Export this environment variable before running the simulator:

```
$ export PYGLET_DEBUG_GL=True
```

Troubleshooting

SYMPTOM Unknown encoder 'libx264' when using gym.wrappers.Monitor

RESOLUTION It is possible to use `gym.wrappers.Monitor` to record videos of the agent performing a task. See examples here.

The libx264 error is due to a problem with the way ffmpeg is installed on some linux distributions. One possible way to circumvent this is to reinstall ffmpeg using conda:

```
$ conda install -c conda-forge ffmpeg
```

Alternatively, screencasting programs such as Kazam can be used to record the graphical output of a single window.

How to cite

Please use this bibtex if you want to cite this repository in your publications:

```
@misc{gym_duckietown,
  author = {Chevalier-Boisvert, Maxime and Golemo, Florian and Cao, Yanjun and
Mehta, Bhairav and Censi, Andrea and Paull, Liam},
  title = {Duckietown Environments for OpenAI Gym},
  year = {2018},
  publisher = {GitHub},
  journal = {GitHub repository},
  howpublished = {\url{https://github.com/duckietown/gym-duckietown}},
}
```