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ACRONYMS

GRAPE Ground Robot for vineyArd Monitoring and ProtEction

ROS Robot Operating System

LIDAR Laser Imaging Detection and Ranging

UGV Unmanned Ground Vehicle

ICC Instantaneous Center of Curvature

1 BACKGROUND AND TOOLS

In this chapter we are going to describe the general concepts this thesis deals with, together with the main tools we used to address the project. Since this thesis is in the frame of GRAPE project (see Chapter 2), most of them are typical of the robotic field and, more specifically, of the agricultural robotics. This last field should be seen in the wider context of the so-called *E-agriculture*; to give a precise definition of this term, we make reference to the FAO (Food and Agriculture Organization) definition[1]:

> *E-agriculture, or ICTs in agriculture, is about designing, developing and applying innovative ways to use ICTs with a primary focus on agriculture. E-agriculture offers a wide range of solutions to agricultural challenges and has great potential in promoting sustainable agriculture while protecting the environment.*

The GRAPE project, that will be described with further details in chapter 2, is about the design and realization of an Unmanned Ground Vehicle (UGV) with control and operative task in a vineyard environment, so in this chapter we'll deal with topics concerning software development in robotics, estimation of the state of a robot, autonomous navigation

ROBOT OPERATING SYSTEM

ROS is the *robotic middleware* we used to develop the sofware components of the system described in this thesis. We decide to use it because of its great modularity, the availability of a very large number of packages, well documented APIs and an active community. Moreover, ROS is a very widespread system, so its power and versatility are well known in the field of software development for robotics. Citing words from its offical website[2], these are ROS main features:

> *It provides the services you would expect from an operating system, including hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. It also provides tools and libraries for obtaining, building, writing, and running code across multiple computers.*

1 http://www.fao.org/fileadmin/templates/rap/files/uploads/E-agriculture_Solutions_Forum.pdf
2 http://wiki.ros.org/ROS/Introduction

ROS is actually a *meta-operating system*, that is, it's not an operating system in the traditional sense (it requires to be run on top of an another operating system; currently, the only officially supported OS is Linux Ubuntu), but it provides a peer-to-peer network that processes can use to create and process data together. This network is implemented through TCP, and it's called *Computation Graph*. In this section, we're going to describe ROS with more detail, with particular emphasis on the different tecniques that nodes can use to communicate among them. Keep in mind that, even if these tecniques differs a lot, they all are strongly typed *i.e.* in order to define a channel (with *channel* we now mean one of the tecnique that we are going to describe. It's not the name of a specific communication tool) you also need to define the types of message that are going to be exchanged throught it. ROS already defines a lot of useful message types (*e.g. LaserScan.msg*, *PoseWithCovarianceStamped.msg*), grouped by domain (*e.g.*, *Sensor_msgs*, *Geometry_msgs*). However a simple message definition language is provided, and users are encouraged to define their own message types to make them as self-explanatory as possible.

ROS MASTER Even if the Computation Graph is a peer-to-peer network, a central process, called **ROS Master**, is required to exist, to provide naming and registration services to all the user processes In this. Once the processes have located each other through the services offered by the Master, they can communicate peer-to-peer without involving a central entity;

NODES The processes that are in the Computation Graph are called **nodes**, and they are the atomic units of the computational graph. The ROS API are available in C++, Python and Lisp, but C++ is the most widely used. One of the aims of ROS is to be modular at a fine-grained scale, so a complex task should be achieved through cooperation of several different nodes, each with quite narrow tasks, rather than one large node that include all the functionalities. Nodes can use different techniques for communication, depending whether the message is a part of data stream or it is a request message (*i.e.* a response message is expected) and, in this last case, on the (expected) duration and complexity of the computation of the response.

TOPICS Topics implements a *publish-subscribe* paradigm, are they the easiest way that nodes can use to communicate with each other, and basically are named channels, characterized by the type of the messages that are sent through it. When a node *publish* a message on a certain topic, the message is read from all the nodes that previously *subscribed* to that topic, interfacing with the Master. Note that:

- this technique leads to a strong decoupling between publishers and subscribers to a topic, because a publisher node

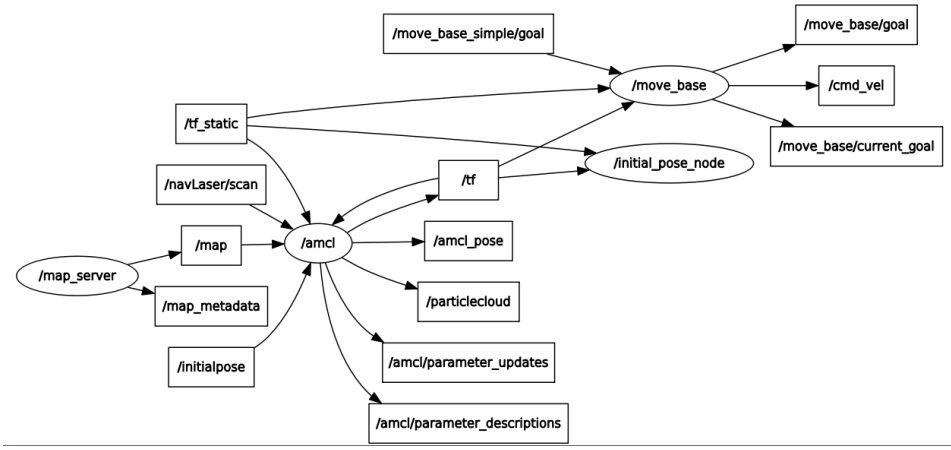


Figure 1.1: *An example of the ROS Computation Graph, visualized with* rqt*: nodes are represented with circles, rectangles represent topics, and arrows go from a node to a topic it publishes on, or from a topic to a node subscribed to it. It's easy to recognize the* many-to-many *relationship.*

is, from an high-level perspective[3], not even aware of the presence of subscribers, and viceversa.

- the relationship between publishers and subscribers is *many-to-many*, *i.e.* multiple nodes can publish on a topic, and multiple nodes can subscribe to a topic.

We can easily conclude that this method is very suitable for passing streams of data (*e.g.* the handler of a Laser Imaging Detection and Ranging (LIDAR) streams its measurements over the network, or a node publish the velocities commands for the wheels of a robot), but there is no notion of a *response* to a message, so it's not suitable for *request-response* communication.

SERVICES Services are defined by a name, and a couple of message types that describe the *request* type and the *response* type. Each service is offered by a Service server to any Service client that perform a call. So, Services implement an inter-node communication that is very similar to traditional function calling in most common programming languages (*e.g.* C++, Java), in the sense that:

- Service calls are blocking
- using Services, the inter-node communication is *one-to-one*

These properties make Services suitable for punctual (in opposition to data stream) inter-node communication, such as: request of parameters values to another node, ask a node that handles

3 Actually, publisher nodes always know the list of nodes subscribed to their topics. But this is only used in connection phase, and to avoid a situation where a node publish on a topic with no subscribers, for the sake of efficiency.

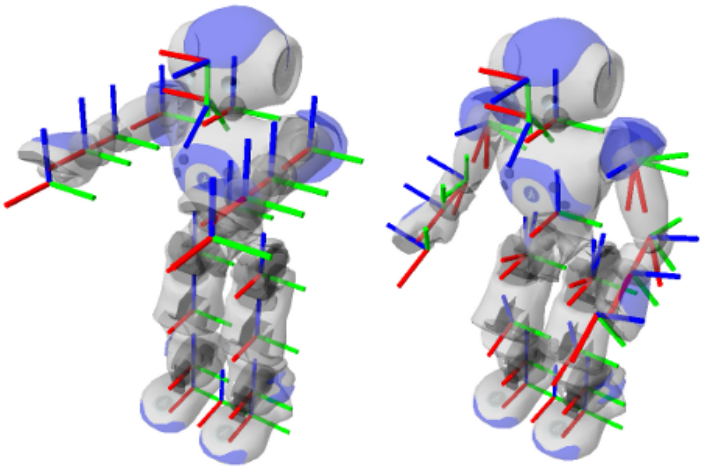


Figure 1.2: *A robot in 2 different positions, with* tf *frames in evidence: x-axis is red, y-axis is green, z-axis is blue. The frames are the same in both configuration, but the transformations (i.e. rototranslations) between them are different.*

a camera to take a picture, ask a node that perform navigation task to clear the current map.

ACTIONS While Services, with their resemblance to traditional function calls, can address pretty well the problem of *one-to-one* inter-node communication, they can be quite unsatisfying if the computation required to produce the response is demanding in term of execution time (*e.g.*, navigation of a robot from one point to another in an environment), because the caller is stuck at the line with the Service invocation until the end of the procedure. Services show their weaknesses also in situations where it could be useful to observe the intermediate results of the computation triggered by the request (*e.g.*, a very complex manipulation procedure). **Actions** are very suitable in this context because, at the cost of a more complex implementation, provide an asynchronous and fully preemptable remote procedure call, with the possibility of monitoring intermediate results if needed. Differently from Topics and Services, Actions are not native in ROS, and their functionalities are built on top of the other ROS messagging systems. Asynchronicity is provided by the use of callbacks.

TF: THE TRANSFORM LIBRARY

tf is a ROS library, which task is very important to understand in order not to get lost in the next sections and chapters. The goal of *tf* is:

> *" [...] provide a standard way to keep track of coordinate frames and transform data within an entire system such that individual*

> *component users can be confident that the data is in the coordinate frame that they want without requiring knowledge of all the coordinate frames in the system" (Foote, 2013)*

The utility of such a component is straightforward, even in quite simple robotic systems. We'll describe here a situation we stumpled upon exactly in the development of the GRAPE project, where of the utility of *tf* is very easy to understand; you'll be able to better contextualize this example after you've read Chapter 6. In this example a LIDAR, mounted on top of the final joint of a robotic arm, acquires data while the arm is moving in order to create a point cloud that will be processed later. To get a meaningful point cloud, it's mandatory to keep track of the movement of the LIDAR with respect to a point with speed equal to zero (*e.g.* the base link of the arm, or the base link of the whole robot), and this gets even more difficult because of the multiple (6 in our specific case) joints of the arm; but this problem can be easily addressed by means of *tf*, that we are now going to describe with more detail. *tf* implementation relies on ROS topics (see Section 1.1) and achieves the goal mentioned before by building an oriented graph where vertices are reference frames, and edges are transformations (rototranslations) between frames. *tf* does not assume a constant structure and, if a path exists between two reference frames in the graph, the direct transformation between them can be computed by composition of transformation. Since, in general, multiple paths between 2 vertices can exists in a directed graph and this could lead to ambiguity in computing the transformation between two reference frames, the graph is forced to be acyclic. Discongit anected subgraphs are allowed, but of course transformation between vertices that belong to different subgraphs cannot be computed. The main components of the library are:

- ***tf* broadcasters**: they are simple software components, that publish a transformation between two reference frames every time an update is available. Different broacasters does not sync together the publishing phase
- ***tf* listeners**: they are more complex components, because they take into account that broadcasters are not synced. Since both transformations and queries to *tf* graph are stamped, listeners make use of queues to store the most recent transformations, and they interpulate old values using SLERP (Spherical Linear intERPolation) to return a transformation for which there is no measured value at the requested timestamp.

In figure 1.2 you can see a graphical representation of the reference frames tracked in a Nao Robot, while figure 1.3 shows an example of *tf* graph visualized with visualization framework *rqt*.

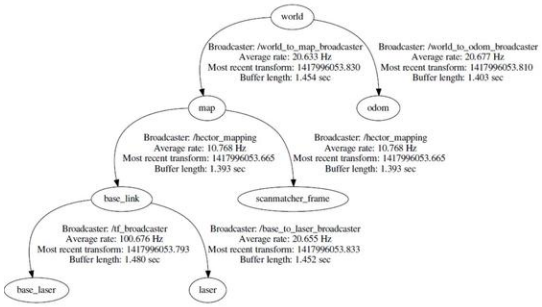


Figure 1.3: *An example of* tf *tree*

Figure 1.4: *Husky platform from Clearpath Robotics is the platform used for the development of* GRAPE *project.*

ODOMETRY

The problem of odometry, *i.e.* estimation of the position of a robot in an environment is harder than it could seem. Formally, odometry estimation is the problem of estimating over time the tuple:

$$< x, y, z, \theta, \dot{x}, \dot{y}, \dot{z}, \dot{\theta} > \tag{1.1}$$

given the measurement of some motion sensors. To better understand the complexity of the problem, let's analyze an extremely simple model: a robot with a single, freely rotating wheel. In this frame, assuming rotary encoders on the wheel, we can think about measuring directly the wheel speed and integrate these measurement to get the travelled distance, and measure the variation in the orientation of the wheel to get the position. But actually there are a lot of imperfection that can lead to error, for example:

- wheel can be non perfectly perendicular to the ground
- the friction between the floor and the wheel might not be enough to avoid slippage (expecially)

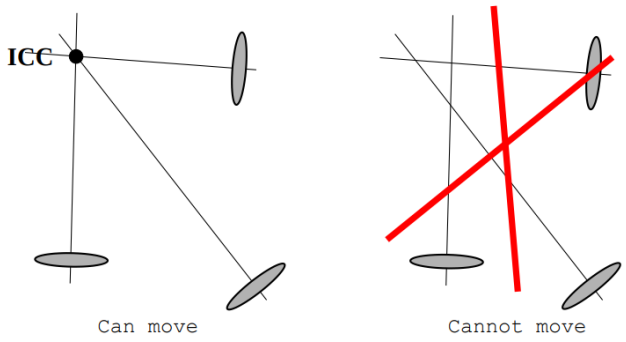


Figure 1.5: *If the axis of all the wheels intersect in a single point, it's called ICC and the robot can move without slipping*

- there is no such thing as a perfect sensor, so the use of encoders introduce an error

Even if all these concurrent causes seem negligible, you have to take into account that the errors sum up over time, so an error of a few millimeters per meter might become significant over time.
Moreover, the probability of slippage gets higher in systems with more than one wheel, because, because for a system with multiple wheels to move without slippage, a point must exists around which all the wheels can move along a circular path. This point is called Instantaneous Center of Curvature (ICC) (see Figure 1.5), and can be easily identified by looking for the intersection of the axis of all wheels. If the intersaction exists in a single point, it's called the ICC. But even if the odometry estimated from the wheels is not a good solution if used alone, it can be used as a starting point for other, more complex, method. For this reason we are now going to descript how to estimate the odometry starting from the wheels encoders in our specific robot. This computation is different according to the **motion model** of the considered robot. As we'll see in Section 3.1, the robot we used is the Husky platform (see Figure 1.4) from Clearpath Robotics, that moves with a *skid steering* kinematics, that is a derivative of *differential drive* kinematics. Thus, we're going to describe these two motion model with more detail.

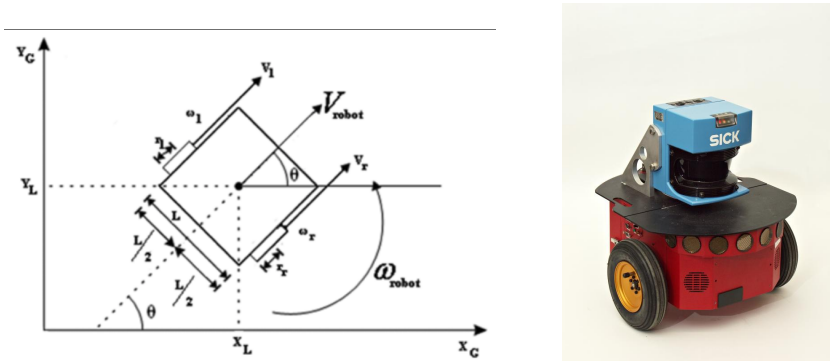
Differential drive robot

In a differential drive system, the movement of the robot is only based on two separately driven wheels, placed on either side of the robot, on the same axis (see Figure 1.6). By recalling the definition of ICC, we observe that, if the weels are correctly aligned, a differential drive robot always have a well-defined ICC and the slippage of the wheels is not very accentuated.
At each instant in time, since the ICC is well-defined, the left and

right wheels follow a path that moves around ICC at the same angular speed ω, and thus:

$$\begin{cases} \omega(R + \frac{L}{2}) = v_r \\ \omega(R - \frac{L}{2}) = v_l \end{cases} \tag{1.2}$$

where L is the



(a) (b)

Figure 1.6: *On figure 1.6a, the scheme of a differential drive motion model; in figure 1.6b, an example of a differential drive robot (Pioneer 3DX).*

- cosa si intende per odometria
- motion models: differential drive e skid steering
- sensor fusion cos'è, e esempio di Robot localization
- localizzazione con amcl

NAVIGATION STACK

SKETCH:

- cos'è navigation stack (immagine http://wiki.ros.org/move_base?action=AttachFile&do=get&tarş
- local/global costmap

2 THE GRAPE PROJECT

The GRAPE project chapter SKETCH:

- descrizione del progetto e i suoi macro goals (navigazione autonoma, monitoraggio della salute della vigna, dispenser dei ferormoni, interfaccia user friendly)
- enti collaborativi (polimi, eurecat, vitirover) con relativi compiti
- difficoltà previste: outdoor, terreno accidentato
- parti su cui ho lavorato io direttamente (design dell'architettura sw, scan motion, parti del deployment)
- qualche foto di vigna/dispensers

3

GRAPE HARDWARE AND SOFTWARE ARCHITECURE

Grape architecture SKETCH:

GRAPE HW ARCHITECTURE

GRAPE SW ARCHITECTURE

- Hardware del robot:
  - scelta dell'husky (adatto per rugged terrain, supporto di pacchetti ROS), foto
  - scelta del braccio, con pro (compatto, 6 dof, power consumption non elevata) e contro (movimenti non precisi, fragile, scarso controllo di collisione)
  - lidar sul braccio per scan
  - lidar davanti per navigazione e eventualmente localizzazione
  - camera montata sul braccio
  - velodyne davanti (a cosa serve?)
  - camera fissa per eventualmente scattare foto alla vigna
  - imu
- foto del robot
- Software del robot
  - descrizione più precisa di quale è nel complesso la procedura: viene dato a mano (interfaccia grafica di Eurecat) una posizione finale, e serie di waypoints intermedi. Procedura di scan che usando PCL trova punti adatti al deployment. Procedura di deploymnet. Waypoint successivo.
  - struttura col coordinatore, che chiama le 3 action (move_base, scan, deploy)
  - di ogni azione, il file che descrive i tipi di goal/result/feedback, con spiegazioni del significato dei parametri

4

THE ROBÌ PROJECT

The Robì project chapter:

- obiettivo: realizzare un'altra base mobile alternativa all'husky su cui portare il sistema GRAPE
- architettura hw: sensori che ci sono montati a bordo, spiegazione sistema controllo motori tramite CAN usando la board STM
- architettura sw: compatibile con quella di Grape, a meno dei nodi driver dei sensori e attuatori
- spiegazioni e immagini del vario hardware

5 SENSOR FUSION AND LOCALIZATION IN GRAPE

Localization Chapter SKETCH:

- problemi avuti: mappa molto ripetitiva, il robot tenta di passare attraverso i filari, odometria delle ruote poco affidabile dato il terreno, problemi con amcl
- virtual obstacles: cenni (perché non l'ho fatto io) e immagini
- configurazione di robot localization, con i sensori usati (ruote+imu+gps)
- non sappiamo ancora quale sarà la soluzione utilizzata alla fine tra la versione mapless e amcl integrato con robot_localization (o eventuali altre soluzioni che salteranno fuori). Una volta che è stata presa una decisione, presentare quella come soluzione definitiva e spiegare perché l'altra è stata giudicata meno efficace

6

KINOVA ARM

Kinova Arm chapter: SKETCH

- moveit: cos'è, concetti di planning e execution
- scopo del braccio in GRAPE: scan della pianta, deployment, automa a stati che rappresenta la sequenza di azioni del braccio
- problema 1 dovuto alla scarsa precisione: accenni alle parti di visual servo con marker per compensare questo problema in fase di grasping e deployment (cenni, fatta da Polito e Bascetta).
- problema 2 dovuto ai limiti di execution di moveit: impossibilità di fare un movimento di scansione fluido e completo usando moveit, metodo della jacobiana e la pubblicazione delle velocità
- utilizzo della camera per validazione del grasping e del deployment
- foto del braccio, immagini della nuvola di punti processata dal codice di ferran, alcune immagini dell'image processing nelle fasi di visual servo e di validazione di grasping/deployment

7 EXPERIMENTAL RESULTS

The experimental results chapter:

- TODO: decidere prima della integration week che cosa vogliamo metterci, così sappiamo che dati procurarci

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