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CONTENTS

1	BACKGROUND AND TOOLS	1
1.1	Robot Operating System	1
1.2	TF: The Transform Library	5
1.3	Odometry	8
1.3.1	Differential drive robot	9
1.3.2	Skid-steering	11
1.4	Sensor fusion	13
1.4.1	Robot Localization	15
1.5	Navigation Stack	16
2	THE GRAPE PROJECT	19
2.1	Project Description and Goals	19
2.2	Contextualization of thesis work in the project	21
2.3	Related Projects	23
3	GRAPE HARDWARE AND SOFTWARE ARCHITECTURE	25
3.1	GRAPE hardware architecture	25
3.1.1	Robotic Base	25
3.2	GRAPE sw architecture	26
4	THE ROBÌ PROJECT	27
5	SENSOR FUSION AND LOCALIZATION IN GRAPE	29
6	KINOVA ARM	31
7	EXPERIMENTAL RESULTS	33
	BIBLIOGRAPHY	35

LIST OF FIGURES

- Figure 1.1 *Three phases of the setup of communication of nodes throught topics.* 3
- Figure 1.2 *An example of the Robot Operating System (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.* 4
- Figure 1.3 *Visualization of the ROS Computation Graph with rqt in the context of a data bag being played: there is a single node (GRAPE_robot) that simultaneously plays recorded topics messages.* 5
- Figure 1.4 *Sketch of the implementation of actionlib, through ROS topics and a callback system.* 5
- Figure 1.5 *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.* 6
- Figure 1.6 *An example of tf tree* 7
- Figure 1.7 *If the axis of all the wheels intersect in a single point, it's called ICC and the robot can move without slipping* 8
- Figure 1.8 *On figure 1.8a, the scheme of a differential drive motion model; in figure 1.8b, an example of a differential drive robot (Pioneer 3DX).* 9
- Figure 1.9 *Differential drive: $(x, y, \theta) \rightarrow (x', y', \theta')$* 11
- Figure 1.10 *Husky platform from Clearpath Robotics is the platform used for the development of Ground Robot for vineyArd Monitoring and ProtEction (GRAPE) project.* 12
- Figure 1.11 *On figure 1.11a, the scheme of a skid steering motion model; in figure 1.11b, an example of a skid steering vehicle.* 12
- Figure 1.12 *The equivalence of differential drive motion model and skid steering model according to Wang et al., 2015* 13
- Figure 1.13 *Sensor fusion 1.13a vs multi-sensor integration 1.13b* 14
- Figure 1.14 *A scheme of Robot Localization senor fusion* 15

- Figure 1.15 Local and global costmap visualized with RViZ. As you can see, the local costmap (in brighter colors) is built around the robot, and moves together with it. [17](#)
- Figure 1.16 A scheme representation of the Navigation Stack; see the color legend for classification in provided, optional provided, and platform specific nodes. [18](#)
- Figure 2.1 A vine before ([2.1a](#)) and after ([2.1b](#)) having leafed out. [20](#)
- Figure 2.2 Different shape of pheromone dispensers available on the market. The model used in GRAPE is the one depicted in image [2.2c](#) [22](#)
- Figure 2.3 Other field robots developed in EU projects in the last 6 years: [2.3a](#) Vinerobot, [2.3b](#) Vinbot. [22](#)
- Figure 2.4 Other field robots developed in EU projects in the last 6 years: [2.4a](#) Rhea, [2.4b](#) CROPS. [24](#)

LIST OF TABLES

LISTINGS

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
IMU	Inertial Measurement Unit

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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) definition¹:

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 software 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 official website², 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 techniques that nodes can use to communicate among them. Keep in mind that, even if these techniques differs a lot, they all are strongly typed *i.e.* in order to define a channel (with *channel* we now mean one of the technique 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 through 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

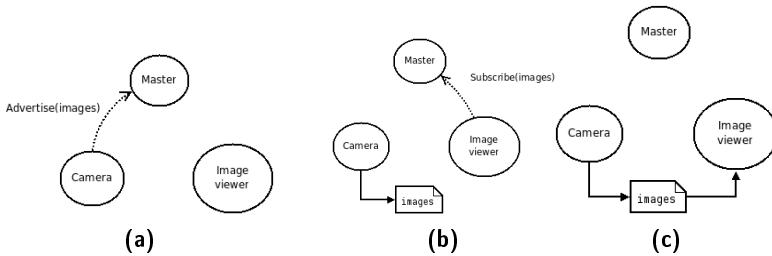


Figure 1.1: Three phases of the setup of communication of nodes through topics.

is, from an high-level perspective³, 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 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

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.

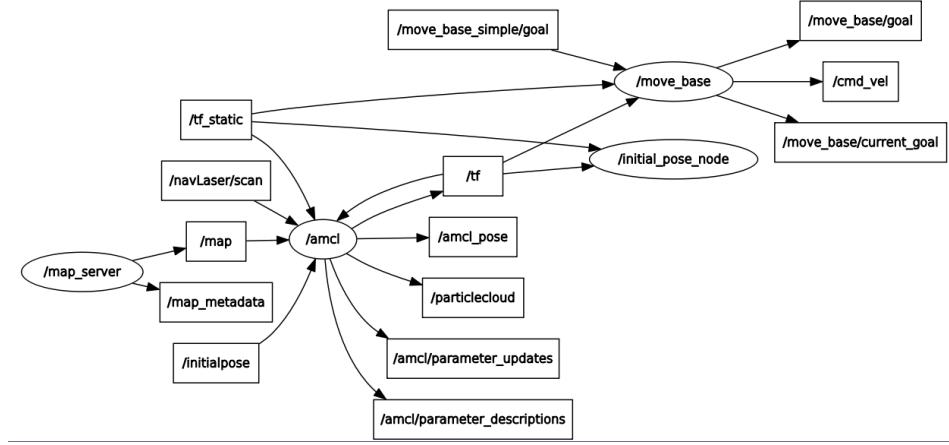


Figure 1.2: An example of the [ROS](#) Computation Graph, visualized with `rqt`: nodes are represented with circles, rectangles represent topics, and arrows go from a node to a topic it publishes on, or from a topic to a node subscribed to it. It's easy to recognize the many-to-many relationship.

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](#) messaging systems (See figure 1.4). Asynchronicity is provided by the use of callbacks.

A final consideration about the [ROS](#) mechanism for recording, and playing back, data published on topics. This software module is called `rosbag`, and takes advantage of the fact that [ROS](#) is aware of all the messages exchanged through its messaging system. This tool gets very useful in a project like [GRAPE](#), where it is not trivial at all to simulate or replicate in a laboratory environment the physical context of a vineyard, and of course meaningful data are required in order to correctly validate algorithms and tools. The paradigm is very simple: in every moment you can invoke a `rosbag record` command, that records every single message exchanged on the [ROS](#) topics; data are logged in a single file with `.bag` extension, that can be later filtered and/or compressed. Bag files can be played back in a very easy way invoking `rosbag play` command; the playing of the bag is implemented with a single node that streams messages on all the topics existing in the bag (see Figure 1.3). The module also provides an option to use *simulated time*, i.e. playing the bag exactly with the same message timing as in

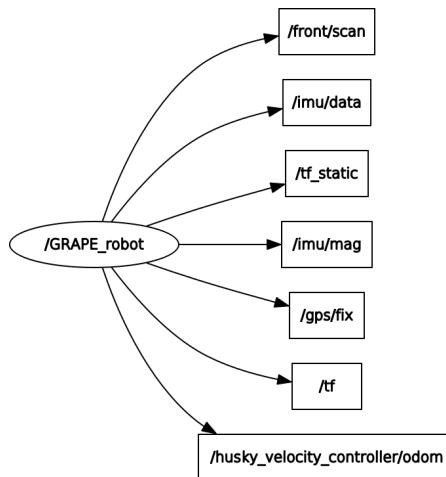


Figure 1.3: Visualization of the ROS Computation Graph with rqt in the context of a data bag being played: there is a single node (GRAPE_robot) that simultaneously plays recorded topics messages.

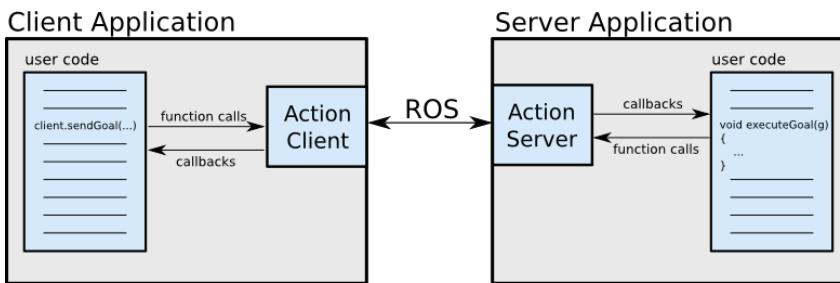


Figure 1.4: Sketch of the implementation of actionlib, through ROS topics and a callback system.

the real recorded session. In this situation, the decoupling induced by *publish-subscribe* is a strong advantage, since you can substitute all publishing nodes with a single one, with no consequences⁴.

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 stumbled upon

⁴ Except in some pathological cases: for example, a node can require the list of active nodes in the computational graph, and the response would be different when the data are recorded and when the corresponding bag is played.

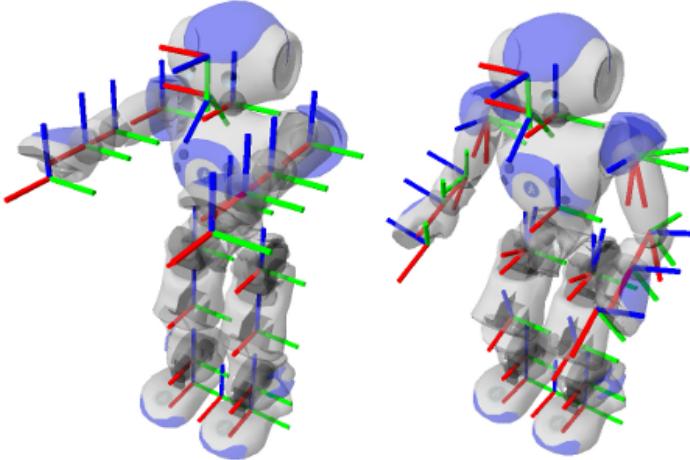


Figure 1.5: A robot in 2 different positions, with *tf* frames in evidence: *x*-axis is red, *y*-axis is green, *z*-axis is blue. The frames are the same in both configuration, but the transformations (i.e. rototranslations) between them are different.

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*.

Note that frames are very useful for two main tasks:

- represent the configuration of the robot, by assigning frames to the significant physical elements of the robot (e.g. joints, sensors, wheels). Since *tf* graph is a tree, a root element of the robot should exists; in a typical configuration, the frame name is *base_link*, it's placed in the geometrical center of the robot, and all the other frames linked to physical components of the robot belong to the subtree with root *base_link*.
- represent the position of the robot in an environment. A typical example is the frame *odom*, that is typically centered in the point where the robot is located when it's switched on. Another example is the frame *map*, that is used as a reference in case the robot is localized not only with respect to its initial point, but in a given map.

We are now giving a bit more technical detail about *tf*. *tf* implementation relies on [ROS](#) topics (see Section 1.1) and achieves the goal

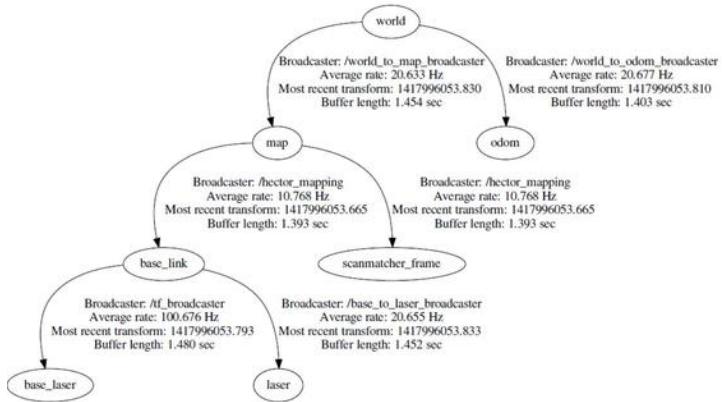


Figure 1.6: An example of *tf* tree

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 exist 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. Disconnected 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 broadcasters do 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 interpolate old values using SLERP (Spherical Linear intERPolation) to return a transformation for which there is no measured value at the requested timestamp.

In figure 1.5 you can see a graphical representation of the reference frames tracked in a Nao Robot, while figure 1.6 shows an example of *tf* graph visualized with visualization framework *rqt*.

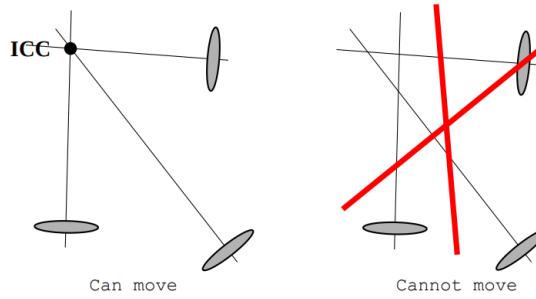


Figure 1.7: If the axis of all the wheels intersect in a single point, it's called **ICC** and the robot can move without slipping

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:

$$\langle x, y, z, \theta, \dot{x}, \dot{y}, \dot{z}, \dot{\theta} \rangle \quad (1.1)$$

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 perpendicular to the ground
- the friction between the floor and the wheel might not be enough to avoid slippage (especially)
- 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 1.7), and can be easily identified by looking for the intersection of the axis of all wheels. If the intersection exists in a single point, it's called the **ICC**. But even if the odometry estimated from the wheels is not a good

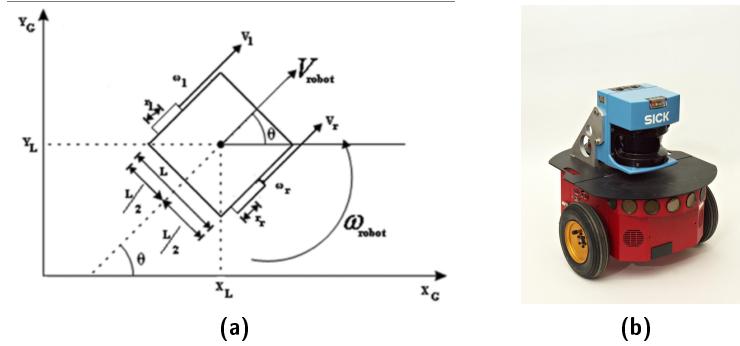


Figure 1.8: On figure 1.8a, the scheme of a differential drive motion model; in figure 1.8b, an example of a differential drive robot (Pioneer 3DX).

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 1.10) 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 1.8), and optionally a central, non-actuated caster wheel for stability. The two side wheels are not steerable, so the changes of direction are realized through application of different speed to the two wheels. For example, intuitively, if the wheels move at the same speed and in the same direction, the robot will move straight; if the wheels move at the same speed but different directions, the robot rotates in place. By recalling the definition of **ICC**, we observe that, if the wheels 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, both the left and right wheel follow a path that moves around **ICC** at the same angular speed \$\omega\$, and thus:

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

$$(1.3)$$

where L is the distance between the center of the two wheels, v_r and v_l are, respectively, the linear velocity of the right and left wheel, R is the signed distance between the [ICC](#) and the midpoint of the wheels. Note that the only parameter constant through time is L , since it's a physical property of the robot structure, while all other parameter evolve during the movement.

By combining [1.2](#) and [1.3](#), we get:

$$R = \frac{L}{2} \frac{(v_r + v_l)}{(v_r - v_l)}, \quad \omega = \frac{(v_r - v_l)}{L} \quad (1.4)$$

Observing these results we can validate the intuitive impressions about particular cases made a few lines above:

- if $v_r = v_l$, the curvature radius is infinite, because the robot is moving straight.
- if $v_r = -v_l$, the robot is moving around the midpoint of the wheels

We give now some details about odometry computation. Let's assume, in a certain moment $t = t_0$, that the robot pose is (x, y, θ) . We assume that in the time interval $t_0 \rightarrow (t_0 + \delta t)$ the values v_r and v_l are constant; if we observe figure [1.9](#) under these condition, we have:

$$\text{ICC} = (x - R\sin\theta, y + R\cos\theta) \quad (1.5)$$

Write now the expressions for (x', y', θ') :

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\omega\delta t) & -\sin(\omega\delta t) & 0 \\ \sin(\omega\delta t) & \cos(\omega\delta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - \text{ICC}_x \\ y - \text{ICC}_y \\ \theta \end{bmatrix} + \begin{bmatrix} \text{ICC}_x \\ \text{ICC}_y \\ \omega\delta t \end{bmatrix}$$

With this procedure we have identified 3 of the elements of the target tuple (see expression [1.1](#)), but we still have to retrieve x, y and θ . For this reason we consider that by assuming an initial pose (x_0, y_0, θ_0) , knowing that:

$$V(t) = \frac{(v_r + v_l)}{2} \quad (1.6)$$

where $V(t)$ represent the complexive speed of the robot, and assuming to know the functions $v_r(t)$ and $v_l(t)$ *i.e.* the linear speed of the wheel in time, we can calculate (x, y, θ) by integrating the speed of the robot over time, that is:

$$x(t) = \int_0^t V(t)\cos(\theta(t))dt \quad (1.7)$$

$$y(t) = \int_0^t V(t)\sin(\theta(t))dt \quad (1.8)$$

$$\theta(t) = \int_0^t \omega(t)d\omega \quad (1.9)$$

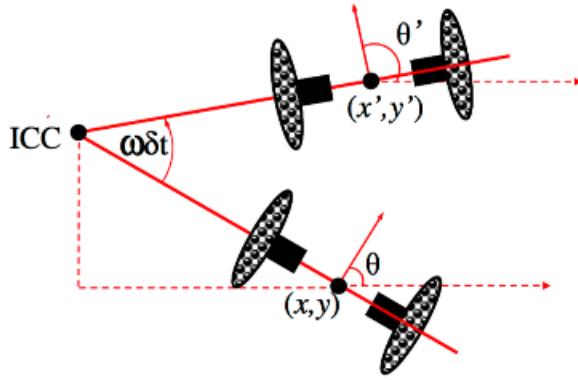


Figure 1.9: Differential drive: $(x, y, \theta) \rightarrow (x', y', \theta')$

and, in our specific case we can write it as function of v_l and v_r , that are the quantities that are directly measured on the wheels.

$$x(t) = \frac{1}{2} \int_0^t (v_r(t) + v_l(t)) \cos(\theta(t)) dt \quad (1.10)$$

$$y(t) = \frac{1}{2} \int_0^t (v_r(t) + v_l(t)) \sin(\theta(t)) dt \quad (1.11)$$

$$\theta(t) = \frac{1}{L} \int_0^t (v_r(t) - v_l(t)) dt \quad (1.12)$$

So the tuple required by the odometry calculation is now complete.

Skid-steering

However, observing image 1.10, it's very easy to contest that the Husky platform used in GRAPE project is not similar to the model described in previous section, because the number of actuated wheels is four instead of two. However, the motion model of the Husky is more similar to the differential drive because:

- wheels are not steerable
- being v_{fr} the speeds of the front wheels, v_{rr} the speeds of the rear wheels, v_{rl} the speeds of the right wheels, v_{ll} the speeds of the left wheels, we always have:

$$v_{fr} = v_{rr} \quad (1.13)$$

$$v_{fl} = v_{rl} \quad (1.14)$$

This type of motion model is called *skid steering*, and is often used in real-world applications (see figure 1.11b) because of its simple and robust mechanical structure that leaving more room in the vehicle for the mission equipment. In addition, it has good mobility on a variety of terrains, which makes it suitable for all-terrain missions.



Figure 1.10: Husky platform from Clearpath Robotics is the platform used for the development of GRAPE project.

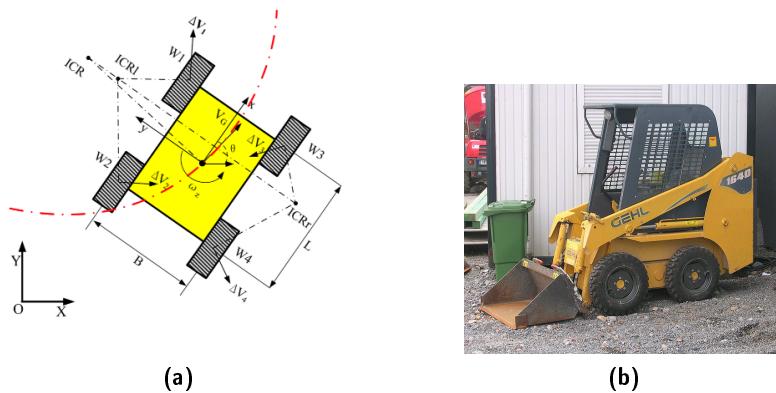


Figure 1.11: On figure 1.11a, the scheme of a skid steering motion model; in figure 1.11b, an example of a skid steering vehicle.

But, of course, it also present a variety of problems and weakness. For example, if you recall what we told about **ICC** in Section 1.3, it's clear that the **ICC** of such a model will always be at the infinite, since wheels are organized in 2 parallel rows that cannot steer. Thus, skid steering robots can't turn without slipping of the wheels! From a theoretical point of view, the main consequence is a complexity in obtaining an accurate kinematics and dynamic model of *skid steering* (Yi et al., 2007). On the other hand, in the context of **GRAPE** project this leads to two major practical problems:

- the slippage of the robot leads to higher power consumption of the electric engines with respect to the a system with explicit steering (Shamah, 1999). This is something to be taken into account in the sizing phase of the power system of the robot.
- the estimation of the odometry is going to be much more imprecise than in the differential drive case, for the error introduced by the slipping of the wheels.

Actually, there is a quite simple way (Wang et al., 2015) to model with an acceptable approximation the skid steering as an equivalent

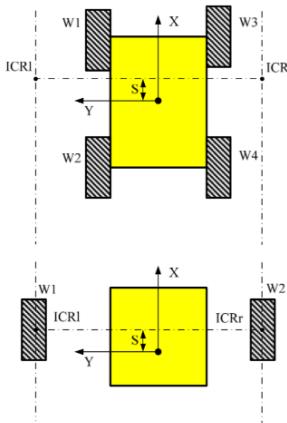


Figure 1.12: The equivalence of differential drive motion model and skid steering model according to Wang et al., 2015

differential drive system, where the distance between the wheels is obtained multiplying the original distance for a factor χ that is function of the physical structure of the robot. This approximation relies on some assumptions:

- the mass center of the robot is located at the geometric center of the body frame.
- the two wheels of each side rotate at the same speed.
- **the robot is running on a firm ground surface, and four wheels are always in contact with the ground surface.**

We cannot guarantee that conditions 1) and 2) will hold in our context, but we are almost sure that condition 3) is **not** going to be verified, given the condition in which our robot is going to operate (vineyard terrain), so this is another reason for the wheel odometry not to be very precise. Thus, the integration of several sensors beyond the wheels encoders is essential to correct the wheel odometry.

SENSOR FUSION

First of all, clarify what we mean for sensor fusion, following the definition of Elmenreich, 2002:

"Sensor fusion is the combining of sensory data or data derived from sensory data in order to produce enhanced data in form of an internal representation of the process environment. The achievements of sensor fusion are robustness, extended spatial and temporal coverage, increased confidence, reduced ambiguity and uncertainty, and improved resolution."

Let's analyze this last list, element by element, recalling the analysis of Remagnino, Monekosso, and Jain, 2011:

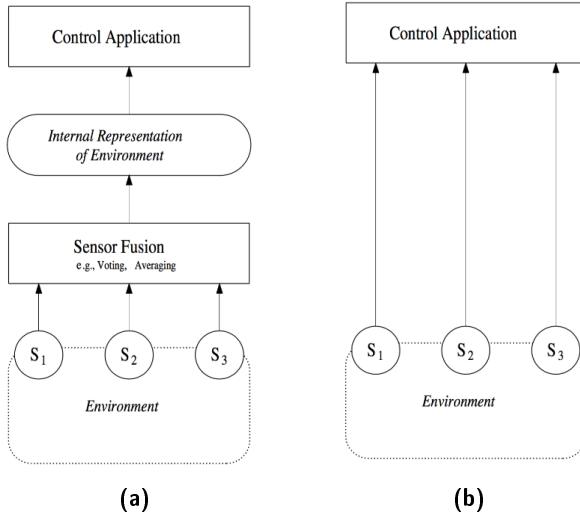


Figure 1.13: Sensor fusion 1.13a vs multi-sensor integration 1.13b

- *robustness*: redundancy generated by the presence of multiple sensors make the robot more resistant to partial failures
- *extended spatial and temporal coverage*: disseminate sensors are more likely to measure the dimension concerned with temporal continuity and from several positions
- *increased confidence*: measures confirmed by more than one sensor are given a larger weight
- *reduced ambiguity and uncertainty*: joint information reduces the set of ambiguous interpretations of the measured value
- *robustness against interference*: by increasing the dimensionality of the measurement space (e.g., measuring the desired quantity with optical sensors and ultrasonic sensors) the system becomes less vulnerable against interference.

Even if the name could be misleading, sensor fusion is different from *multi-sensor integration* in the sense that multi-sensor integration only consists in the simultaneous use of disparate sensor sources in order to accomplish a goal task. Sensor fusion techniques make a step further, and aim to the construction of a single common representation, using all the available sensor sources. The difference between multi-sensor integration and sensor fusion is described graphically in image 1.13, to underline that sensor fusion actually provides one single representation of the state of the environment that is used as a single input stream by the control application, while in multi-sensor integration the application uses each of the sensor data streams as direct input. In this context, we are assuming the definition of environment, from Thrun, 2002: pose of the robot, velocity of the robot,

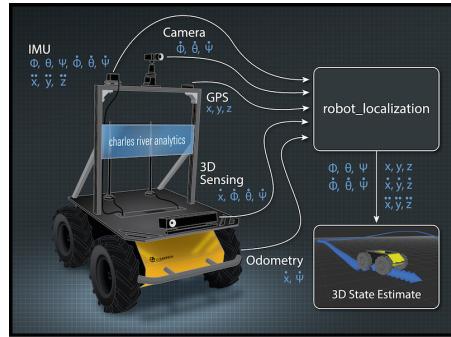


Figure 1.14: A scheme of Robot Localization sensor fusion

and velocity of the joints, configuration of actuators, location and features of surrounding objects, location and velocity of moving object and people.

In ROS ecosystem, several open source solutions exist that implements *sensor fusion-based* odometry; we tried two of them, which gave proof of good functioning in the past: ROAMFREE (Cucci and Matteucci, 2013, Calabrese, 2014, Cucci and Matteucci, 2014), a graph-based algorithm, and **Robot Localization** (Moore and Stouch, 2014, Dudek, Szykiewicz, and Winiarski, 2016, Mohanty et al., 2016), based on Kalman filters.

After the experimental campaign in Casciano Terme, ROAMFREE turned out to be harder to configure for our specific problem, while Robot Localization had some specific documentation about its usage in the required context⁵, so we opted for this last one. Further details about our usage of Robot Localization will be given in Chapter 5, while we are now giving a few hints about its general functioning.

Robot Localization

Citing Robot Localization documentation⁶:

"Robot_localization is a collection of state estimation nodes, each of which is an implementation of a nonlinear state estimator for robots moving in 3D space. It contains two state estimation nodes, ekf_localization_node and ukf_localization_node". In addition, robot_localization provides navsat_transform_node, which aids in the integration of GPS data."

The Robot Localization algorithm is implemented specifically for ROS, and it's widely adopted by ROS community for its documentation, and its easiness of use and configuration. It fuses an unlimited number of sensor sources, for each of which you can specify a configuration vector given in the frame id of the input message i.e. you

⁵ http://docs.ros.org/kinetic/api/robot_localization/html/integrating_gps.html

⁶ http://docs.ros.org/kinetic/api/robot_localization/html/

can specify the message fields to be fused in the global estimate. For example, since GPS output is not so precise about altitude estimation, you can specify that only latitude and longitude parameters to be fused in the global estimate.

The state variables considered by Robot Localization are:

$$< x, y, z, \psi, \theta, \phi, \dot{x}, \dot{y}, \dot{z}, \dot{\psi}, \dot{\theta}, \dot{\phi}, \ddot{x}, \ddot{y}, \ddot{z} > \quad (1.15)$$

where ψ, θ, ϕ correspond to the euler angles *roll, pitch, yaw*. The node accepts as inputs several types of [ROS](#) messages:

- *nav_msgs/Odometry*: the odometry estimation output by another node can be used entirely as input; this is the case of the odometry estimated only using wheels encoders, and it also allows for cascaded localization nodes. This will be useful in the [GRAPE](#) project, as we'll see in Chapter 5.
- *sensor_msgs/Imu*: the output of an Inertial Measurement Unit ([IMU](#)) sensor *i.e.* a device composed by accelerometer, gyroscope, and magnetometer
- *geometry_msgs/PoseWithCovarianceStamped*: an estimate of the position and orientation of the robot, together with the timestamp of the measure and its covariance matrix
- *geometry_msgs/TwistWithCovarianceStamped*: an estimate of the linear and angular velocities of the robot, together with the timestamp of the measure and its covariance matrix.

Moreover, the Kalman filter implemented in Robot Localization is capable of *continuous estimation*: if for some reason no data are received from the various sensors for a large enough amount of time, the filter keeps producing odometry estimation exploiting an internal motion model. Remember that Robot Localization can be configured also to publish the *tf* transformation associated to the estimated odometry. This is one of the usage of *tf* described in Section 1.2.

NAVIGATION STACK

In Computer Science, a software stack is a set of programs that collaborate, in order to achieve a common goal. Since we are talking about [ROS](#) ecosystem, the programs are [ROS](#) nodes, and in the case of Navigation Stack, the common goal is to provide a modular out-of-the-box navigation system for [UGVs](#). It was originally developed for Willow Garage's *PR2* robot, but its usage can be easily extended to differential drive and holonomic wheeled robots. The planner, Move Base, is known to be a very good solution for indoor navigation (Marder-Eppstein et al., 2010), so we were not sure about its performance in an

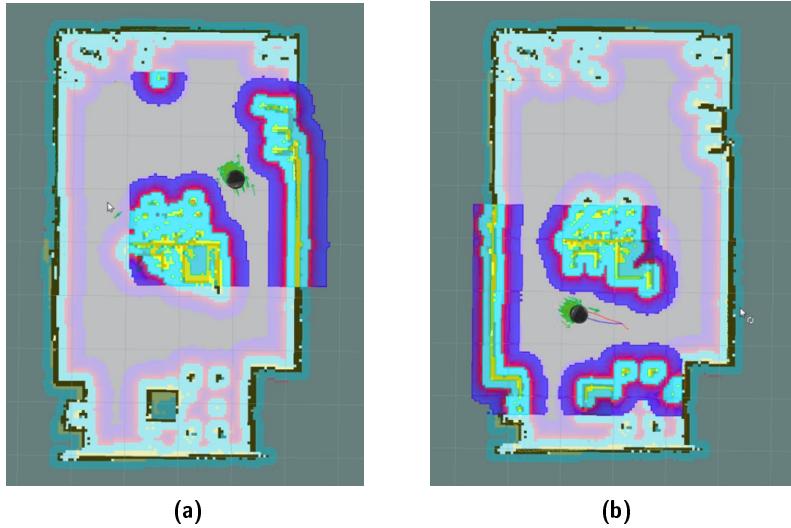


Figure 1.15: Local and global costmap visualized with RViz. As you can see, the local costmap (in brighter colors) is built around the robot, and moves together with it.

outdoor environment as required in GRAPE project. Luckily, it turned out to be a very good solution even in our situation, so it was integrated in the final navigation system. We are now giving a brief description of the main building blocks of the Navigation Stack (figure 1.16):

ODOMETRY SOURCE A topic from which read the pose estimated from the odometry system e.g. simple wheels odometry, output of a sensor fusion node as Robot Localization or ROAMFREE.

SENSOR SOURCE A topic from which read the data coming from the laser sensors ([LIDAR](#)) that are probing the environment, for obstacle avoidance, localization and possibly mapping tasks.

AMCL Implementation of a probabilistic localization system, based on the Monte Carlo localization, as described in Fox et al., [1999](#). (TODO se alla fine lo usiamo lo descrivo meglio magari).

MAP SERVER A [ROS](#) node where the map is published as a single topic message. This block is not used if Move Base is used in mapless mode

BASE CONTROLLER This is the only output topic of the Navigation Stack, and of course it contains speed commands for the base of the robot.

LOCAL AND GLOBAL COSTMAP They represent the information about the obstacles on the 2D plane of the ground, with a certain inflation radius that represent the size of the robot base. Each

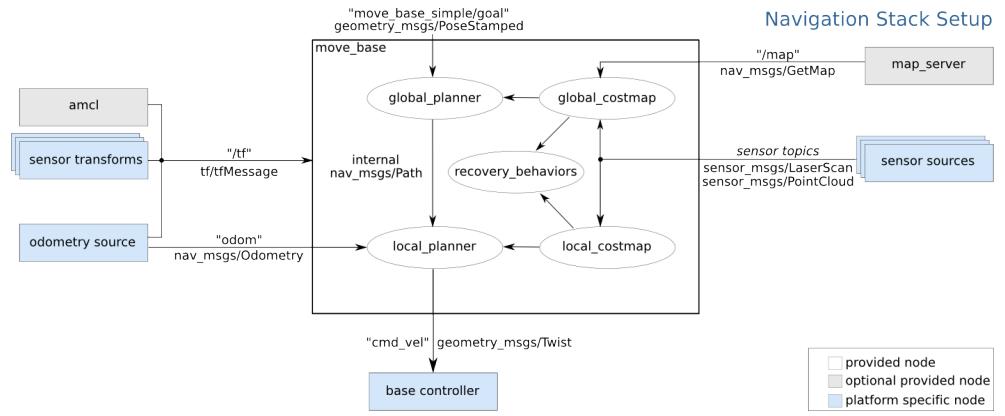


Figure 1.16: A scheme representation of the Navigation Stack; see the color legend for classification in provided, optional provided, and platform specific nodes.

cell of the gridmap is associated to a certain cost that measure "how hard is it" to traverse that cell of the gridmap; possible values to represent the severity of obstacles are *Lethal obstacle*, *Inscribed*, *Possibly circumscribed*, *Freespace*, *Unknown*. The **global** costmap represent whole environment as is build from a known map, while the **local** costmap is built using only incoming laser scans. Local map is, in general, a scrolling window that moves in the global costmap in relation to robot current pose, and it's continuously updated.

LOCAL AND GLOBAL PLANNERS Global planner takes as input the global costmap, and traces the path with lowest cost from current position of the goal position; the local planners instead takes care of continuously update (if required) the global plan in the light of the incoming laser measurements. This combination is essential in case of unexpected obstacles.

2

THE GRAPE PROJECT

In this chapter, we are going to give a description of the project this thesis work is part of, with particular emphasis on the parts that were specifically addressed in the thesis work. For the description of the project, we make reference to its official proposal.

PROJECT DESCRIPTION AND GOALS

GRAPE is an experimental project of European Clearing House for Open Robotics Development Plus Plus (**ECHORD++**) and, as hinted in the first part of Chapter 1, it focuses on vineyard farming activities and aims at setting up a robotic manipulation platform able to support lead users to develop a variety of farming applications. In effect, the main goal of **GRAPE** is not the complete development of an industrial platform, but, coherently with the research scenario, the primary objectives are:

1. the development of example applications in the pre-mentioned context, exploiting and improving the so-called *key enabling technologies*¹ in robot navigation, perception and manipulation of the project partners; the resulting capabilities are likely to allow to make it easier for small and medium enterprises working in the fields of agricultural robots and, more in general, plant protection.
2. increase of robot acceptance by farmers and agronomists: since the very last goal of this project is not solely about pure research but about the enterprise world too, particular attention is given into the realization of a robotic platform that could be accepted by potential end users. For this reason, a constant interaction between the project partners and the potential stakeholders (*i.e.* vinegrowers) is maintained also in development phases.

The example applications have been selected in order to challenge perception and action capabilities, to achieve vineyard monitoring, navigation and manipulation tasks. This decision is taken in the scope of turning traditional farming into precision farming; the realization of such a turn would allow for both the decrease of the chemical load

¹ Key Enabling Technologies are a group of six technologies: micro and nanoelectronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies. They have applications in multiple industries and help tackle societal challenges; they are considered crucial in the creation of advanced and sustainable economies.



Figure 2.1: A vine before (2.1a) and after (2.1b) having leafed out.

in food and environment, and an improvements of profits and yield for farmers, that would get a return for their investment (Herring, 2001). The introduction of precision farming techniques leads indeed to a lot of advantages, for example early detection of plants diseases, or application of pesticides and fungicides with high precision and only when/where needed.

It's clear that some of these high-precision tasks are still too complex to be automated, and current state-of-the-art in research and technology have been proved to be not yet mature to give rise to a commercial product able to compete with a skilled agricultural agent. The goal of **GRAPE** is creating the enabling technologies to allow agricultural companies to develop vineyard robots to keep filling the gap that exists with respect to traditional methods.

GRAPE project specification identifies these two application examples:

- **Vineyard monitoring and autonomous navigation:** the developed robotic platform must be able to autonomously navigate the vineyard and localize itself into a map of the environment (downstream a mapping phase), to be able to monitor the state of the vineyard (e.g. foliage and grapes inspection). The actual project implementation focused on a semi-autonomous monitoring, that considers a fully autonomous navigation platform, with video stream capability that allows human users to observe in person the live data streamed by the robot by means of cameras for assessment of crop condition. The localization and navigation parts, however, are a key point for any kind of tasks for an **UGV** field robot, because of the probability of high slope ground, rugged terrain morphology and unstructured map. We'll see the characterization and analysis of the problem of navigation in a rugged outdoor environment in chapter 5.
- **Autonomous application of pheromone dispensers:** pheromone dispensers are used for *mating disruption* techniques, to protect grapevines from grape moths, by disrupting the bugs' reproductive cycle making use of synthesized sex pheromones.

Also in this case, the most relevant challenge is brought by the unstructured environment, that makes the sensing and manipulation tasks significantly harder. However, note that pheromones deployment task gets easier if you think that the timing of the reproductive cycle (on which of course we have no control at all) forces this operation to be performed in a season where grape plants are pruned, and have not leafed out yet (Cardé, 1995). Of course, the absence of foliage and grapes makes this task significantly easier (see Image 2.1).

For what concern the second goal of the project *i.e.* a major commitment about the acceptance of the robotic system in a field that's still strongly led by traditional methods, its realization consists mostly in the creation of an user-friendly interface (possibly for smartphones or tablets) for the **GRAPE** system, that allows an user to:

- constantly and easily visualize the position and activity of the robot
- perform supervisory control on the platform *e.g.* selection of the plants for the dispensers deployment
- in case of a failure of the **UGV** in an autonomous task, provide a teleoperation interface to carry out the operation

The whole project was also to be designed with and adequate degree of modularity, in order to naturally support the possible extension to a fleet of robot able to operate in parallel. Note that, as described in Section 1.1, this goal gets very easy by the usage of **ROS** framework.

The **GRAPE** projects involved three partners, each with different assignments, and different responsibilities in the project context: **PoliMi**, **Eurecat** (a technology center located in Catalonia, that operates in many industrial and research fields, including robotics), and **Vitirover** (an agricultural robots company, located in France). To make the different teams interact and test the compatibility of the different parts of the system, some communal sessions of integration and tests, that we'll call *integration weeks*, have been carried out within the duration of the whole project. In this thesis we are going to focus mostly on the experiments and results carried out during the last **GRAPE** integration week, held in March 2018.

CONTEXTUALIZATION OF THESIS WORK IN THE PROJECT

Since the timespan of the **GRAPE** project as a whole covers 18 months, we took advantage of the preceding work described in Serrano et al., 2017, that is a description of the ongoing work around the **GRAPE** project. As stated in the paper, some results were already accomplished in a few subjects:

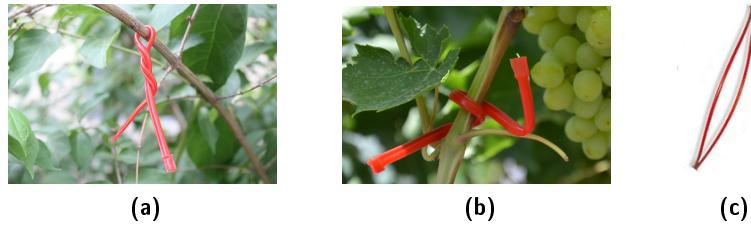


Figure 2.2: Different shape of pheromone dispensers available on the market. The model used in [GRAPE](#) is the one depicted in image 2.2c

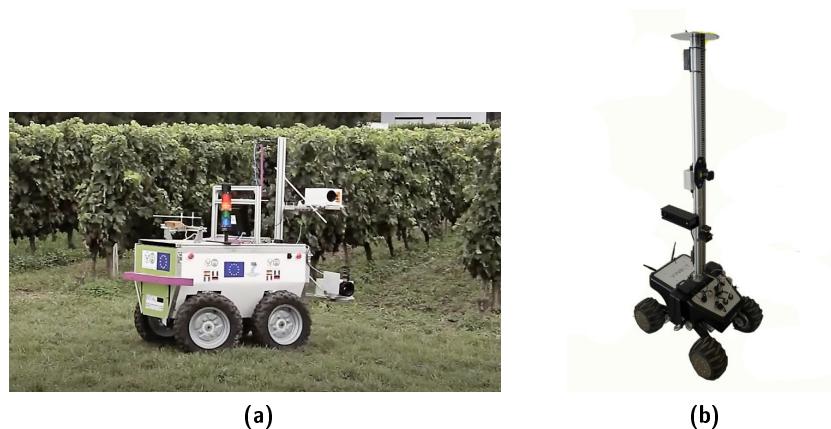


Figure 2.3: Other field robots developed in EU projects in the last 6 years: [2.3a](#) Vinerobot, [2.3b](#) Vinbot.

- in-depth analysis of the main challenge and obstacles in the project, and requirement extraction
- identification and obtainment of the specific hardware components (mobile platform, robotic arm, **LIDARS**, **IMUs**, cameras, network equipment, computational unit)
- segmentation of the macro objectives into smaller subtasks
- results of intermediate experiments carried out during the first integration week in Garriguella, Spain. The experiments mostly concern the mapping, localization and navigation tasks
- collection of data generated during the same integration week, making use of **ROS** data logging tool (as described in Chapter [1.1](#))

The problems tackled in this thesis are a subset of the ones assigned to PoliMi in the project proposal. The problems we faced are the following, and will be described in depth in next chapters:

- design of the overall software architecture in the **ROS** framework (see Chapter [3](#))
- revision and enhancement of the mapping, localization and navigation systems (see Chapter [5](#))
- design and part of the implementation of the pheromone dispenser application (see Chapter [6](#))

RELATED PROJECTS

We are now presenting a short list of EU projects related to robotics for precision farming, with direct or indirect application to vineyards. All these projects have been developed in the last 6 years, and demonstrate the growing interest of the scientific community and potential end users to this application and research field.

VINEROBOT Automated measurement and monitoring of parameters such as grape yield, vegetative growth, water status and grape composition in vineyards by use of an **UGV** (see Figure [2.3a](#)) endowed with artificial intelligence with sensing technologies. Chlorophyll-based fluorescence, RGB machine vision and thermography technologies are used to monitor vineyard on-the-go (Diago, Tardaguila, et al., [2015](#)).

VINBOT Creation of an all-terrain autonomous mobile robot (see Figure [2.3b](#)) with a set of sensors capable of capturing and analysing vineyard images together with 3D data, by means of cloud computing applications, to determine the yield of vineyards



Figure 2.4: Other field robots developed in EU projects in the last 6 years: [2.4a](#) *Rhea*, [2.4b](#) *CROPS*.

and to share information with the winegrowers, in order to mix the grapes of homogeneous quality to efficiently market a range of wines by quality and price. (Lopes et al., [2017](#)).

RHEA Design, development, and testing of a new generation of automatic and robotic systems for both chemical, mechanical and thermal effective weed management focused on both agriculture and forestry, and covering a large variety of European products including agriculture wide row crops and forestry woody perennials. RHEA aims at diminishing the use of agricultural chemical inputs in a 75%, improving crop quality, health and safety for humans, and reducing production costs by means of sustainable crop management using a fleet (see Figure [2.4a](#)) of heterogeneous robots, both ground and aerial, equipped with advanced sensors, enhanced end effectors and improved decision control algorithms (Santos, Ribeiro, and Fernandez-Quitanilla, [2012](#)).

CROPS Design and development of an highly configurable, modular and clever carrier platform that includes modular parallel manipulators and intelligent tools (sensors, algorithms, sprayers, grippers) for high value crops like greenhouse vegetables, fruits in orchards, and grapes for premium wines. The CROPS robotic platform (see Figure [2.4b](#)) is capable of site-specific spraying (targets spray only towards foliage and selective targets), selective harvesting of fruit (detects the fruit, determines its ripeness, moves towards the fruit, grasps it and softly detaches it), reliable detect and classificate obstacles and other objects to enable successful autonomous navigation and operation in plantations and forests (Oberti et al., [2014](#)). Further development in CROPS projects also includes Sweeper project (Ringdahl et al., [2016](#)).

3

GRAPE HARDWARE AND SOFTWARE ARCHITECTURE

In this chapter we are going to describe in a detailed way the architecture of the robotic platform we used to implement the system to fulfill the requirements described in Section 2.1. First, in Section 3.1, we are giving an overview of the hardware components, from the robot base to all the actuators/sensors present on board. In Section 3.2, we'll start to analyze the software architecture of the system, explaining what the main modules are, and the relationships between them.

GRAPE HARDWARE ARCHITECTURE

Robotic Base

The choice of the robotic base is, of course, a crucial point in the development of our system, for two reasons:

- without a well-functioning robotic base, no other objective can be achieved
- the vineyard environment is particularly challenging in nature (this particular aspect will be well-justified in Chapter 5), so we cannot rely on a non-prudent choice.

As anticipated in Section 1.3, the choice fell on the **Husky UGV** from Clearpath Robotics¹, (see Figure 1.10). There are several reasons for the adoption of this specific model:

- it's a widely used platform (e.g.: Madhavan et al., 2015; Hinkel et al., 2015; Ostafew, Schoellig, and Barfoot, 2013)
- it has a *skid steering* kinematics that, as already seen in Section 1.3, can be essentially reduced to a *differential drive* kinematics, that is very simple.
- it's specifically designed for outdoor use, so robustness and ability to deal with unstructured terrain are problems addressed by its rugged construction and high-torque drivetrain.
- it offers a large payload capacity, to host the multitude of sensors, actuators and computational units we need

¹ <https://www.clearpathrobotics.com/husky-unmanned-ground-vehicle-robot/>

- it's fully supported in [ROS](#), with open source drivers, configuration files and examples

This choice turned out to be substantially a good choice. The wheel odometry turned out to be better than expected (TODO grafico della posizione xy dell'odometry delle ruote vs grafico della posizione stimata con robot localization), and the [ROS](#) were actually pretty easy to use

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 deployment. 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

The studies of Singhal, 1997

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

BIBLIOGRAPHY

- Calabrese, Luca (2014). "Robust odometry, localization and autonomous navigation on a robotic wheelchair." In: (cit. on p. 15).
- Carde Ring T Minks, Albert K (1995). "Control of moth pests by mating disruption: successes and constraints." In: *Annual review of entomology* 40.1, pp. 559–585 (cit. on p. 21).
- Cucci, Davide A and Matteo Matteucci (2014). "Position tracking and sensors self-calibration in autonomous mobile robots by gauss-newton optimization." In: *Robotics and Automation (ICRA), 2014 IEEE International Conference on*. IEEE, pp. 1269–1275 (cit. on p. 15).
- Cucci, Davide Antonio and Matteo Matteucci (2013). "A Flexible Framework for Mobile Robot Pose Estimation and Multi-Sensor Self-Calibration." In: *ICINCO* (2), pp. 361–368 (cit. on p. 15).
- Diago, Maria P, Javier Tardaguila, et al. (2015). "A new robot for vineyard monitoring." In: *Wine & Viticulture Journal* 30.3, p. 38 (cit. on p. 23).
- Dudek, Wojciech, Wojciech Szynkiewicz, and Tomasz Winiarski (2016). "Nao robot navigation system structure development in an agent-based architecture of the RAPP platform." In: *Challenges in Automation, Robotics and Measurement Techniques*. Springer, pp. 623–633 (cit. on p. 15).
- Elmenreich, Wilfried (2002). "Sensor fusion in time-triggered systems." In: (cit. on p. 13).
- Foote, Tully (2013). "tf: The transform library." In: *Technologies for Practical Robot Applications (TePRA), 2013 IEEE International Conference on*. Open-Source Software workshop, pp. 1–6 (cit. on p. 5).
- Fox, Dieter, Wolfram Burgard, Frank Dellaert, and Sebastian Thrun (1999). "Monte carlo localization: Efficient position estimation for mobile robots." In: *AAAI/IAAI 1999*.343–349, pp. 2–2 (cit. on p. 17).
- Herring, David (2001). "Precision farming: Feature articles." In: (cit. on p. 20).
- Hinkel, Georg, Henning Groenda, Lorenzo Vannucci, Oliver Denninger, Nino Cauli, and Stefan Ulbrich (2015). "A domain-specific language (DSL) for integrating neuronal networks in robot control." In: *Proceedings of the 2015 Joint MORSE/VAO Workshop on Model-Driven Robot Software Engineering and View-based Software-Engineering*. ACM, pp. 9–15 (cit. on p. 25).
- Lopes, Carlos M, Albert Torres, Robert Guzman, João Graça, Miguel Reyes, Gonçalo Vitorino, Ricardo Braga, Ana Monteiro, and André Barriguinha (2017). "Using an unmanned ground vehicle to scout vineyards for non-intrusive estimation of canopy features and grape yield." In: *GiESCO International Meeting, 20th, Sustainable*

- able viticulture and wine making in climate change scenarios, 5-10 November 2017.* GiESCO (cit. on p. 24).
- Madhavan, Raj, Lino Marques, Edson Prestes, Renan Maffei, Vitor Jorge, Baptiste Gil, Sedat Dogru, Gonçalo Cabrita, Renata Neu land, and Prithviraj Dasgupta (2015). *2015 humanitarian robotics and automation technology challenge* (cit. on p. 25).
- Marder-Eppstein, Eitan, Eric Berger, Tully Foote, Brian Gerkey, and Kurt Konolige (2010). "The Office Marathon: Robust Navigation in an Indoor Office Environment." In: *International Conference on Robotics and Automation* (cit. on p. 16).
- Mohanty, Vikram, Shubh Agrawal, Shaswat Datta, Arna Ghosh, Vishnu Dutt Sharma, and Debasish Chakravarty (2016). "DeepVO: a deep learning approach for monocular visual odometry." In: *arXiv preprint arXiv:1611.06069* (cit. on p. 15).
- Moore, T. and D. Stouch (2014). "A Generalized Extended Kalman Filter Implementation for the Robot Operating System." In: *Proceedings of the 13th International Conference on Intelligent Autonomous Systems (IAS-13)*. Springer (cit. on p. 15).
- Oberti, Roberto, Massimo Marchi, Paolo Tirelli, Aldo Calcante, Marcello Iriti, M Hocevar, and H Ulbrich (2014). "Crops agricultural robot: application to selective spraying of grapevine's diseases." In: *Proceedings of the Second RHEA International Conference on Robotics and associated High-technologies and Equipment for Agriculture* (cit. on p. 24).
- Ostafew, Chris J, Angela P Schoellig, and Timothy D Barfoot (2013). "Visual teach and repeat, repeat, repeat: Iterative learning control to improve mobile robot path tracking in challenging outdoor environments." In: *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*. IEEE, pp. 176–181 (cit. on p. 25).
- Remagnino, Paolo, Dorothy N Monekosso, and Lakhmi C Jain (2011). *Innovations in Defence Support Systems-3: Intelligent Paradigms in Security*. Vol. 336. Springer Science & Business Media (cit. on p. 13).
- Ringdahl, Ola, Polina Kurtser, Ruud Barth, and Yael Edan (2016). "Operational flow of an autonomous sweetpepper harvesting robot." In: *The 5th Israeli Conference on Robotics 2016, 13-14 April 2016. Air Force Conference Center Hertzilya, Israel* (cit. on p. 24).
- Santos, Pablo Gonzalez-de, Angela Ribeiro, and C Fernandez-Quitanilla (2012). "The RHEA Project: using a robot fleet for a highly effective crop protection." In: *Proceedings of the International Conference of Agricultural Engineering (CIGR-Ageng'12), Valencia, Spain* (cit. on p. 24).
- Serrano, Daniel, Pietro Astolfi, Gianluca Bardaro, Alessandro Gabrielli, Luca Bascetta, and Matteo Matteucci (2017). "GRAPE: Ground Robot for vineyard Monitoring and Protection." In: *ROBOT 2017: Third Iberian Robotics Conference*. Vol. 1. Springer, p. 249 (cit. on p. 21).

- Shamah, Benjamin (1999). "Experimental Comparison of Skid Steering vs. Explicit Steering for Wheeled Mobile Robot," M. Sc." In: (cit. on p. 12).
- Singhal, Amit (1997). "Issues in autonomous mobile robot navigation." In: *Computer Science Dept, U. of Rochester*, p. 74 (cit. on p. 29).
- Thrun, Sebastian (2002). "Probabilistic robotics." In: *Communications of the ACM* 45.3, pp. 52–57 (cit. on p. 14).
- Wang, Tianmiao, Yao Wu, Jianhong Liang, Chenhao Han, Jiao Chen, and Qiteng Zhao (2015). "Analysis and experimental kinematics of a skid-steering wheeled robot based on a laser scanner sensor." In: *Sensors* 15.5, pp. 9681–9702 (cit. on pp. 12, 13).
- Yi, Jingang, Junjie Zhang, Dezhen Song, and Suhada Jayasuriya (2007). "IMU-based localization and slip estimation for skid-steered mobile robots." In: *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*. IEEE, pp. 2845–2850 (cit. on p. 12).