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Design, development and deployment of a mobile manipulator for vineyard monitoring and protection

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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
IMU	Inertial Measurement Unit
ECHORD++	European Coordinator Hub for Open Robotics Development Plus Plus
PCL	Point Cloud Library
FSA	Finite State Automata
API	Application Programming Interface
AMCL	Adaptive Monte Carlo Localization

ABSTRACT

This thesis work is placed in the context of GRAPE project, an agricultural robotics project launched by European Coordinator Hub for Open Robotics Development Plus Plus (ECHORD++) that aims to the creation of an autonomous mobile manipulator for automatic deployment of synthetic pheromones dispensers in the vineyards. These devices are used in vineyards for some pest management techniques, as *mating disruption*. The team that carried out the project development included people from both Politecnico and Eurecat, a Catalan research center.

The first part of the work focused on the design of the overall software architecture, together with the identification of subtasks and the interfaces between the software modules that implement them.

The thesis work proceeded with the development of odometry system, autonomous navigation, and part of the manipulation components for the target platform. The challenges induced by the unstructured nature of the vineyard environment led, after several refining steps, to the creation of a sensor fusion system that exploits Inertial Measurement Unit (IMU), GPS, and wheels velocities to estimate the robot pose, and a mapless autonomous navigation system. On the other hand, the development of the manipulation part was complicated by the objective flaws of the robotic arm we had at disposal, that we override using techniques based on inversion of differential kinematics.

The system also underwent two one-week validation sessions on the field, carried out in vineyards in Casciano Terme (IT) and Garriguella (ES); during these sessions, we were able to both make the system more robust with respect to unexpected complications, and measure the performance of the system in its actual environment.

SOMMARIO

Questo lavoro di tesi è da collocare nel contesto del progetto GRAPE, un progetto di robotica agricola bandito da ECHORD++ che mira alla creazione di un manipolatore mobile autonomo per la distribuzione automatica di erogatori di ferormoni sintetici all'interno dei vigneti. Erogatori di questo tipo vengono impiegati in alcune tecniche di disinfestazione, dette di *confusione sessuale*. Il team di sviluppo del progetto GRAPE era composto sia da membri del Politecnico di Milano, sia da membri di Eurecat, un centro tecnologico catalano.

Inizialmente il lavoro di tesi si è focalizzato sulla progettazione dell'architettura software complessiva del sistema, attraverso l'identificazione di sottoproblemi e la definizione delle interfacce tra i diversi moduli software corrispondenti.

Il passo successivo è stato la realizzazione del sistema odometrico, del sistema di navigazione autonoma, e di parte della logica del manipolatore per la piattaforma in oggetto. La struttura geometricamente indefinita del terreno e degli ostacoli nell'ambiente del vigneto ha portato, dopo svariati perfezionamenti, a un sistema di fusione sensoriale basato sull'utilizzo di IMU, GPS, e velocità delle ruote per la stima di posizione e orientamento del robot nel tempo, e un sistema di navigazione autonoma svincolato dall'uso di mappe. Lo sviluppo della logica del manipolatore, invece, è stato fortemente influenzato dagli oggettivi limiti di funzionalità del braccio robotico in dotazione, per aggirare i quali sono state sviluppate diverse tecniche basate sull'inversione della cinematica differenziale.

Il sistema è stato anche sottoposto a due sessioni di validazione sul campo, da una settimana l'una: la prima a Casciano Terme (IT), la seconda a Garriguella (ES), in cui il sistema è stato reso più robusto alle complicanze non previste in laboratorio, e le performance della piattaforma sono state testate nell'effettivo ambiente di utilizzo.

1 INTRODUCTION

In this thesis we worked on the design and development of the software components of a mobile manipulator for vineyard monitoring and protection, and on extensive validation of the whole platform during two *on-the-field* sessions. The research and technology field this work belongs to is called called *agricultural robotics*, and it's oriented to the introduction of ICTs in an innovative way as solution for agricultural challenges. The successful introduction of these technique could gradually turn traditional farming into precision farming, with consequently decrease of the chemical load in food and environment, and improvement of profits and yield for farmers.

GRAPE is an experimental project published by ECHORD++, a robotic research project which aims to promote the interaction between robot manufacturers, researchers and users. More specifically, the goal of the platform developed in GRAPE was to accomplish automatic distribution of synthetic pheromones for integrated pest control in vineyards. The teams that carried out the whole system design, development and testing across the 18 months project duration was composed by both people from Politecnico, and people from Eurecat, a Catalan research center.

The first, fundamental problem this thesis deals with is the development of an odometry and navigation systems for the Unmanned Ground Vehicle at issue; even if those problems could seem not so hard, they are significantly different to solve with respect to the correspondant indoor problems, because of some highly destabilizing factors due to the vineyard environment: bumpiness, steepness and consistency of the soil, time-varying weather conditions, unpredictable vegetation. The presence of these factors makes the LIDAR sensor less reliable, and the pose estimation through wheel velocities almost completely untrustworthy.

The other main component of the platform treated in this thesis is the on-board manipulator, that realizes the actual deployment of the pheromone dispensers on the vines, and other tasks related to the selection of the most suitable point for deloyment; the main difficulties on this topic were due to the motion limits of the manipulator itself, in terms of both accuracy and mobility.

THESIS CONTRIBUTION

STRUCTURE OF THE THESIS

2

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 3), 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 3, is about the design and realization of an 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 Application Programming Interface (API)s 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 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 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

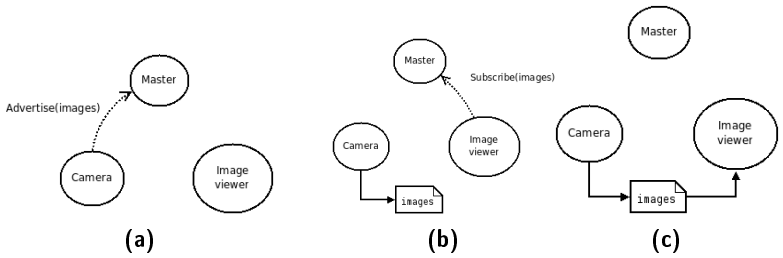


Figure 2.1: *Three phases of the setup of communication of nodes throught topics.*

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

- 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 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.

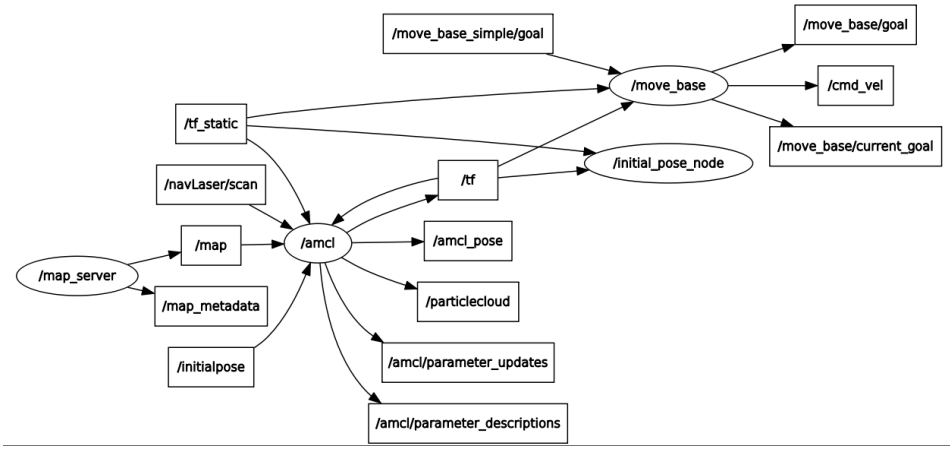


Figure 2.2: *An example of the ROS Computation Graph, visualized with* rqt*: nodes are represented with circles, rectangles represent topics, and arrows go from a node to a topic it publishes on, or from a topic to a node subscribed to it. It's easy to recognize the* many-to-many *relationship.*

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, and a native exit status to check the state (active, rejected, preempted, succeeded, aborted...) of the execution. 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 2.4). 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 call *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 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 lately 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 2.3). The module also provides an option to use *simulated*

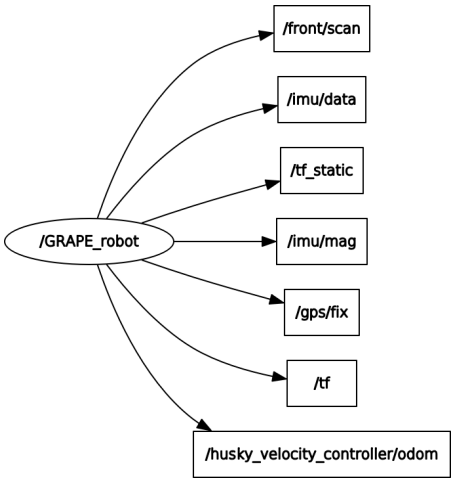


Figure 2.3: *Visualization of the ROS Computation Graph with* rqt *in the context of a data bag being played: there is a single node* (GRAPE_robot) *that simultaneously plays recorded topics messages.*

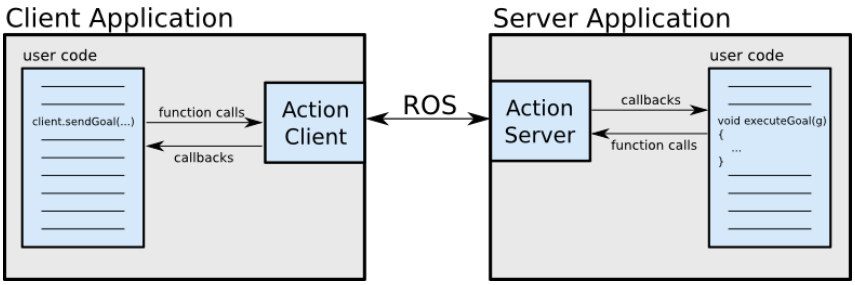


Figure 2.4: *Sketch of the implementation of actionlib, through ROS topics and a callback system.*

time, *i.e.* playing the bag exactly with the same message timing as in 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 consequences[4].

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)*

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.

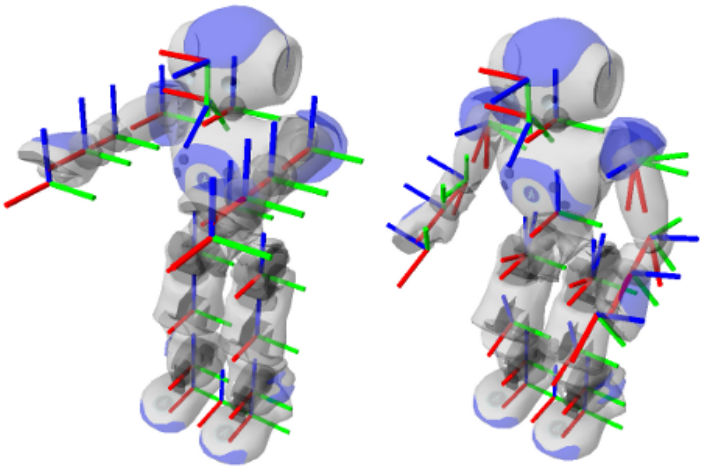


Figure 2.5: *A robot in 2 different positions, with* tf *frames in evidence: x-axis is red, y-axis is green, z-axis is blue. The frames are the same in both configuration, but the transformations* (i.e. *rototranslations) between them are different.*

The utility of such a component is straightforward, even in quite simple robotic systems. We'll describe here a situation we stumbled 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 **??**. 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.

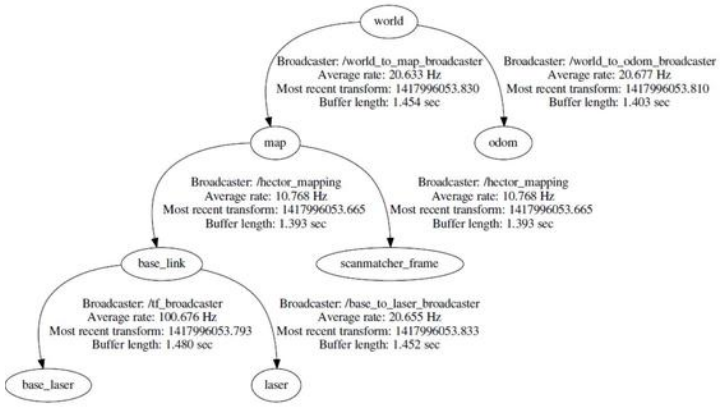


Figure 2.6: *An example of* tf *tree*

We are now giving a a bit more techical detail about *tf*. *tf* implementation relies on ROS topics (see Section 2.1) 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. 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 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 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 2.5 you can see a graphical representation of the reference frames tracked in a Nao Robot, while figure 2.6 shows an example of *tf* graph visualized with visualization framework *rqt*.

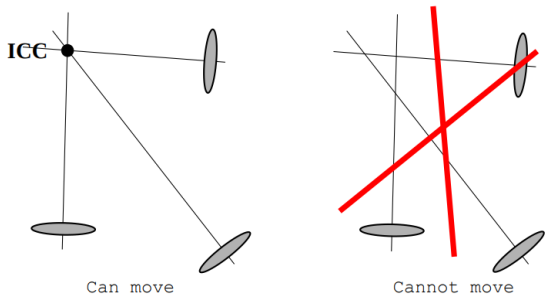


Figure 2.7: *If the axis of all the wheels intersect in a single point, it's called ICC and the robot can move without slipping*

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:

$$< x, y, z, \theta, \dot{x}, \dot{y}, \dot{z}, \dot{\theta} > \tag{2.1}$$

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 traveled 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 (expecially)
- 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 2.7), 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

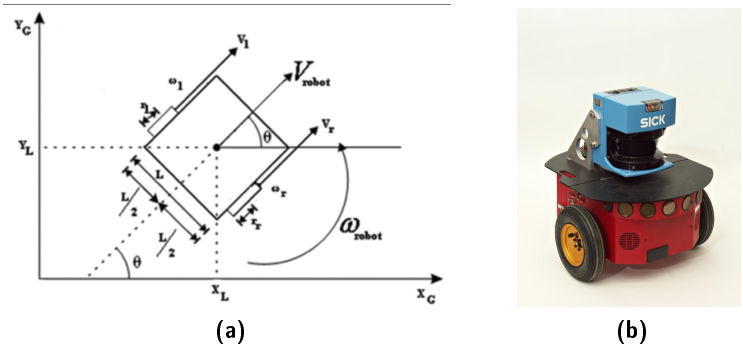


Figure 2.8: *On figure 2.8a, the scheme of a differential drive motion model; in figure 2.8b, an example of a differential drive robot (Pioneer 3DX).*

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 describe 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 4.1, the robot we used is the Husky platform (see Figure 2.10) 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 2.8), 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 ω, and thus:

$$\begin{cases} \omega(R + \frac{L}{2}) = v_r & (2.2) \\ \omega(R - \frac{L}{2}) = v_l & (2.3) \end{cases}$$

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 2.2 and 2.3, we get:

$$R = \frac{L}{2}\frac{(v_r + v_l)}{(v_r - v_l)}, \qquad \omega = \frac{(v_r - v_l)}{L} \tag{2.4}$$

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 2.9 under these condition, we have:

$$ICC = (x - R\sin\theta, y + R\cos\theta) \tag{2.5}$$

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

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

With this procedure we have identified 3 of the elements of the target tuple (see expression 2.1), 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:

$$V(t) = \frac{(v_r + v_l)}{2} \tag{2.6}$$

where $V(t)$ represent the overall 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:

$$x(t) = \int_0^t V(t)\cos(\theta(t))dt \tag{2.7}$$

$$y(t) = \int_0^t V(t)\sin(\theta(t))dt \tag{2.8}$$

$$\theta(t) = \int_0^t \omega(t)d\omega \tag{2.9}$$

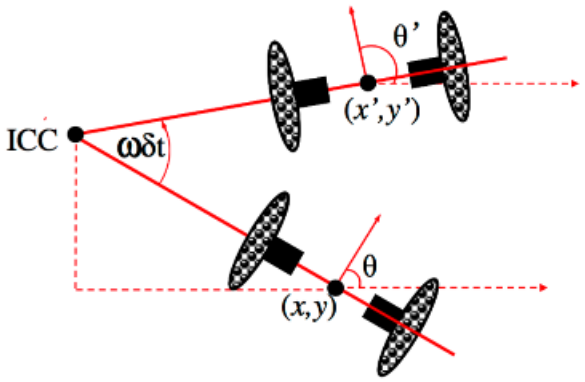


Figure 2.9: *Differential drive:* $(x, y, \theta) \rightarrow (x', y', \theta')$

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.

$$x(t) = \frac{1}{2}\int_0^t (v_r(t) + v_l(t))\cos(\theta(t))dt \tag{2.10}$$

$$y(t) = \frac{1}{2}\int_0^t (v_r(t) + v_l(t))\sin(\theta(t))dt \tag{2.11}$$

$$\theta(t) = \frac{1}{L}\int_0^t (v_r(t) - v_l(t))(t) \tag{2.12}$$

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

Skid-steering kinematics

However, observing image 2.10, 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:

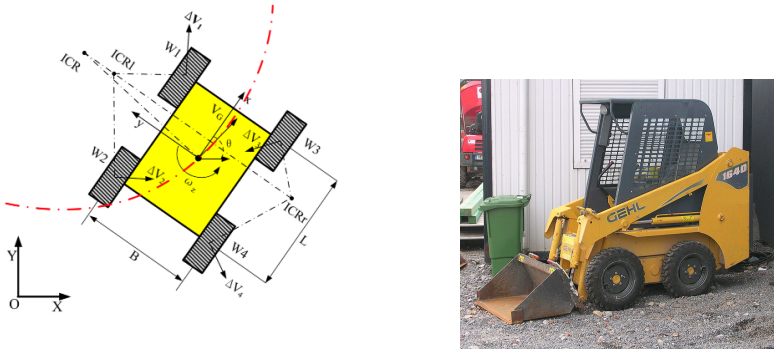
- wheels are not steerable
- being $v_{f\star}$ the speeds of the front wheels, $v_{r\star}$ the speeds of the rear wheels, $v_{\star r}$ the speeds of the right wheels, $v_{\star l}$ the speeds of the left wheels, we always have:

$$v_{fr} = v_{rr} \tag{2.13}$$

$$v_{fl} = v_{rl} \tag{2.14}$$

This type of motion model is called *skid steering*, and is often use in real-world applications (see figure 2.11b) 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 2.10: *Husky platform from Clearpath Robotics is the platform used for the development of GRAPE project.*



(a) (b)

Figure 2.11: *On figure 2.11a, the scheme of a skid steering motion model; in figure 2.11b, 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 2.3, 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 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

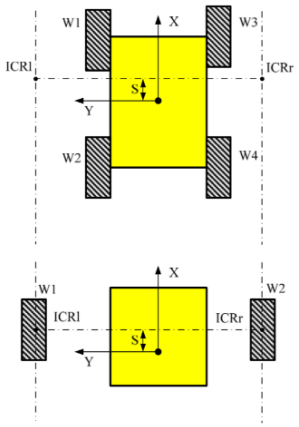


Figure 2.12: *The equivalence of differential drive motion model and skid steering model according to Wang et al., 2015*

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 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:

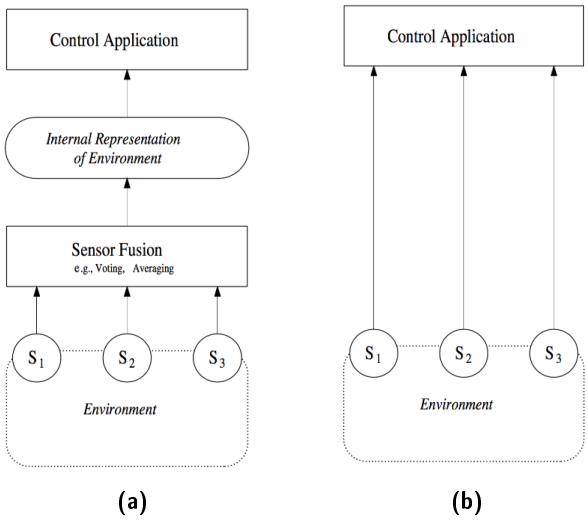


Figure 2.13: *Sensor fusion 2.13a vs multi-sensor integration 2.13b*

- *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 that 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 2.13, 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,

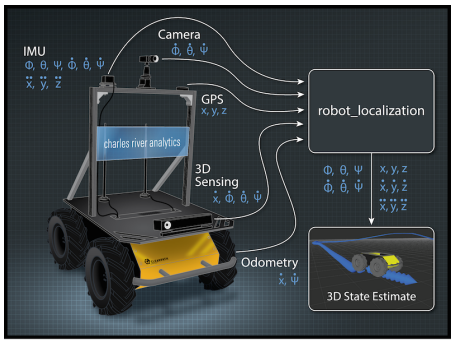


Figure 2.14: *A scheme of Robot Localization senor fusion*

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, Szynkiewicz, 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 the its usage in the required context[5], so we opted for this last one. Further details about our usage or Robot Localization will be given in Chapter **??**, while we are now giving a few hints about its general functioning.

Robot Localization

Citing Robot Localization documentation[6]:

> *"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:

$$< x, y, z, \psi, \theta, \phi, \dot{x}, \dot{y}, \dot{z}, \dot{\psi}, \dot{\theta}, \dot{\phi}, \ddot{x}, \ddot{y}, \ddot{z} > \tag{2.15}$$

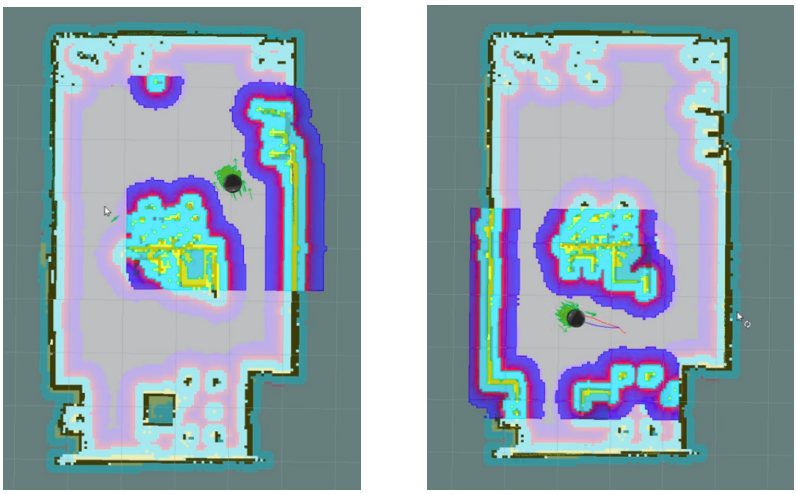
where ψ, θ, ϕ correspond to the Euler angles *roll, pitch, yaw*. The node accepts as inputs several types of ROS messages:

- *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 se in Chapter **??**.
- *sensor_msgs/Imu*: the output of an 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 2.2.

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 outdoor environment as required in GRAPE project. Luckily, it turned



(a) (b)

Figure 2.15: *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.*

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 2.16):

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

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 cell of the gridmap is associated to a certain cost that measure "how hard is it" to traverse that cell of the gridmap; possible

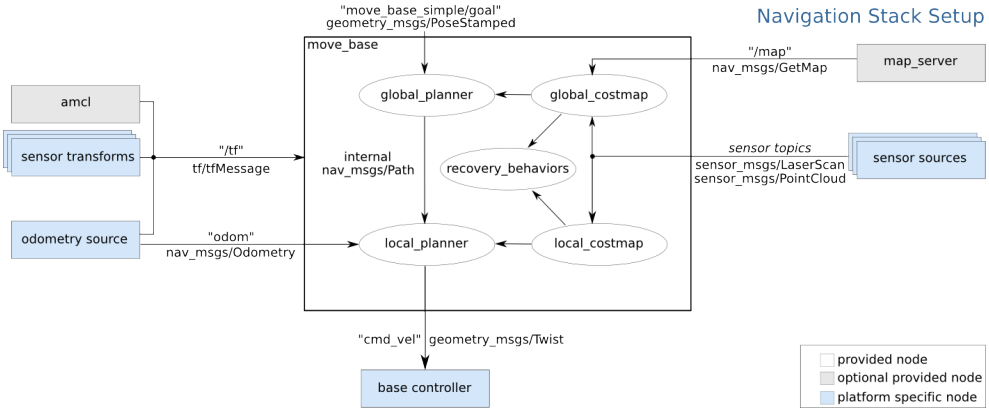


Figure 2.16: *A scheme representation of the Navigation Stack; see the color legend for classification in provided, optional provided, and platform specific nodes.*

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.

MOTION PLANNING

Motion planning is a term used in robotics for the process of breaking down a desired movement task into discrete motions that satisfy movement constraints, and possibly optimize some aspect of the movement. This process is essential for autonomous systems, that accepts high-level description of tasks and should require no further human intervention; in this way the user can focus on *what* he wants done, instead of *how* to do it (Latombe, 2012). Motion planning can be applied to any kind of mechanical device equipped with actuators and sensors under the control of a computing system (*e.g.* a robotic arm that perform *pick-and-place*, a differential drive robot that has to reach a goal in an environment). Motion planning includes (among other): obstacle avoidance, computation of collision-free paths, building reliable sensory-based motion strategies.

More concisely, the basic problem of motion planning is, given:

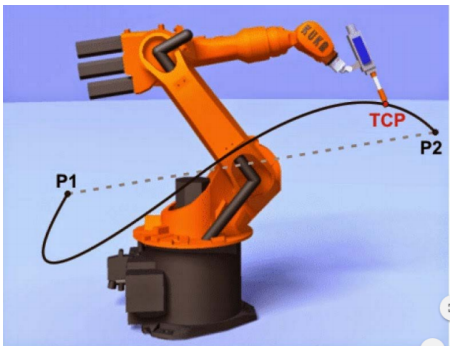


Figure 2.17: *A graphical representation of the trajectory planned for moving a robotic arm from start (P1) to goal pose (P2), satisfying geometrical constraints of the robot.*

- a start pose of the robot
- a desired goal pose (position, orientation)
- a geometric description of the world
- a geometric description of the robot (both as geometric shape, and as kinematic constraints due to kinematic motion model of the robot)

finding a path that moves the robot gradually from start to goal while never touching any obstacle.

Even if the movement of the robot has to be executed in the real world, the planning of the motion is typically computed in the *configuration space*, or *C-space* (Lozano-Perez, 1983). Formally, let: the robot A, at a certain position and orientation, be described as a compact subset of $W = \mathbb{R}^n$, $N = 2$ or 3, and the obstacles $B_1, \ldots, B_n$ be closed subsets of W. In addition, let F_a and F_w be Cartesian frames embedded in A and W, respectively. F_a is a moving frame, while F_w is fixed. A **configuration** q of A is a specification of the position T and the orientation Θ of F_a with respect to F_w. The **configuration space** of A is the space C of all the configurations of A. Usually, configuration space is high dimensional; a configuration is expressed as a vector of positions and orientations, so the robot in configuration space is always represented as a point. We distinguish the configuration space from the *workspace*, that is the physical environment in which the robot move. A few examples:

- the robot is a single point and the workspace is a 2-dimensional plane; C is a plane, and a configuration can be represented using two parameters (x, y).
- the robot is a 2D shape that can translate and rotate, the workspace is a 2-dimensional plane; C is 3-dimensional and a configuration can be represented using 3 parameters (x, y, θ).

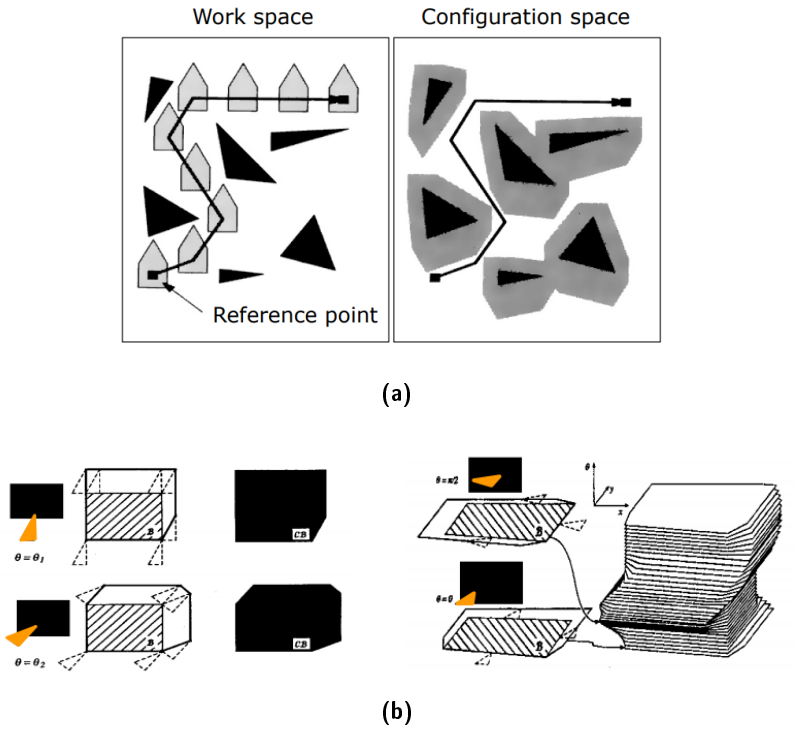


Figure 2.18: *The graphical construction of C-space from workspace, by sliding robot shape along the borders of obstacle regions. In Figure 2.18a you can see the procedure in 2D, in Figure 2.18a in 3D. Note that in 3D you only need to compute 2D procedure for each θ, and then stack all obtained images.*

- the robot is a solid 3D shape that can translate and rotate, the workspace is 3-dimensional; C is 6-dimensional, and a configuration requires 6 parameters: (x, y, z) for translation, and Euler angles (ψ, θ, ϕ).
- the robot is a fixed-base manipulator with N revolute joints and no closed-loops; C is N-dimensional.

Note that, as physical workspace, the configuration space is splitted in free space (C_{free}), and obstacle space (C_{obs}). From a practical point of view, *C-space* can be drawed by virtually sliding the robot shape along the edge of the obstacle regions, inflating them of the area covered by the robot. You can see some graphical examples of this procedure in Figure 2.18.

In simple configuration spaces, *grid-based search* algorithms can be used. With this approach, a grid is overlaid to configuration space, and assume that each configuration is identified with a grid point. With this approach, the problem is reduced to a graph search and exact algorithms like Dijkstra and A*, or suboptimal algorithms like A*, ARA*, AD* can be used.

But this approach gets easily unfeasible (for example, A* has complexity $O(b^d)$ (Hart, Nilsson, and Raphael, 1968), with b branching

factor and d depth of shortest path), so **sample-based approaches** are currently state-of-the-art planning algorithms. Sampling bases approaches, in a nutshell:

- are more efficient in most practical problems but offer weaker guarantees
- are probabilistically complete: increasing computing time, the probability tends to 1 that a solution is found if one exists (otherwise it may still run forever)
- performance degrades in problems with narrow passages

In sample-based planning there isn't a explicit characterizing of C_{free} and C_{obs}, but only a collision detection algorithm that probes C to see whether a certain configuration lies in C_{free} or not. An example of sample-based planning algorithm is **Rapidly exploring random trees** (LaValle, 1998); its pseudocode is shown in Algorithm 1.

Algorithm 1 RapidlyExploringRandomTrees(q_{goal})

```
1:  G.init(q_0)
2:  iterNumber ← 0
3:  N ← 100                                          ▷ for example
4:  repeat
5:      if iterNumber mod N ≠ 0 then
6:          q_rand ← RANDOM_CONFIG(C)
7:      else
8:          q_rand ← q_goal
9:      q_near ← NEAREST(G, q_rand)
10:     G.add_edge(q_near, q_rand)
11:     iterNumber ← iterNumber + 1
12: until q_near = q_goal
```

In the context of GRAPE project, motion planning is an essential component in two different modules:

1. Navigation module: **Move Base**, described in Section 2.5 is a motion planner, that makes use of grid-based planning algorithm, and is used for the navigation of the robotic base in the vineyard environment
2. Manipulation module: **MoveIt!**[7] is a state-of-the-art sample-based planner, and is used to plan the motion of our robotic arm in manipulation tasks (see Figure 2.20 for a block scheme of *MoveIt!* architecture).

7 http://moveit.ros.org/

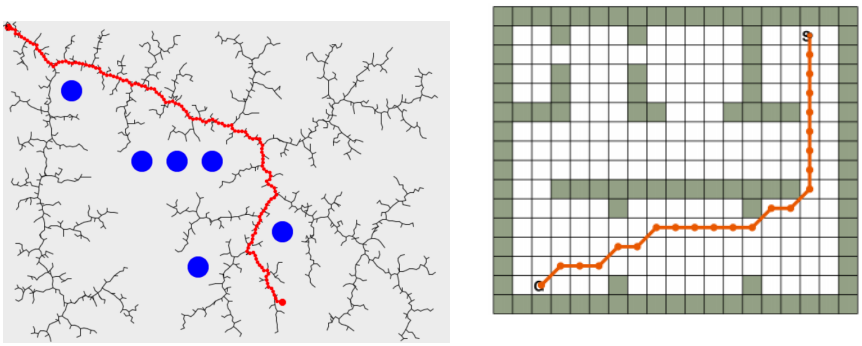


Figure 2.19: *Graphical representation of the ways of proceeding of a sample-based planner (2.19a), and of a grid-based planner (2.19b)*

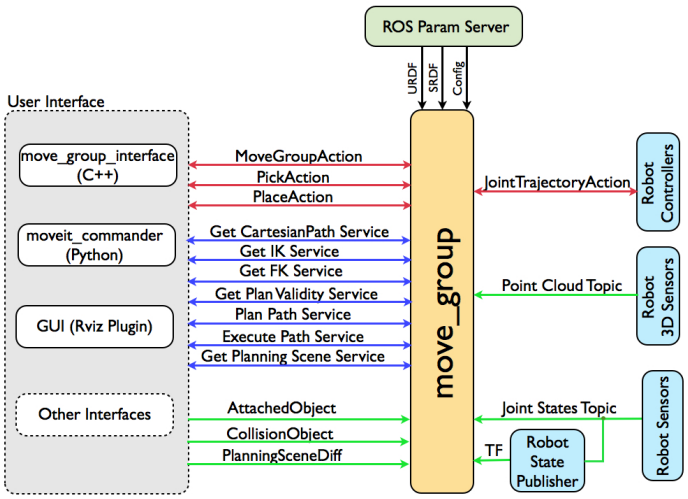


Figure 2.20: *A block scheme representing the high-level MoveIt! architecture.*

3

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 ECHORD++ and, as hinted in the first part of Chapter 2, 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 mantained 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 in food and environment, and an improvement of profits and yield

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 consedidered crucial in the creation of advanced and sustainable economies.

(a) (b)

Figure 3.1: *A vine before (3.1a) and after (3.1b) having leafed out.*

for farmers, that would get a return for their investment (Herring, 2001). The introduction of precision farming tecniques 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 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 **??**.

- **Autonomous application of pherormone dispensers**: pherormone dispensers are used for *mating disruption* tecniques, to protect grapevines from grape moths, by disrupting the bugs' reproductive cycle making use of synthesized sex pherormones. 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 pherormones deployment task gets easier if you think that the timing of the reproductive cycle (on which of course we have no control

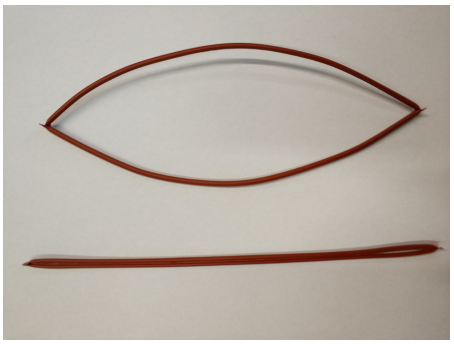


Figure 3.2: *Detail of our dispenser type.*

at all) forces this operation to be performed in a season where grape plants are pruned, and have not leafed out yet (Carde, 1995). Of course, the absence of foliage and grapes makes this task significantly easier (see Figure 3.1).

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 2.1, 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.

(a) (b) (c)

Figure 3.3: *Different shape of pherormone dispensers available on the market. The model used in GRAPE is the one depicted in image 3.3c*

(a) (b)

Figure 3.4: *Other field robots developed in EU projects in the last 6 years: 3.4a Vinerobot, 3.4b Vinbot.*

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:

- 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

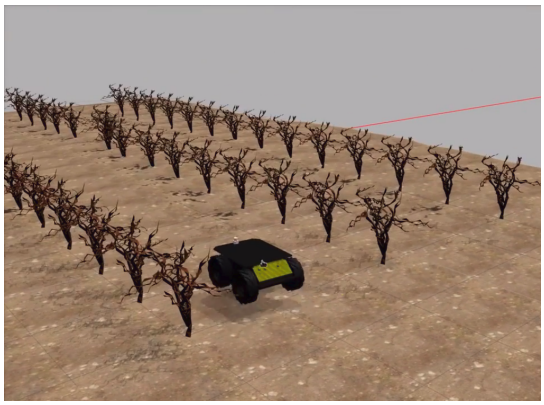


Figure 3.5: *Simulation of the Husky robot in the vineyard environment. Simulation built using Gazebo simulation software.*

Figure 3.6: *The 3D printed vine tree mockup, used in validation phase of the dispenser application task algorithm.*

- creation of a simulated vineyard and Husky environment using Gazebo simulation tool (see Figure 3.5)
- collection of data generated during the same integration week, making use of ROS data logging tool (as described in Chapter 2.1)
- creation of a 3D printed mockup vine tree (see Figure 3.6), to make the laboratory work more efficient and meaningful for the development and validation of the parts that would interact directly with the vine trees (*i.e.* dispenser application task). The mockup was created from the laser scans of a real vine tree in Figueres (ES).

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 4)

(a) (b)

Figure 3.7: *Other field robots developed in EU projects in the last 6 years: 3.7a Rhea, 3.7b CROPS.*

- revision and enhancement of the mapping, localization and navigation systems (see Chapter **??**)
- design and part of the implementation of the pherormone dispenser application (see Chapter **??**)

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 scientic 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 3.4a) 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 3.4b) with a set of sensors capable of capturing and analysing vineyard images togethere with 3D data, by means of cloud computing applications, to determine the yield of vineyards 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 3.7a) 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 3.7b) 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).

4

GRAPE HARDWARE AND SOFTWARE ARCHITECURE

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 3.1. First, in Section 4.1, we are giving an overview of the hardware components, from the robot base to all the actuators/sensors present on board. In Section 4.2, 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 **??**), thus a non-prudent choice could be very dangerous.

As anticipated in Section 2.3, the choice fell on the **Husky** UGV from Clearpath Robotics[1], (see Figure 2.10). 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 2.3, 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/

Figure 4.1: *Husky platform after a navigation session in environment. You can easily note the amount of stones and mud stuck into the wheels.*

- it's fully supported in ROS, with open source drivers, configuration files and examples

This choice turned out to be substantially good. The wheels 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 drivers and config files were actually pretty easy to use and modify. The only major weakness identified in the Husky is related to its behavior on muddy ground, and is due to the wheels shape. After a few minutes of navigation in the mud, the UGV tends to collect a significant amount of earth and stones in the wheels groves (see Figure 4.1) and, consequentely, lose grip on the ground. This problem could be attenuated or solved by use of tracks instead of wheels.

Robotic Arm

By observing how pherormone dispensers must be deployed on the vine plant in Figure 3.3 (in Figure 3.3c, you can see the dispenser shape that we actually used for GRAPE project; in Figure 3.2, a close-up of our dispenser type), it's easy to understand that we require a very flexible robotic arm, with advanced movement capacity and capable of precise movement. Additional constraints also come from the limited space available on the Husky base, and from the limited power supply at disposal aboard. The choice fell on *Jaco*^{2} arm from Kinova Robotics[2] (see Figure 4.2a, Table 4.1 for product specifications), for these reasons:

- 6 DOF provide the required flexibility
- 3 fingers can be used for the dispensers deployment

2 http://www.kinovarobotics.com/wp-content/uploads/2017/06/JACO%C2%B2-User-Guide-Asstive-Robotics-April-2017.pdf

PARAMETER	VALUE
Degrees of Freedom	6
Weight	5.2 Kg
Payload	1.3 Kg
Reach	90 cm
Maximum Linear arm speed	20 cm/s
Power supply	18 ÷ 29 VDC
Average Power	25W
Peak power	100W
Communication Protocol	RS485
Material	Carbon fiber

Table 4.1: Product specifications of Jaco^2 from Kinova Robotics.

- while programmatic control is necessary for GRAPE purpose, the joystick control make it easy to perform quick tests and analyze the robot capabilities
- unlimited joints rotations
- provided mechanical support for sensors mounting on top of the arm
- reduced weight and power consumption
- small overall dimensions
- ROS open source drivers already provided by Kinova Robotics

Some of the nice features of this device (weight, dimensions) actually derive from the original purpose of the arm, that is in the context of assistive devices for disabled people, to improve quality of life and independence of people on power wheelchairs (see Figure 4.2b). But this fact also brought some unexpected weaknesses, that introduced a series quite serious problems that slowed down the development process. The identified weaknesses are:

- a very large imprecision in the movements piloted via programmatic control: this is probably due to joystick control seen as a "main control mode" since, as previously stated, the arm is born as an assistive device. This problem was partially solved modifying the open source drivers of the arm, but entire control strategies were introduced to compensate this weakness. The magnitude of the error, measured as distance between the desired cartesian position of the end effector and the actual one, is

(a) (b)

Figure 4.2: *Robotic arm Jaco^2 with 3 fingers, from Kinova Robotics (4.2a) and the same arm mounted on a wheelchair 4.2b*

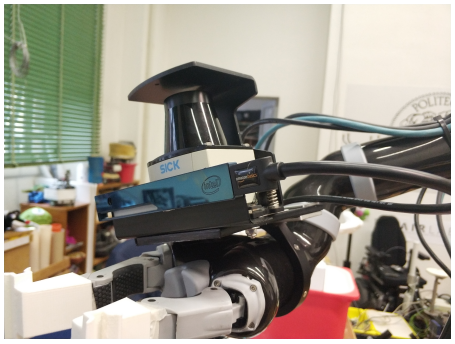


Figure 4.3: *The final configuration of the sensors (LIDAR and RGB-D camera) mounted on top of the end effector.*

$0 \div 5$ cm after the changes to the ROS driver of the arm. TODO sarebbe bello avere dei dati per supportare questa misura

- buggy implementation of joints constraints, probably due to the same cause of the previous point. This created a major problem mostly because of the wiring used for the sensors (described in next Sections) mounted on the arm, that kept rolling up because of the unlimited joints rotation capability. TODO a seconda di come alla fine la risolviamo definitivamente (messi a posto i driver, o procedure di controllo) lo scrivo.

After the analysis of the macro goals of GRAPE project (Section 3.1), it was decided to use the arm as a support for other sensors, as well as manipulation tool, for the dispenser deployment task: a LIDAR and an RGB-D camera (see Image 4.3).

	VLP-16	TIM561	UTM-30LX-EW
Number of Channels	16	1	1
Scan Angle	360°	270°	270°
Rotation rate	5Hz 10Hz 20Hz	15 Hz	40Hz
Angular Resolution	0.1° 0.2° 0.4°	0.33°	025°
Range	100m	10m	30m
Power Consumption	8W	4W	<8W
Weight	590g	250g	210g

Table 4.2: Comparison of Husky on-board LIDARs

LIDARs

The final robotic system mounts three different LIDARs: two in front of the Husky for visualization and navigation purposes, and the other one mounted on a metal support on top of the arm end effector. The purpose of this last LIDAR will be cleared in Chapter **??**; for now, all you need to know is that it's used in the procedure of identification of the most suitable point for dispenser deployment. The LIDARs come from different producers, but they are quite similar being designed for outdoor use. The two used for navigation are **Velodyne VLP-16**[3] and **Hokuyo UTM-30LX-EW**[4], the one on top of the arm is **SICK Tim561**[5]. Main differences and similarities between these models are highlighted in Table 4.2

RGB-D camera

The other sensor mounted on top of the arm end effector is a **RealSense** RGB-D camera from Intel. This camera is able to sense the depth of the acquired images (see Figure TODO screenshot di rgb e profondità), by means of an active infrared stereo technology. The main usage of the camera is to provide images used for the feedback loop of the visual servo control of the Jaco[2] arm. Visual servoing is a technique which uses feedback information extracted from a vision sensor to control the motion of a robot (Hutchinson, Hager,

3 http://velodynelidar.com/vlp-16-lite.html
4 https://www.hokuyo-aut.jp/search/single.php?serial=170
5 https://www.sick.com/de/en/detection-and-ranging-solutions/2d-lidar-sensors/tim5xx/tim561-2050101/p/p369446

(a) (b) (c)

Figure 4.4: *Three LIDARs mounted on our UGV: Tim561 (4.4b) from SICK, Puck Lite (4.4a) from Velodyne, UTM-30LX-EW (4.4c) from Hokuyo.*

and Corke, 1996), and it's used in this project to compensate the lack of precision in the arm motion operations (see Section 4.1.2). This camera also applies to operation validation operations (validation of dispenser grasping, validation of dispenser deployment on the plant) and identify exceptional cases (no dispenser left). The positive aspect of this camera model comes from its contained size and weight. We spotted only one significant weak point, that is a quite high minimum depth distance (20 cm), due to an intrinsic limit of the embedded depth technology. This problem created a few complications in dispenser application tasks, but they were easily bypassed.

Tools for dispensers grasping

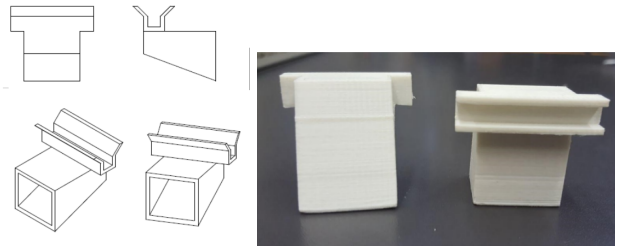
Additional hardware was placed on the UGV specifically for the accomplishment of the grasping of the dispenser, for two separate reasons:

- the shape of the dispenser (see Figure 3.2) was not directly compatible with the grasping capability of the end effector of Jaco^2 arm (see the Jaco^2 fingers in Figure 4.2a)
- the dispensers have to be stored on the Husky platform, in such a way to make them graspable

We required very custom hardware to accomplish these objectives so, given the prototype nature of the project, 3D stamped hardware was used. For what concern the storage of the pheromone dispensers, the final version of the dispenser feeder was built out of two 3D-printed small towers (see Figure 4.5a), with a sequence of very smooth aligned grooves, parallel to the horizontal plane, where the dispensers are slotted in. The smoothness of the grooves is the critical part of the design, indeed the previous versions of the towers, with sharper grooves, highlighted a difficulty of the grasping phase if the dispensers got caught on the feeder's corners.

(a) (b)

Figure 4.5: *The final version of the 3D-printed dispenser feeder (4.5a), and a perspective drawing of one of the earlier versions of it (4.5b), with sharper edges.*



(a) (b)

Figure 4.6: *The final version of the 3D-printed nails (4.6b), and their perspective drawing (4.6a)*

The fingers of the robot are not all the same, because one of them act as a sort of "opposable thumb", that is useless in our application. So, two "nails" were printed to be applied to the two symmetric fingers, with a side dispenser-sized groove each, in order to grasp the dispenser by opening the two symmetric fingers.

Other sensors

The UGV holds onboard a collection of other sensors, useful for the accomplishment of the established tasks. In this section we'll give a short overview of the few remaining ones:

IMU SENSOR Device including a magnetometer, accelerometer, gyroscope. These sensors were used in the odometry estimation system through sensor fusion algorithms (see Chapter **??**)

GPS Also this sensor data stream was included in the odometry estimation system

CAMERAS Additional camera mounted in a slightly lifted position with respect to the robot base; they are useful in case of teleop-

Figure 4.7: *The complete robotic platform, with sensors/actuators final arrangement.*

eration of the Husky or the robotic arm, and for visualization and monitoring purposes.

You can see the final sensor/actuators arrangement in Figure 4.7 TODO foto migliori

GRAPE SOFTWARE ARCHITECTURE

Now that the hardware configuration is clear, we'll focus on the *behavior* of the UGV. We'll start by a description of the subproblems that we identified starting from the macro goals we talked about in Section 3.1, and then move to the software architecture.

Evaluation of vineyard navigation

The problem of autonomous navigation of UGVs is a very well-known problem, studied at least from the nineties (Gage, 1995), because of course it's the first problem to deal with in almost all systems involving mobile robots. For this reason, and being our robotic system a prototype, for us the problem of vineyard navigation reduced to the following subproblems:

- identification of a sensor fusion framework in ROS, to provide an odometry estimate, and configuration of such a framework, with particular attention to which sensors fuse together
- identification of a navigation framework in ROS, to provide motion planning and speed control of the mobile base, and configuration of such a framework to fit our problem

Even if these tasks seem trivial, two major problems arose:

- complex framework like these ones have tenths of parameter to tune, and the documentation is not always very precise
- the *off-the-shelf* navigation systems are usually born for indoor environments, that differ a lot from the very unstructured nature of the vineyards.

As hinted in Section 2.5 and 2.4.1, our choices fell on **Move Base** package for the navigation, and **Robot Localization** as odometry system. We'll present more detail of the subproblems mentioned above in Chapter **??**. Move Base offers an *action* (see Section 2.1) as interface with the ROS ecosystem.

Evaluation of vineyard monitoring task

For the vineyard monitoring task, as foreseen by the project proposal, we opted for a semi-autonomous monitoring: we provided the UGV with a camera with video stream capability, that allows human users with competences in the domain of plants health to observe in person the live data streamed by the robot for assessment of crop condition. Human operators are also provided teleoperation interface for navigation and manipulation, for supervisioning and emergency handling function.

This choice came from both the absence in the project proposal of precise objectives on this topic, and the complexity of feature extraction and evaluation in this context.

Evaluation of dispenser application task

While navigation task is a very common problem and *off-the-shelf* solutions are easy to find, dispenser application is a completely non-standard task, so we could only rely on libraries and package for low level subtasks but we had to design and implement the whole procedure from scratch. We divided the procedure in 3 subproblems:

1. **Creation of a point cloud of the tree:** the robot is sitting still, with a vine on the same side of the Jaco^2 arm. When the procedure is triggered, the arm moves in order to produce a point cloud of the trees close to it, using the LIDAR mounted onto it.
2. **Deployment points identification:** once the point cloud has been produced, an algorithm based on Point Cloud Library (PCL) trims the point cloud from the points that don't belong to the tree, process it, and outputs a sequence of 3D points (x, y, z) corresponding to points on the tree suitable for the deployment of the dispenser, typically a protuberance of the tree, ordered

from the best one to the worst one according to a suitable metric.

3. **Deployment of the dispenser:** the arm starts the dispenser deployment procedure, taking as input the sequence of points got in the previous step:
   a) it grasps the dispenser (if any) from the dedicated support
   b) it applies the dispenser on the best feasible point from the input sequence
   c) it goes back to a retired position, to achieve better stability during the movement of UGV.

   In figure 4.10, you can see an example of successful dispenser application, using the mockup plant. **NOTE:** the integration weeks were not all held in the same place (two of them in Garriguella (ES), and one in Casciana Terme (IT)), so we could observe that the vine trees shape is very different in the different locations (for example, the trees in Garriguella tend to have small almost vertical branches on the top of the pruned tree, while the Italian ones had smaller protuberances with variable orientation). This factor makes our system much harder to validate, because it's even more difficult to identify useful features in the unstructured vineyard environment. Thus, we introduced a further deployment mode, to be used in case our deployment procedure on the plants turned out not versatile enough to be efficient on a new tree type. Since we wanted to bypass the problems due to different tree structures, in this mode we assume to have some appropriately shaped nails, expressly arranged for dispenser applications. As we'll see in Chapter **??**, this deployment mode also requires the application of *binary square fiducial markers* (see Figure 4.8), so in this way our application pushes a bit more towards a vineyard that modifies in order to be more suitable to robotic applications.
   The steps of this deployment mode are slightly different from the previous ones:
   a) it grasps the dispenser (if any) from the dedicated support
   b) it applies the dispenser on the nail, regardless of the input sequence (which become useless)
   c) it goes back to a retired position, to achieve better stability during the movement of UGV.

All these procedures are quite long and complex, we wanted the user to have a high control on them, including the monitoring of intermediate results. For these reasons, these procedure are implemented as ROS actions.

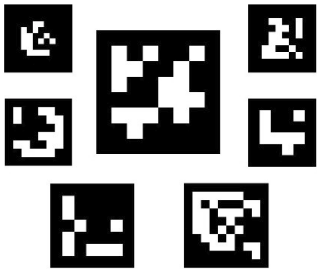


Figure 4.8: *Examples of visual markers (more specifically, ArUco markers) as the ones we used in visual servoing applications.*

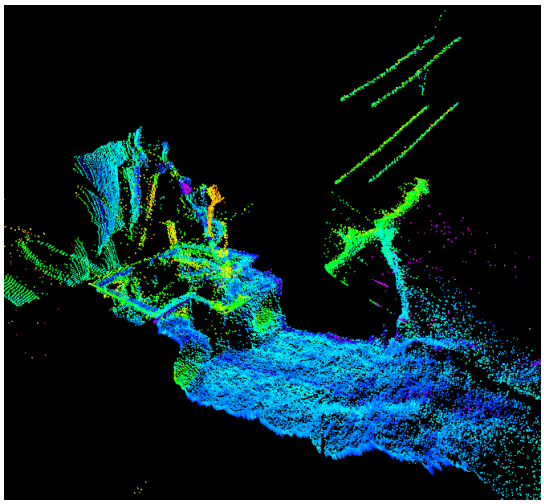


Figure 4.9: *Examples of laser scans collected in Casciana Terme during the integration week in January 2018, with the LIDAR mounted on top of the end effector of the arm. You can recognize the vine plant, and part of the Husky base. The colors are only for visualization purpose.*

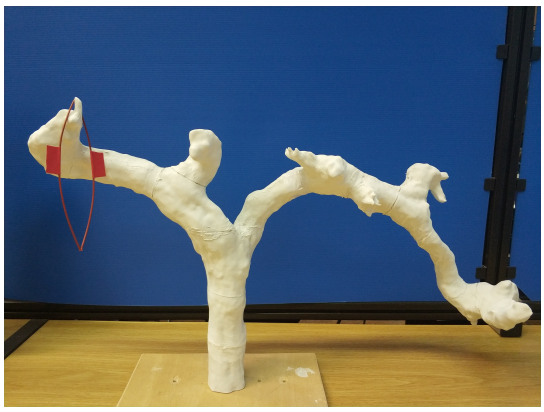


Figure 4.10: *Example of a dispenser application task, correctly executed on a mockup plant.*

Details of the actions interfaces

In this section we are giving a detailed description of the action interfaces, to better understand their scope and goals. Note that none of them includes a flag to check for correctness of execution, because we decided to use the internal status variable embedded in ROS actions.

Move Base action interface

- **Goal Message**:
  - *target_pose*: the pose (position, orientation) we want our robot to reach
- **Result Message**:
  - *base_position*: the final pose (position, orientation) of the robot; in case of success, it should be very close to the specified *target_pose*
- **Feedback Message**: *n.a.*

Scan motion action interface

- **Goal Message**: *n.a.*
- **Result Message**: *n.a.*
- **Feedback Message**: *n.a.*

Note that even an empty ROS action like this makes sense, because of the length (~30 seconds) of the procedure triggered by an action call.

Point cloud processing action interface

- **Goal Message**: *n.a.*
- **Result Message**:
  - *deployment_pose*: contain an array (x, y, z) of possible deployment poses, identified from the plant point cloud; it will be used as input to the dispenser deployment action server (see Table 4.5)
- **Feedback Message**: *n.a.*

Dispenser deployment action interface

- **Goal Message**:
  - *deployment_poses*: sequence of feasible deployment points, ordered from the best one to the worst one. These are the points output by *Point cloud processing action*

Goal Message	`geometry_msgs/PoseStamped target_pose`
Result Message	`geometry_msgs/PoseStamped base_position`
Feedback Message	`---`

Table 4.3: Move Base action specification

Goal Message	`---`
Result Message	`---`
Feedback Message	`---`

Table 4.4: Scan motion action specification

  - *deploy_mode*: an integer, used to select the technique to be used for the dispenser deployment; in fact, three different mode has been developed, in order to fit the different condition that the UGV could face. In short, the modes available for selection are:
    * Closed loop control, deployment target is an expressely placed nail, hammered into a pole
    * Closed loop control, deployment target is a protuberance of the vine tree
    * Open loop control, deployment target is a protuberance of the vine tree

    Details about the deployment mode are given in Chapter **??**.

- **Result Message**: *n.a.*
- **Feedback Message**:
  - *ManipulationStatus status*: a message of proprietary type, that contains structures used to communicate the action caller the current execution state (*e.g.* dispenser fallen, arm moving in front of the target point).

Goal Message	`---`
Result Message	DeploymentPose[] deployment_poses
Feedback Message	int8 execution_percent range [0,100]

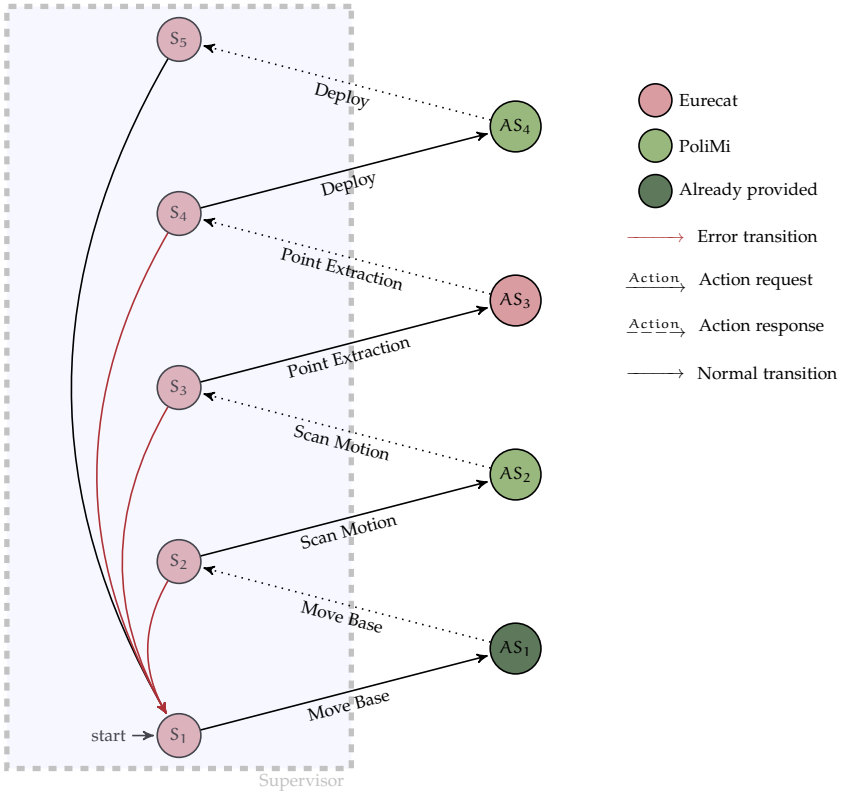
Table 4.5: Process point cloud action specification

Goal Message	DeploymentPose[] deployment_poses int32 deployMode
Result Message	- - -
Feedback Message	ManipulationStatus status

Table 4.6: Dispenser Deployment action specification

The supervisor

Since all main operations in the project structure are implemented through action servers, of course a list of action clients must exists. For our implementation, we opted for a single software module that acts as an action client for all the actions mentioned above. We call this module *Supervisor*, and its implementation uses behavior trees (Colledanchise and Ögren, 2017) as an overall model. The objective of the supervisor is to implement the global Finite State Automata (FSA) of the system, where basically **nodes** are action servers or action clients.



As pointed out by Figure 4.2.5, all action clients belong to the supervisor software module, and major tasks are implemented through action servers. In that graph we also specify the division of labor between the different teams:

- Software modules entrusted to **PoliMi**
  - AS_2: Scan motion action server
  - AS_4: Dispenser deployment action server
- Software modules entrusted to **Eurecat**
  - AS_2: Point cloud processing action server
  - S_i: Supervisor (*i.e.* all action clients and FSA implementation)

Software modules treated in this thesis

After this global overview of the hardware and software components of the GRAPE project as a whole, we can finally specify which of the aforementioned topics has been directly treated in this thesis work. They are:

- UGV navigation system (see Chapter **??**)
- development of Scan motion action server (see Chapter **??**)
- development of part of Dispenser deployment actions server (see Chapter **??**).

5 CONCLUSIONS

In this work we designed, developed and validated the software components of an autonomous mobile manipulator. The system is equipped with an odometry system that robustly provides an accurate estimation of the robot geolocalized pose and orientation, exploiting data from GPS, IMU, and wheels velocities. The pose estimation is used by the platform to achieve autonomous navigation on steep, rough, and very bumpy terrain and, by means of a single-plane frontal LIDAR, the vehicle is able to deal with irregular obstacles such as the vines trunks and other accidental vegetation (*e.g.* high weeds) in the vineyard. Adaptive Monte Carlo Localization (AMCL) localization algorithm was not able to deal with the high degree of repetitiveness of the vineyard map, so we opted for the substitution of the global map with an handcrafted *prohibition layer* to represent the vineyard rows as obstacles. Even if this operation has to be made by hand, we consider it more efficient solution than the map usage because:

- the vineyard rows are very simple and regular obstacles to be specified by hand, since they are identified by only two geolocalized endpoints each; thus, GPS coordinates of endpoints can also be extracted via satellite imagery
- the *prohibition layer* specification is easier and faster than traditional mapping phase, and in our case fully substitutes it
- the inclusion of *prohibition layers* in both local and global costmaps avoids row crossing problem

The main goal of GRAPE project, the automatic deployment of pheromones dispensers in the vineyard, is executed by means of the on-board manipulator, and validated via computer vision techniques designed to detect the expressly-placed dispenser's red wings in the image frame. We designed two different execution modes for the dispenser deployment operation:

1. application of the dispenser in a point output by the processing of a 3D reconstruction of the target vine
2. application of the dispenser on a target nail, via visual servoing control with the help of specifically placed binary fiducial markers

These solutions can be selected according to the willingness of the wine growers not to modify the vineyard structure at all (solution 1), or to carry out a simple preparation of the vineyard in order to enjoy

an easier and more robust dispenser deployment procedure (solution 2).

After two *on-the-field* sessions, we can certify the robustness of sensor fusion, localization, and manipulation systems in the actual vineyard environment. However, we were also able to identify some weaknesses in the resulting platform, that could be addressed in future work:

- during the system development, no particular emphasis to the power consumption problem was given; thus, the current power supply system of the Husky can support the platform for about 4 hours. Even if the change of batteries is a simple and fast operation, it's carried out by humans and it largely decreases the platform potential. A power-aware restyling of both software and hardware components of the system would be one of the main improvements of the platform

- the sensor fusion system strongly relies on high-precision GPS, that actually is not available worldwide. Navigation system is the component that would mainly suffer from faulty localization, so a possible solution to disengage it in some measure from high-precision GPS would be to introduce a (maybe partially) image-driven navigation system, that exploits the regularity of vine rows to select the navigation direction

- the computer vision operations that do not rely on binary fiducial markers (*i.e.* validation of grasping and deployment of the dispenser, detection of dispenser availability in the feeder) turned out to be weaker then expected when executed in strong and direct sunlight conditions, but for mere lack of time we could not directly address this problem. A more fine-grained configuration of the procedures might be sufficient to significantly improve their performance.

BIBLIOGRAPHY

Bascetta, Luca, Marco Baur, and Giambattista Gruosso (2017). "ROBI': A Prototype Mobile Manipulator for Agricultural Applications." In: *Electronics* 6.2, p. 39.

Calabrese, Luca (2014). "Robust odometry, localization and autonomous navigation on a robotic wheelchair." In: (cit. on p. 17).

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. 27).

Chatzimichali, Anna P, Ioannis P Georgilas, and Vassilios D Tourassis (2009). "Design of an advanced prototype robot for white asparagus harvesting." In: *Advanced Intelligent Mechatronics, 2009. AIM 2009. IEEE/ASME International Conference on*. IEEE, pp. 887–892.

Colledanchise, Michele and Petter Ögren (2017). "Behavior Trees in Robotics and AI, an Introduction." In: *arXiv preprint arXiv:1709.00084* (cit. on p. 46).

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. 17).

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. 17).

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. 30).

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. 17).

Elmenreich, Wilfried (2002). "Sensor fusion in time-triggered systems." In: (cit. on p. 15).

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. 7).

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. 19).

Gage, Douglas W (1995). *UGV history 101: A brief history of Unmanned Ground Vehicle (UGV) development efforts*. Tech. rep. NAVAL COM-

MAND CONTROL, OCEAN SURVEILLANCE CENTER RDT, and E DIV SAN DIEGO CA (cit. on p. 40).

Hart, Peter E, Nils J Nilsson, and Bertram Raphael (1968). "A formal basis for the heuristic determination of minimum cost paths." In: *IEEE transactions on Systems Science and Cybernetics* 4.2, pp. 100–107 (cit. on p. 22).

Herring, David (2001). "Precision farming: Feature articles." In: (cit. on p. 26).

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. 33).

Hutchinson, Seth, Gregory D Hager, and Peter I Corke (1996). "A tutorial on visual servo control." In: *IEEE transactions on robotics and automation* 12.5, pp. 651–670 (cit. on p. 37).

Latombe, Jean-Claude (2012). *Robot motion planning*. Vol. 124. Springer Science & Business Media (cit. on p. 20).

LaValle, Steven M (1998). "Rapidly-exploring random trees: A new tool for path planning." In: (cit. on p. 23).

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 viticulture and wine making in climate chenge scenarios, 5-10 November 2017*. GiESCO (cit. on p. 30).

Lozano-Perez, Tomas (1983). "Spatial planning: A configuration space approach." In: *IEEE transactions on computers* 2, pp. 108–120 (cit. on p. 21).

Madhavan, Raj, Lino Marques, Edson Prestes, Renan Maffei, Vitor Jorge, Baptiste Gil, Sedat Dogru, Gonçalo Cabrita, Renata Neuland, and Prithviraj Dasgupta (2015). *2015 humanitarian robotics and automation technology challenge* (cit. on p. 33).

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. 18).

Mohanty, Vikram, Shubh Agrawal, Shaswat Datta, Arna Ghosh, Vishnu Dutt Sharma, and Debashish Chakravarty (2016). "DeepVO: a deep learning approach for monocular visual odometry." In: *arXiv preprint arXiv:1611.06069* (cit. on p. 17).

Moore, T. and D. Stouch (2014). "A Generalized Extended Kalman Filter Implementation for the Robot Operating System." In: *Proceed-*

ings of the 13th International Conference on Intelligent Autonomous Systems (IAS-13). Springer (cit. on p. 17).

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. 31).

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. 33).

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. 15).

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. 31).

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. 31).

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. 28).

Shamah, Benjamin (1999). "Experimental Comparison of Skid Steering vs. Explicit Steering for Wheeled Mobile Robot," M. Sc." In: (cit. on p. 14).

Thrun, Sebastian (2002). "Probabilistic robotics." In: *Communications of the ACM* 45.3, pp. 52–57 (cit. on p. 16).

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. 14, 15).

Yaguchi, Hiroaki, Kotaro Nagahama, Takaomi Hasegawa, and Masayuki Inaba (2016). "Development of an autonomous tomato harvesting robot with rotational plucking gripper." In: *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on*. IEEE, pp. 652–657.

Yi, Jingang, Junjie Zhang, Dezhen Song, and Suhada Jayasuriya (2007). "IMU-based localization and slip estimation for skid-steered mo-

bile robots." In: *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*. IEEE, pp. 2845–2850 (cit. on p. 14).