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Multi-Robot Behavioural Algorithms Implementation in Khepera III Robots

FINAL PROJECT DEGREE IN INDUSTRIAL ENGINEERING

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Preface

This report describes the project work carried out at the *Faculty of Arts, Computing, Engineering and Sciences* (ACES) at Sheffield Hallam University during the period between February 2010 and July 2010.

The contents of the report are in accordance with the requirements for the award of the degree of Industrial Engineering in the *Universitat Politècnica de València*.

Acknowledgements

It is my desire to express my gratitude to those people and institutions who made possible the realization of this project, like *Sheffield Hallam University* for its support and teachings and *Universitat Politècnica de València*, for all this years of study and education.

Specially, I would like to say thanks to these people for their valuable contributions to my project:

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My family and my girlfriend, for their endless love and support in my months in the United Kingdom.

Abstract

The purpose of this study is to develop non-communicative behavioural algorithms for being implemented in a team of two *Khepera III* robots. One robot is the leader, and realize tasks such as wall following and obstacle avoidance, and the other robot is the follower, which recognizes the leader differentiating it from the rest of the environment and follows it. The aim is that robots are able to do the requested actions only using a laser ranger as a sensor and its own motors and odometry measures.

With that purpose, simulations in the Player/Stage simulation software have been made for test the developed code that lately has been run in the real robots. For the follower robot, a movement detection system by comparing laser scans in two consecutive instants of time has been developed to obtain the direction of the leader.

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Chapter 1

Introduction

1.1 Introduction

The purpose of this thesis is to develop behavioural algorithms for being implemented in real mobile robots, in this case Khepera III robots. The project has been made for being implemented in two robots: one takes the role of the leader robot and the other one is denominated as the follower robot. Therefore, we can consider algorithms for the real robot like obstacle avoidance and wall following and algorithms for the follower robot, like obstacle avoidance and robot following.

Some of this approaches in multi-robot systems include the use of fiducials makers as point of reference or measure [JSPP08] [KLM06]. This can be very helpful when detecting the position of the robot on the group, as one robot can automatically know the position of the others, and therefore, if initial positions are known, its global position in the environment. Unfortunately, this fiducial tool is only available for simulation, as it is not existing for real robots. In addition, any similar solution in real robots implies any kind of communication between them, which we are trying to avoid in this thesis.

The tools that use the robots are a laser range finder and the odometry. The laser range finder is used to measure the distance to the objects in the environment. This allow the robot, for example, to know the distance to the closest wall to follow or to the closest object to avoid. It can also be used to detect the approximate position of the other robot. It can be said that the laser range finder is the only way to receive data from the environment. The odometry part is used for sending motion orders to the robot motors and also for calculate the current orientation of the robot.

Another important factor to consider is that results in simulation will vary from real results, as there are more factors to take in account when working with physical robots. These factors include inaccuracy of the laser and the position proxy measures, non-exact response of the motors, wheel slipping, accumulative errors in sensors . . . Moreover, there are a few functions from the odometry system that works with no problems in the simulation environment but that are not available when implemented in Khepera robots. That reduces the range of options available when looking for a solution, and makes the simulation code being made from the functions available for the real robots.

1.2 Background

The use of multi-robot teams working together have lots of advantages in front of single-robot systems. They can be used for environment exploration and mapping, with one ore more robots taking data from the scenario. One of the advantages of this systems is that they are more robust, because if one robot fails, the rest of then can keep doing the assigned task.

The above-mentioned tasks has been implemented, for example, in the *GUARDIANS* and *View-Finder* projects, both developed at *Sheffield Hallam University* in collaboration with several European partners, including South Yorkshire Fire and Rescue Services [GUA] [Vie]. These robots will assist in the search and rescue in dangerous circumstances by ensuring the communication link and helping the human team to estimate the safety of the path they are taking and the best direction to follow.

Non-communicative approaches are also wide used in robotics. The groups of robots can operate together for accomplish a goal, but without sharing any data or sending information [JRK04]. This concept has also the advantage of the high reliability, as if one robot fail the others will keep working as they are not using the data from the failed robot to do its task.

Taking in account all this information, I have tried to create two separate algorithms using minimum physical resources (taking data only a laser sensor and the odometry) to realize wall following, obstacle avoidance and robot following algorithms.

1.3 Motivation

The main motivation for develop this thesis is to create the aforementioned algorithms for their implementation in real robots. There are lots of thesis and projects that rely only in simulation codes, assuming that all the data they use is ideal, without considering the non-linearities of the real systems. Likewise, they use some functions and features that don't exist or are very difficult to implement in physical systems.

Also, the Department had the desire of the implementation of this algorithms in the Khepera III robots and the URG-04LX UG01 laser range finders that they own, so all the efforts were focused to develop the best possible code with the features and characteristics of the available hardware .

1.4 Objectives/deliverables

The main objectives of this dissertation are the followings:

- Introduction and comprehension of Linux and Player/Stage software.
- Research of information for the correct development of the thesis.
- Develop of navigation algorithms (wall following and obstacle avoidance) for the leader robot, using laser and odometry in Player/Stage.
- Develop of following algorithms (robot following and obstacle avoidance) for the follower robot, using laser and odometry in Player/Stage.
- Field tests of the final codes in physical Khepera III robots.

1.5 Project flow diagram

This flow diagram of the activities made in this thesis can be seen in the figure 1.1

1.6 Thesis guideline/structure

This thesis is organized as follows:

- Chapter 2 introduces and explains all the characteristics and peculiarities of the Player/Stage software used for run programs in the robots and for make simulation test.
- Chapter 3 shows the hardware devices used in the implementation of the code and its characteristics.

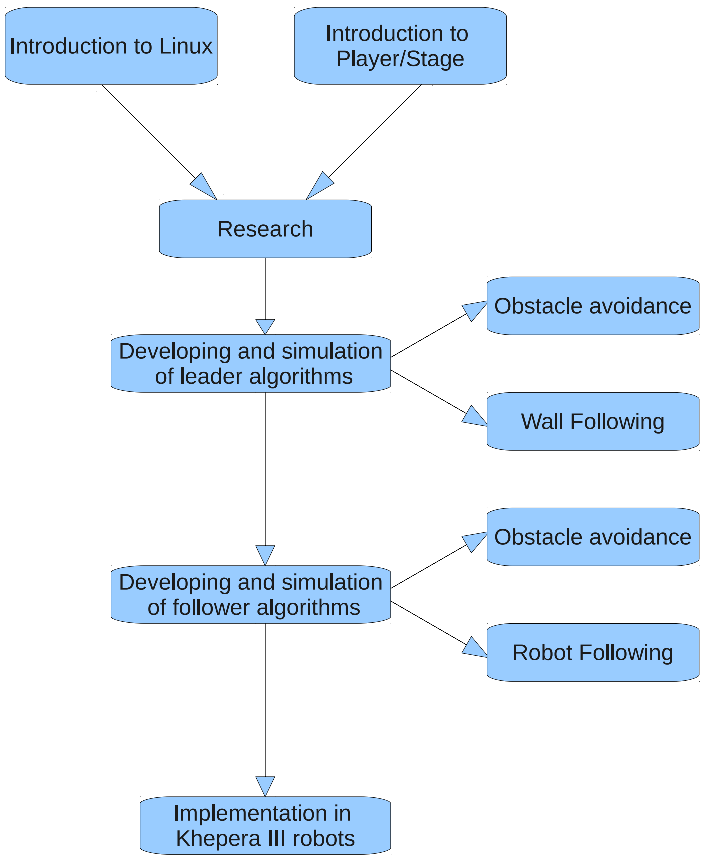

Introduction to Linux
Introduction to Player/Stage
Research
Developing and simulation of leader algorithms
Obstacle avoidance
Wall Following
Developing and simulation of follower algorithms
Obstacle avoidance
Robot Following
Implementation in Khepera III robots

Figure 1.1: *Project flow diagram*

- Chapter 4 exposes all the related theory and literature consulted in the research phase.
- Chapter 5 deals with the developed robot behaviour algorithms for both leader and follower robots.
- Chapter 6 concludes the the dissertation by discussing about the carried work and purposes some further work guide-lines.

Chapter 2

Player/Stage

2.1 Introduction

The Player/Stage software is a project to provide free software for research into robotics and sensor systems. Its components include the Player network server and Stage and Gazebo robot platform simulators. The project was founded in 2000 by Brian Gerkey, Richard Vaughan and Andrew Howard at the University of Southern California at Los Angeles [Vau00], and is widely used in robotics research and education. It releases its software under the GNU General Public License with documentation under the GNU Free Documentation License. Also, the software aims for POSIX compilance [sou].

2.1.1 Features

These are some features of the Player/Stage software (table 2.1)

Developers	Brian Gerkey, Richard Vaughan and Andrew Howard
Latest release	Player 3.0.2, June 28, 2010
Operating systems	Linux, Mac OS X, Solaris, BSD
Languages supported	C, C++, Java, Tcl, Python
License	GNU General Public Licence
Website	`http://www.player.sourceforge.net`

Table 2.1: *Player/Stage main features*

The software is designed to be language and platform independent, if the language support TCP sockets and the platform has a network connection to the robot, respectively. This gives the user freedom to use the most suitable tools for each project. It also allows support of multiple devices in the same interface, providing high flexibility.

The code made for Player can be simulated in a virtual environment thanks to the Stage simulation tool, in which the robot and the rest of the environment are simulated in a 2D representation. There are several advantages simulating the code before implement it on physical systems. Here are some of them:

- Evaluating, predicting and monitoring the behavior of robot.
- Fastening error finding the implemented control algorithm.
- Reducing testing and development time.
- Avoiding robot damage and operator injures due to control algorithm failure, which indirectly reducing robot repair cost and medical cost.
- Offering data access that is hard to be measured on real mobile robot.
- Allowing testing on several kinds of mobile robots without need of significant adaptation of the implemented algorithm.
- Easy switching between a simulated robot and a real one.
- Providing high probability of getting success when implemented on real robot if the algorithm tested in simulation is proved to be successful.

The communication protocol between the parts of the system is made via TCP protocol, as shown in figure 2.1

Player uses a Server/Client structure in order to pass data and instructions the user's code the robot's hardware or the simulated robots. Player is a server, and a device on the robot (real or simulated) is subscribed as a client to the server via a thing called a proxy. This concepts will be explained in depth in the next sections.

2.2 Player, network server

Player is a *Hardware Abstraction Layer*. It communicates with the devices of the robot, such as ranger sensors, motors or camera via an IP network, and allows the user's code to control them, saving the user all the robot's work. The code communicates with the

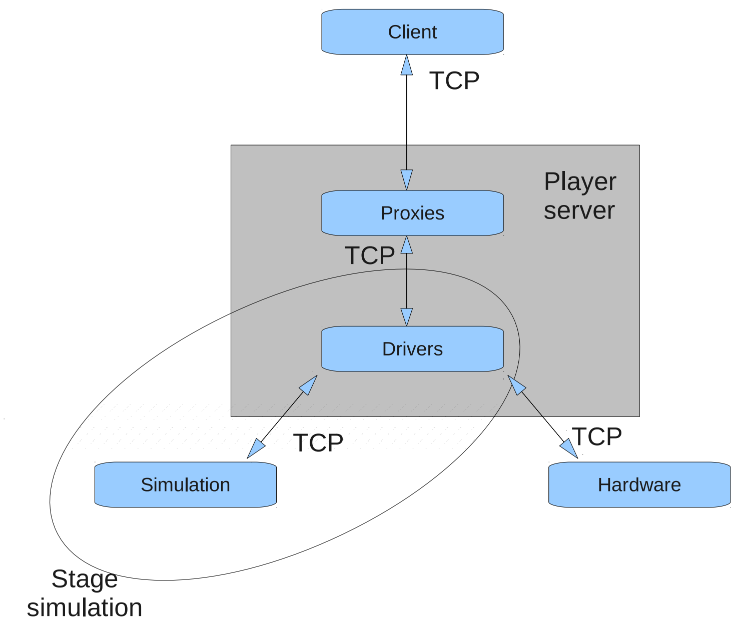


Figure 2.1: *The server/client control structure of Player/Stage when used as a simulator or in physical robots*

robot via a TCP socket, sending data to the actuators and receiving it from the sensors. Simplifying, it can be said that Player gets the code made by the user in the chosen programming language (Player Client), "translate" it into orders that the robot and its devices can understand and send them to the mentioned devices (Player Server).

The communication protocol used by Player can be seen in figure 2.2. The process works as follows.

Firstly, the Player client establishes communication with the server (step 1). As has been said, there are different connection points for each robot and devices, so the client has to say the server which ones want to use (step 2). All this "dialogue" is made through a TCP socket.

Once the communication is established and the devices are subscribed, it starts a continuous loop, where the server sends data received from the sensors to the program and the client sends orders to the actuators. This endless loop happens at high speed, providing a fast robot response and allowing the code to behave in the expected way, trying to minimize the delays.

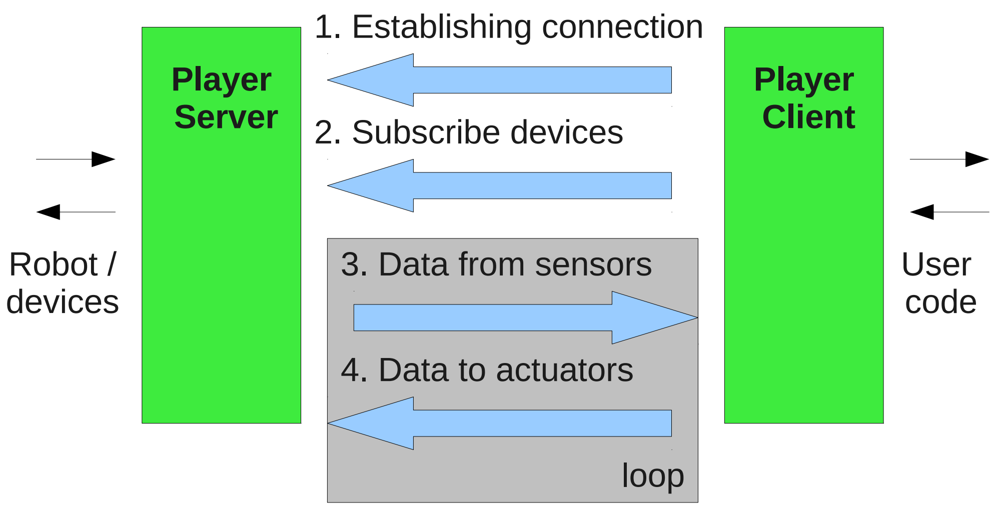


Figure 2.2: *Player communication protocol*

2.3 Stage, robot platform simulator

Stage is a simulation software, which together with Player recreates mobile robots and determined physical environments in two dimensions. Various physics-based models for robot sensors and actuators are provided, including sonar, laser range finder, camera, colour blob finder, fiducial tracking and detection, grippers, odometry localization . . .

Stage devices are usually controlled through Player. Stage simulates a population of devices and makes them available through Player. Thus, Stage allows rapid prototyping of controllers destined for a real robot without having a physical device.

In figure 2.3 there is an example of some robots moving and interacting in a simulated environment.

2.4 Gazebo, three dimensional simulator

The Player/Stage suite is completed with the 3D environment simulator Gazebo. Like Stage, it is capable of simulating a population of robots, sensors and objects, but does so in a three-dimensional world. It generates both realistic sensor feedback and physically plausible interactions between objects [Gaz].

Client programs written using one simulator can be used in the other one with little or no modification. The main difference between these two simulators is that while Stage is

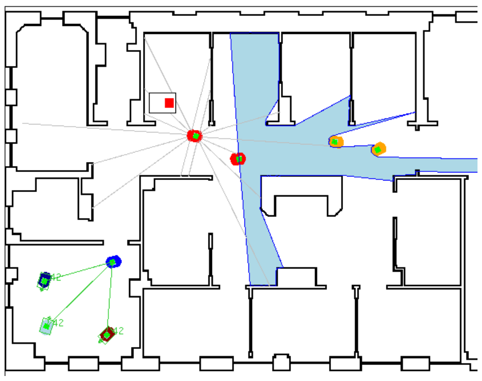


Figure 2.3: *Snapshot of a Stage simulation*

designed to simulate a very large robot population with low fidelity, Gazebo is designed to simulate a small population with high fidelity.

Figure 2.4 shows how a Gazebo environment looks like.

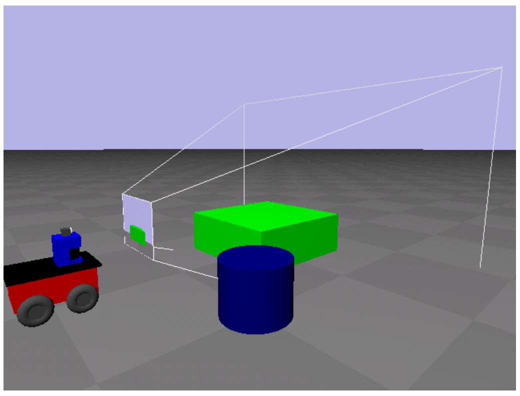


Figure 2.4: *Snapshot of a Gazebo simulation*

2.5 Player/Stage tools

In this section, the main features and tools provided by Player/Stage will be explained, like the *playerv* sensor visualization tool, client libraries, proxies and some Stage tools.

2.5.1 Sensor visualization: *playerv*

Player provides a sensor visualization tool called *player viewer* (*playerv*), which gives the possibility of visualization of the robot sensors, both in simulation and in real robots.

Let's explain how playerv works with a simulated robot. Once Player opens the configuration file (explained in 2.6), the application is "listening" for any program or code. After that, the program can be opened typing in shell (if working in Linux) the next command:

-$ *playerv*

Then, a window is opened, where all the available devices can be shown, and even the robot can be moved through the environment if the position device is subscribed. For instance, figure 2.5 shows a robot in which the sonar device is subscribed. In this case, only one robot is used, calling then *playerv* the default port 6665. If there were more robots, the ports wanted to call each robot should be specified in the configuration file, as shown in the next example.

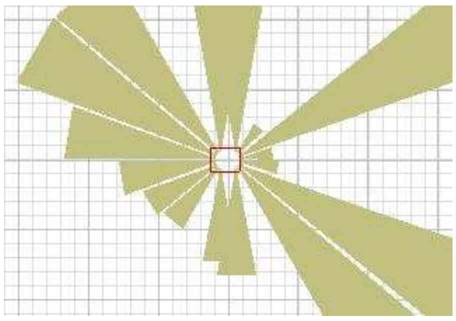


Figure 2.5: *Player viewer visualization tool*

```
driver
  (
  name "stage"
  provides ["6665:position2d:0" "6665:laser:0" "6665:sonar:0"]
  model "robot"
  )
```

The driver is called "stage" because it is calling a simulated robot using the 6665 port, which has position control, laser and sonar sensors. The name of the model is "robot". Now, if one wants to visualize this specific robot, the line to type in shell is:

-$ *playerv -p 6665*

With “*-p 6665*”, we are telling player that the device to use is the one defined in the configuration file in the port 6665. Therefore, if more robots are needed, they can be defined with the successive port numbers *6666*, *6667* . . .

The above mentioned shell commands are used in simulated environments. For using *playerv* in real robots, slightly different changes should being made. The configuration file should be adequate for its use in physical systems and have to be run in the robot. The shell line to type while Player is “listening” presents this aspect:

-$ *playerv -h robotIP*

With this command *playerv* is run in a host (hence *-h*) which IP number is *robotIP*. Hence, the robot devices actions and measurements can be monitored in the same way than in the simulation, presenting a similar presentation as in figure 2.5.

2.5.2 Client libraries

When using the Player server (whether with hardware or simulation), client libraries can be used to develop the robot control program. Libraries are available in various languages to facilitate the development of TCP client programs.

There are three available libraries, although more third-party contributed libraries can be found at [lib].

- ***libplayerc***, library for C language
- ***libplayerc_py***, library for Python
- ***libplayerc++***, library for C++

As the code use for develop the algorithms is c++, the library used was *libplayerc++*.

2.5.3 Proxies

The C++ library is built on a ”service proxy” model in which the client maintains local objects that are proxies for remote services. There are two kinds of proxies: the special server proxy PlayerClient and the various device-specific proxies. Each kind of proxy is implemented separately. The user first creates a *PlayerClient* proxy and uses it to establish a connection to a Player server. Next, the proxies of the appropriate device-specific types are created and initialized using the existing PlayerClient proxy. There are thirty-three different proxies in the version used for this dissertation (2.1.2), but it have been used only three of them: *PlayerClient* proxy, *Position2d* proxy and *Laser* proxy.

PlayerClient proxy is the base class for all proxy devices. Access to a device is provided by a device-specific proxy class. These classes all inherit from the *Client* proxy class which defines an interface for device proxies.

2.5.3.1 Position2d proxy

The class Position2dProxy is the C++ proxy in Player which handles robots position and motion. It calculates the X, Y positions and angle coordinates of the robot and returns position information according to the client programs demands. The odometry system takes negative angles clockwise and positive counter-clockwise, as can be seen in the odometry coordinate system in fig 2.6.

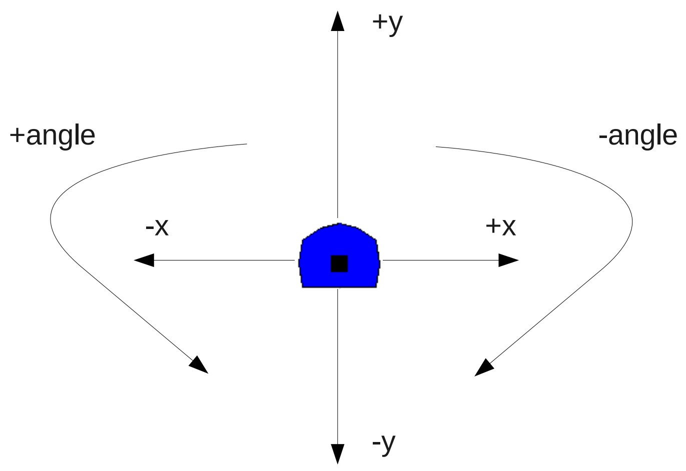


Figure 2.6: *Odmetry coordinate system*

Hereafter some of the main commands available in the proxy are shown.

ResetOdometry() Reset odometry to (0,0,0) Although this command could be very useful when working with global/local coordinates, it has been proved not to work properly, specially in physical robots.

SetOdometry (double aX, double aY, double aYaw) . Sets the odometry to the pose (x, y, yaw). In the same way as *ResetOdometry*, this function does not work in a good way, being then usefulness.

GetXPos Get current X position.

GetYPos Get current Y position.

GetYaw Get current angular position.

SetSpeed(Xspeed, YawSpeed) Send commands to motor with linear and angular speed.

As it will be seen in the chapter 5.3, GetYaw function will be a key function for the success of the algorithm.

2.5.3.2 Laser proxy

One of the most important proxies used to develop this thesis algorithms is the *LaserProxy* provided by Player. In fact, is the only way the robot has to interact with the environment. It plays major role in wall following and collision avoiding processes, as well as in robot following algorithm. Player provides standard set of commands to control LaserProxy data such as:

GetCount() Get the number of points scanned.

GetMaxRange() Maximum range of the latest set of data, in meters.

GetRange(Index) Get the range of the beam situated in the "Index" position.

GetBearing(Index) Get the angle of the beam situated in the "Index" position.

The main properties of the laser device will be explained in chapter 3.

2.5.4 Stage tools

Stage provides a graphical interface with the user (GUI) for watching the proper working of the simulation developed in Player. To simplify this work, Stage provides some tools.

The environment where the robots are operating in Stage is called "world", these "worlds" are bitmap files. So, these files can be created and changed with any drawing software.

All the white spaces will be considered as open spaces while different colors are considered as obstacles or walls.

It is possible to zoom by clicking the right mouse button and moving in any part of the map. A circumference in the middle of the map will appear. By dragging the mouse towards the centre "zoom in" will be achieved and, by reversing this operation, "zoom out" will be performed. With the left-click in any part of the map it is possible to move the map "Up-Down-Right-Left" accordingly.

Also it is possible to change the robot position by dragging the robot with the left mouse button; and changing its orientation with the right button. Besides the aforementioned, it is possible to save an image of the current display of the map. *Select File→Screenshot→Single Frame*. To save an image sequence with a fixed interval, use the option *File→Screenshot→Multiple Frames* selecting previously the interval duration in the same menu. The image is saved in the current working directory.

Other useful menu options can be found in the tab "view", for example, it is possible to represent the grid, view the path taken by the robot with the option *Show trails* (useful to identify where the robot has been before), view the robot position lines projected on the global frame of reference, view velocity vectors, display laser data and so on.

2.6 Programming in Player

This section is an overview about the different files present on a Player/Stage project. These are:

- World files (*.world*)
- Configuration files (*.cfg*)
- Make files
- Include files (*.inc*)
- *.h* files
- Main program file
- Bitmaps

Some of this files will be explained in the next sub-sections.

2.6.1 World file

The .world file tells Player/Stage what things are available to put in the simulated world. In this file the user describes the robots, any items which populate the world and the layout of the world. Parameters such as resolution and time step size are also defined. The *.inc* file follows the same syntax and format of a *.world* file but it can be included. So if there is an object in the world wanted to be used in other worlds, such as a model of a robot, putting the robot description in a *.inc* file just makes it easier to copy over, it also means that if a robot description is wanted to be changed, then the only thing needed to do is to change it in one place and your multiple simulations are changed too.

2.6.2 Configuration file

The *.cfg* file is what Player reads to get all the information about the robot. This file tells Player which drivers it needs to use in order to interact with the robot, if the user is using a real robot these drivers are built in to Player , alternatively, if the user wants to make a simulation, the driver is always Stage. The *.cfg* file tells Player how to talk to the driver, and how to interpret any data from the driver so that it can be presented into the user code.

Items described in the *.world* file should be described in the .cfg file if the user wants the code to be able to interact with those item (such as a robot), if the code is not needed to interact with the item then this is not necessary. The *.cfg* file does all this specification using interfaces and drivers.

For each driver we can specify the following options:

name: The name of a driver to instantiate, (required).

plugin: The name of a shared library that contains the driver, (optional).

provides: The device address or addresses through which the driver can be accessed. It can be combination of strings (required).

requires: The device address or addresses to which the driver will subscribe. It can be a combination of strings, (optional).

An simple example of this is shown below:

2.6.3 Makefile

```
driver
(
name ‘‘stage’’
provides [‘‘6665:position:0’’
 ‘‘6665:sonar:0’’
 ‘‘6665:blobfinder:0’’
 ‘‘6665:laser:0’’]
)
```

Once the Player/Stage files are ready, the client code should be compiled in order to create the executable file to run. For that purpose, the following line should be typed in shell:

```
g++ -o example ‘pkg-config --cflags playerc++‘ example.cc ‘pkg-config
--libs playerc++‘
```

That will compile a program to a file called example from the C++ code file example.cc.

2.6.4 Main program file

This file is the main code that the user wants to run through Player into the physical systems or in the simulation. It can be written into C, C++, or Python, as it was explained in the above sections.

All programs follows the same structure, as the one shown below. It’s also the similar than in the behaviour explained in 2.1.

```
int main (int argc, char **argv)
{
    // ESTABLISH CONNECTION
    PlayerClient robot(gHostname, gPort);

    // INSTANTIATE DEVICE
    LaserProxy lp(&robot,0);
    PositionProxy pp(&robot,0);
    While(1)
    {
      // DATA ACQUISITION
      robot.Read();

      // PROCESS DATA
      // send command
    }
}
```

In first place, the *PlayerClient* subscribes a device called robot, with *gHostaname* adress and situated in the port *gPort*. Secondly, the sensors and devices of the robot are subscribed as well, in this case Laser and Position proxies. Then starts the think-act-loop, where the code interacts with the different devices. With the *robot.Read* command, the data from the robot is acquired, and after being processed the orders to the actuators are sent.

2.7 Running program

This section explains how to run the client code into the Stage simulation or in physical robot.

Stage simulation

For run the client code into a Stage simulation, the first thing is to open the *configuration file* on a shell. This file should be linked to the *.world* file, where the simulation objects are defined. Once this is done, Player is listening for any binary file to be executed. This file is generated from the main client file (in this this case, from a *.cc* file) as explained in the section 2.6.3. The only thing to is do is run it using the syntax *./file*. After that, the code would be run in the simulated world.

Physical robot

Te process for run the client code into physical systems is slightly different. The way here explained is for the Khepera robots used in this project. The first thing that should be done is connect the computer with the robot or robots via wireless. Once the link is established, a secure connection is made from the computer to the robot via SSH [BSB05]. Once inside the robot, the *configuration file* should be run (notice that this file will be different than the ones for simulations). Then, the robot will be "listening" for any program do be run. So, the user should run it from a shell window in its computer, specifying the IP of the robot, as said in the previous sections.

Chapter 3

Robot and laser characteristics

3.1 Introduction

This chapter explains the main features and characteristics of the robot utilized for accomplish this project. The robots are Khepera III, from the Swiss company K-Team [kte] and the laser used is the Hokuyo URG-04LX Laser, from the Japanese company Hokuyo Automatic Co.,LTD [Hok].

3.2 Khepera III

The Khepera III is a small differential wheeled mobile robot(3.1). Features available on the platform can match the performances of much bigger robots, with a upgradable embedded computing power using the KoreBot system, multiple sensor arrays for both long range and short range object detection, swappable battery pack system for optimal autonomy, and differential drive odometry. The Khepera III architecture provides exceptional modularity, using an extension bus system for a wide range of configurations.

The robot base can be used with or without a KoreBot II board. Using the KoreBot II, it features a standard embedded Linux Operating System for quick and easy autonomous application development. Without the KoreBot II, the robot can be remotely operated, and it is easily interfaced with any Personal Computer. Remote operation programs can be written with Matlab, LabView, or with any programming language supporting serial

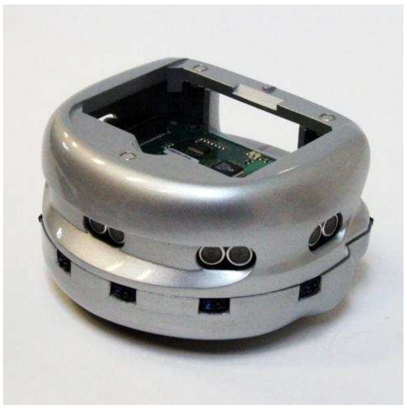
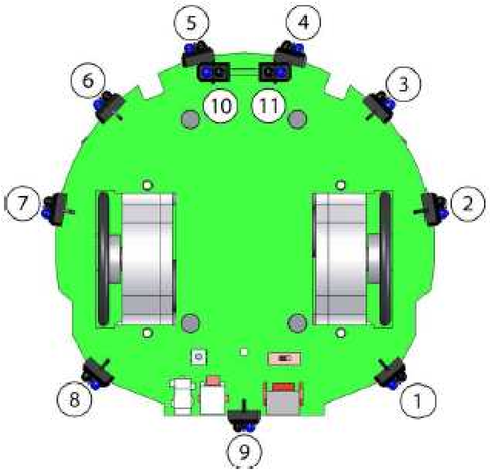


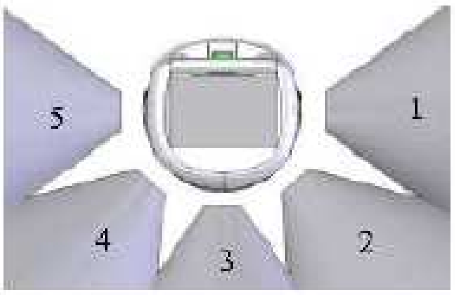
Figure 3.1: *Khepera III robot*

port communication. In this project, the robot was used with the KoreBot board, so that the configuration files were run on it, thanks to its embedded Linux.

The robot base includes an array of 9 infrared Sensors for obstacle detection (figure 3.2,a) as well as 5 ultrasonic Sensors for long range object detection (figure 3.2,b). It also proposes an optional front pair of ground Infrared Sensors for line following and table edge detection. The robot motor blocks are Swiss made quality mechanical parts, using very high quality DC motors for efficiency and accuracy. The swappable battery pack system provides an unique solution for almost continuous experiments, as an empty battery can be replaced in a couple of seconds.



a) Infrared



b) Sonar

Figure 3.2: *Ranger sensor of the Khepera III robots*

Processor	DsPIC 30F5011 at 60MHz
RAM	4 KB on DsPIC, 64 MB KoreBot Extension
Flash	66 KB on DsPIC, 32MB KoreBot Extension
Motion	2 DC brushed servo motors with incremental encoders (∼22 pulses per mm of robot motion)
Speed	Max: 0.5 m/s
Sensors	11 infrared proximity and ambient light sensors 5 Ultrasonic sensors with range 20cm to 4 meters
Power	Power Adapater Swapable Lithium-Polymer battery pack (1400 mAh)
Communication	Standard Serial Port, up to 115kbps USB communication with KoreBot Wireless Ethernet with KoreBot and WiFi card
Size	Diameter: 130 mm Height: 70 mm
Weight	690 g

Table 3.1: *Khepera III characteristics*

Trough the KoreBot II, the robot is also able to host standard Compact Flash extension cards, supporting WiFi, Bluetooth, extra storage space, and many others.

Some of the Khepera III features:

- Compact
- Easy to Use
- Powerful Embedded Computing Power
- Swapable battery pack
- Multiple sensor arrays
- KoreBot compatbible Extension bus
- High quality and high accuracy DC motors

3.2.1 Characteristics

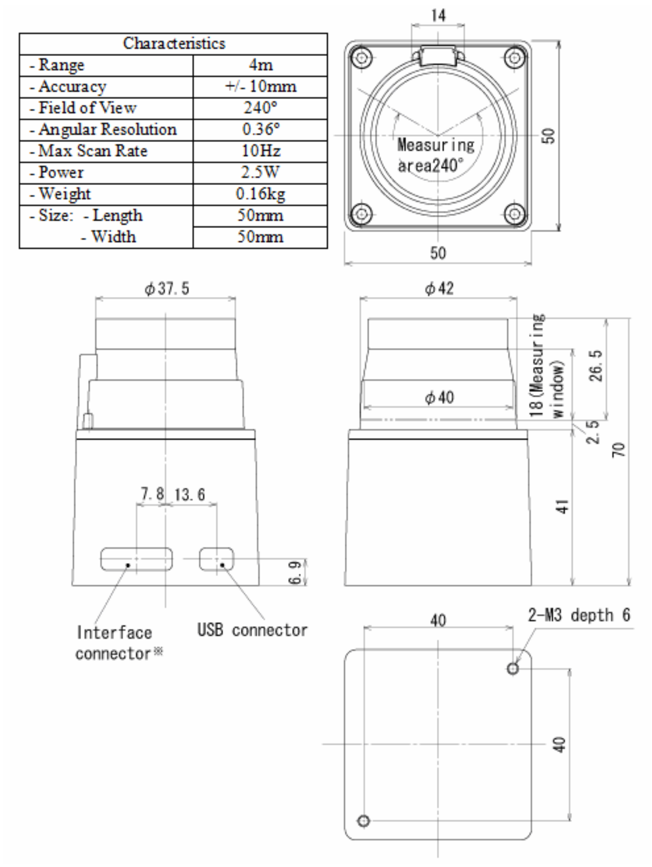
The specifications of Khepera III robot are shown in table 3.1. Further information can be found on the “Khepera III user manual”, version 2.2 [FG].

3.3 Hokuyo URG-04LX Laser

A laser ranger is an optional component which can be added to the Khepera robot, and gives reliable and precise length measurements. This device mechanically scans a laser beam, producing a distance map to nearby objects, and is suitable for next generation intelligent robots with an autonomous system and privacy security. The URG-04LX is a lightweight, low-power laser rangefinder.

3.3.1 Characteristics

This sensor offers both serial (RS-232) and USB interfaces to provide extremely accurate laser scans. The field-of-view for this detector is 240 degrees and the angular resolution is 0.36 degrees with a scanning refresh rate of up to 10Hz. Distances are reported from 20mm to 4 meters. Power is a very reasonable 500mA at 5V. Some of its characteristics, features and its physical dimensions scheme are shown in figure 3.3.



Characteristics	
- Range	4m
- Accuracy	+/- 10mm
- Field of View	240°
- Angular Resolution	0.36°
- Max Scan Rate	10Hz
- Power	2.5W
- Weight	0.16kg
- Size: - Length	50mm
- Width	50mm

Figure 3.3: *Laser characteristics*

More info can be found in [Hok08], [Hl].The Laser range finder covers a range of 240 degrees. Note that the angles are measured positive counter clockwise and negative in clockwise. The 120 degrees of area covering back side of the robot is considered as the blind area as the laser does not operate in that area. Figure 3.4 shows the scheme of the laser range.

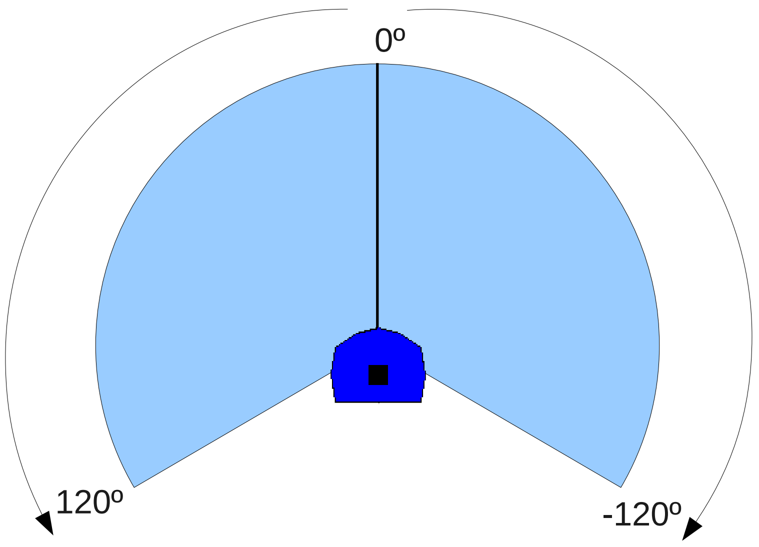


Figure 3.4: *Field of view of the laser*

3.4 Robot with laser

The Hokuyo URG-04LX laser is connected to the Khepera III robot via USB. In the configuration file that should be open in the Khepera, there is an instantiation of the laser driver, as shown below:

```
driver
(
   name "urglaser"
   provides ["laser:0"]
   port "/dev/ttyACM0"
)
```

It accesses a device called *urglaser*, which provides a laser ranger connected in the route */dev/ttyACM0*. The whole configuration file is shown in the appendix A.

The resultant robot-laser system can be seen in figure 3.5.

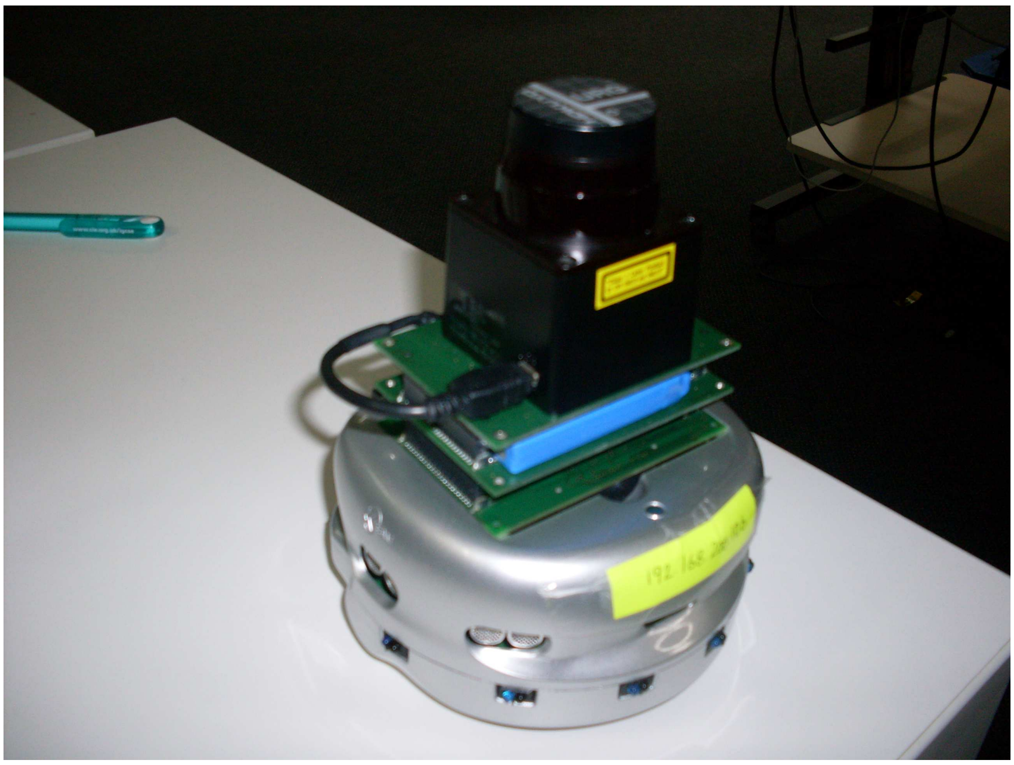


Figure 3.5: *Khepera III robot with laser range finder*

Chapter 4

Literature and review

4.1 Introduction

This chapter contains a brief discussion over some basic technologies and other related projects and researches worked by other parties to make a foundation of the main objectives of this dissertation, which are multi-robot behaviours for different tasks such as wall following, obstacle avoidance and robot following.

4.2 Wall following

The goal of wall following robot behaviour is to navigate through open spaces until it encounters a wall, and then navigate along the wall at some fairly constant distance. The successful wall follower should traverse the entire environment at least once without straying either too close, or too far from the walls. The following subsections show different approaches to de problem by using different kind of sensors.

4.2.1 Artificial vision

The idea of the artificial vision approach comes from source [DRGQ07]. A visual and reactive wall following behaviour can be learned by reinforcement. With artificial vision the environment is perceived in 3D, and it is possible to avoid obstacles that are invisible to other sensors that are more common in mobile robotics. Reinforcement learning reduces the need for intervention in behaviour design, and simplifies its adjustment to the environment, the robot and the task. In order to facilitate its generalization to other behaviours and to reduce the role of the designer, it can be used a regular image-based codification of states. Even though this is much more difficult, its implementation converges and is robust.

4.2.2 Neuro-fuzzy controllers

Neuro-fuzzy refers to combinations of artificial neural networks and fuzzy logic. In [SKMM10], an intelligent wall following system that allows an autonomous car-like mobile robot to perform wall following tasks is used. Soft computing techniques were used to overcome the need of complex mathematical models that are traditionally used to solve autonomous vehicle related problems. A neuro-fuzzy controller is implemented for this purpose, which is designed for steering angle control, and is implemented with the use of two side sensors that estimate the distance between the vehicle front side and the wall, and the distance between the vehicle back side and the wall. These distances get then inputted to a steering angle controller, which as a result outputs the appropriate real steering angle. A neuro fuzzy controller overcomes the performance of the previously implemented fuzzy logic based controller, and significantly reduces the trajectory tracking error, but at the expense of using more DSP resources causing a slower throughput time. This autonomous system can be realized on an FPGA platform, which has the advantage of making the system response time much faster than software-based systems.

4.2.3 Emitting signal sensor

In [Jon] is presented a set consisting of a robot obstacle detection system which navigates with respect to a surface and a sensor subsystem aimed at the surface for detecting the surface. The sensor subsystem includes an emitter which sends out a signal having a field of emission and a photon detector having a field of view which intersects with that field of emission at a region. The subsystem detects the presence of an object proximate to the mobile robot and determines a value of a signal corresponding to the object. It compares the obtained value to a predetermined value, moves the mobile robot in response to the comparison, and updates the predetermined value upon the occurrence of an event.

4.2.4 Autonomous robots

Autonomous robots are electromechanical devices that are programmed to achieve several goals. They are involved in a few tasks such as moving and lifting objects, gathering information related to temperature and humidity, and follow walls. From a system's engineering point of view, a well designed autonomous robot has to be adaptable enough to control its actions. In addition, it needs to perform desired tasks precisely and accurately. The source of this idea is in the paper [Meh08]. The robot follows a wall using a PIC 18F4520 microcontroller as its brain. PIC 18F4520 receives input from Ultrasonic Distance Meter (UDM). Some computations are performed on this input and a control signal is generated to control the robot's position. This control signal is generated through a PD (Proportional and Derivative) controller, which is implemented in the microcontroller. Afterwards, microcontroller is programmed in C language using a CCS (A Calculus of Communicating Systems) compiler.

4.2.5 3D Laser Rangefinder

The technical report [MA02] shows a technique for real-time robot navigation. Off-line planned trajectories and motions can be modified in real-time to avoid obstacles, using a reactive behaviour. The information about the environment is provided to the control system of the robot by a rotating 3D laser sensor which have two degrees of freedom. Using this sensor, three dimensional information can be obtained, and can be used simultaneously for obstacle avoidance, robot self-localization and for 3D local map building. Obstacle avoidance problem can also be solved with this kind of sensor. This technique presents a great versatility to carry out typical tasks such as wall following, door crossing and motion in a room with several obstacles.

4.2.6 Odometry and range data

In [BPC02], an enhanced odometry technique based on the heading sensor called "clino-gyro" that fuses the data from a fibre optic gyro and a simple inclinometer is proposed. In the proposed scheme, inclinometer data are used to compensate for the gyro drift due to rollpitch perturbation of the vehicle while moving on the rough terrain. Providing independent information about the rotation (yaw) of the vehicle, clino-gyro is used to correct differential odometry adversely affected by the wheel slippage. Position estimation using this technique can be improved significantly, however for the long term applications it still suffers from the drifts of the gyro and translational components of wheel skidding. Fusing this enhanced odometry with the data from environmental sensors (sonars, laser range finder) through Kalman filter-type procedure a reliable positioning can be obtained. Obtained precision is sufficient for navigation in underground mining drifts. For open-pit mining applications further improvements can be obtained by fusing proposed localization algorithm with GPS data

4.3 Obstacle avoidance

The obstacle avoidance algorithm is one of the basic and common behaviour for almost every autonomous robot systems. Here are shown some approaches to this problem.

4.3.1 Fuzzy control

Fuzzy control algorithms are used sometimes for obstacle avoidance behaviour [JXZQ09]. Autonomous obstacle avoidance technology is a good way to embody the feature of robot strong intelligence in intelligent robot navigation system. In order to solve the problem of autonomous obstacle avoidance of mobile robot, an intelligent model is used. Adopting multisensor data fusion technology and obstacle avoidance algorithm based on fuzzy control, a design of intelligent mobile robot obstacle avoidance system is obtained. The perceptual system can be composed of a group of ultrasonic sensors to detect the surrounding environment from different angles, enhancing the reliability of the system on the based of redundant data between sensors, and expanding the performance of individual sensors with its complementary data. The processor receives information from perceptual system to calculate the exact location of obstructions to plan a better obstacle avoidance path by rational fuzzy control reasoning and defuzzification method.

4.3.2 Probabilistic approach

In this approach, emerged after consult [BLW06], autonomous vehicles need to plan trajectories to a specified goal that avoid obstacles. Previous approaches that used a constrained optimization approach to solve for finite sequences of optimal control inputs have been highly effective. For robust execution, it is essential to take into account the inherent uncertainty in the problem, which arises due to uncertain localization, modelling errors, and disturbances.

Prior work has handled the case of deterministically bounded uncertainty. This is an alternative approach that uses a probabilistic representation of uncertainty, and plans the future probabilistic distribution of the vehicle state so that the probability of collision with obstacles is below a specified threshold. This approach has two main advantages; first, uncertainty is often modelled more naturally using a probabilistic representation (for example in the case of uncertain localization); second, by specifying the probability of successful execution, the desired level of conservatism in the plan can be specified in a meaningful manner.

The key idea behind the approach is that the probabilistic obstacle avoidance problem can be expressed as a Disjunctive Linear Program using linear chance constraints. The resulting Disjunctive Linear Program has the same complexity as that corresponding to the deterministic path planning problem with no representation of uncertainty. Hence the resulting problem can be solved using existing, efficient techniques, such that planning with uncertainty requires minimal additional computation.

4.3.3 Camera

Other interesting approach for obstacle avoidance is the use of a a vision based system using a camera [WKPA08]. The technique is based on a single camera and no further sensors or encoders are required. The algorithm is independent of geometry and even moving objects can be detected. The system provides a top view map of the robot's field of view in realtime. First, the images are segmented reasonably. Ground motion estimation and stereo matching is used to classify each segment either belonging to the ground plane or belonging to an obstacle. The resulting map is used for further navigational processing like obstacle avoidance routines, path planning or static map creation.

4.4 Robot following

Here are some ideas and theories found about robot following formation.

4.4.1 Attraction-repulsion forces

The background of this section comes from the source [BH00], where the main idea of applying the potential functions is developed.

A potential function is a differentiable real-valued function $U : \Re^m \to \Re$, in our case m will be equal to 1. The value of a potential function can be viewed as energy and therefore the gradient of the potential is force. The gradient is a vector which points in the direction that locally maximally increases U.

There is a relationship between work and kinetic energy. Work is defined in physics as the result of a force moving an object a distance ($W = Fd$). But the result of the force being applied on the object also means that the object is moving with some given velocity ($F = ma$). From those two equations, it can be shown that work is equivalent to kinetic energy: $UKE = \frac{1}{2}mv^2$. When U is energy, the gradient vector field has the property that work done along any closed path is zero.

4.4.2 Selfmade follower

This idea come from [FFB05]. In this approach, the control law of the follower robot includes the states of the leader robot. This is a drawback for implementing the control laws on real mobile robots. To overcome this drawback, a new follower's control law is purposed, called the self-made follower input, in which the state of the leader robot is estimated by the relative equation between the leader and the follower robots in the discrete-time domain. On the other hand, a control law of the leader robot is designed with a chained system to track a given reference path.

4.5 Localization problem

For numerous tasks a mobile robot needs to know "where it is" either at the time of its current operation or when specific events occur. The Localization problem can be divided mainly in to two sub sections, Strong Localization and Weak Localization [GM00]. Estimating the robots position with respect to some global representation of space is called Strong Localization. The Weak Localization is mainly based on the correspondence problem, and in this case complete qualitative maps can be constructed using Weak Localization.

There are many approaches to solve localization problem such as dead reckoning, simple landmark measurements, landmark classes, Triangulation, and Kalman filtering [GM00]. There are many researches dedicated to investigate on robot localization such as Monte Carlo, the bounded uncertainty approach, and by using Bayesian statistic. Basically the Bayesian approach is the widely used robot localization method. Not only for the localization, but also for building maps the Bayesian rule is widely used.

4.5.1 Odometry Sensors

Mobile robots often have odometry sensors; them calculate how far the robot has traveled based on how many wheel rotations took place. These measurements may be inaccurate due to many reasons such as wheel slipping, surface imperfections, and small modeling errors. For example, suppose a bicycle wheel of a 2 meter circumference has turned 10 revolutions, then the odometry reading is 10 and the calculated answer would be 20m.

Some of the problems of the odometry sensors can be listed as below:

- Weak supposition (Slide errors, accuracy, etc)

- Methodical errors
    - Different wheel diameter problems
    - Wheel alignment problems
    - Encoders resolution and sampling problems
- Non-Systematic errors
    - Wheel Slides problems
    - Floor Roughness problems
    - Floor Object problems

4.5.2 Laser range finders

Laser scanners mounted on mobile robots have recently become very popular for various indoor robot navigation tasks. Their main advantage over vision sensors is that they are capable of providing accurate range measurements of the environment in large angular fields and at very fast rates [BAT03]. Laser range finders are playing a great role not only in 2D map building but in 3D map building too. The laser range finder sensor data can be also used for variety of tasks such as wall following and collision avoiding. There are many projects and research work have used laser range finders. The efficiency and the accuracy of the laser range finder depends on many factors such as: transmitted laser power, carrier modulation depth, beam modulation frequency, distance from the target, atmospherics absorption coefficient, target average reflectivity, collecting efficiency of the receiver, and pixel sampling time [BBF+00].

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Chapter 5

Robot behaviour algorithms and theory

5.1 Introduction

This chapter describes the algorithms developed for the implementation of the robot´behaviour. This work was carried once understood the operation of Player/Stage and after the research and investigation stage. With all the collected information, the developing of the code started, using structured *C++* language.

Section 5.2 shows the algorithms developed for the leader robot, which are **obstacle avoidance** and **wall following**, with their respective sub-functions. All the codes are first tried in a Stage simulation to determine their reliability and accuracy and to detect and solve any problems or errors.

Section 5.3 is where the follower robot related algorithms are shown. These algorithms can be divided in two groups: **robot following** and **obstacle avoidance**. For the robot following algorithm, first it was made a code assuming there is no environment, just the leader and the follower robots. After, it was improved for make the robot to move in a environment with walls and obstacles. As with the leader algorithms, here all the codes were first simulated in Stage, and after implemented in the Khepera III robots.

All the code generated for make the algorithms and also the Player/Stage configuration and world files are shown in the appendixes, at the end of this document.

5.2 Leader robot

This section explains the main solutions taken for implement the leader robot algorithms. They can be divided into obstacle avoidance algorithms and wall following algorithms. The only proxies used for these task are *Position2dProxy* and *LaserProxy*.

5.2.1 Obstacle avoidance

This part of the program is maybe the basic behaviour of the robot, because if it fails, the robot can crash and suffer important damages. Then, it is important its correct performance for the development of further algorithms.

The main idea of this algorithm is based in the measures taken by the laser ranger. It is constantly scanning and taking samples of the environment, detecting the obstacles around them and their distance to the robot. If this distances are smaller than a determined value (set by the user), then the robot is too close to an obstacle and it has to stop or change its direction.

For accomplish that, the field of view of the robot was divided in three part, as seen in the figure 5.1.

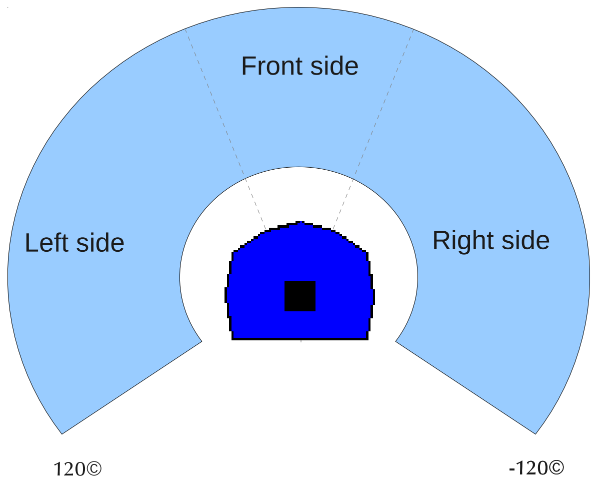


Figure 5.1: *Division of laser sensor*

It can be seen that the frontal field of view defined is not very wide, otherwise the robot would have problems when entering narrow corridors or small spaces. The pseudo code of the function is the following.

```
  for all laser scans do
    if the obstacle is in the right part and closer than detection distance then
      sum right part;
      if new measure is smaller than the minimum, save new minimum;
    end if
    if the obstacle is in the central part and closer than detection distance then
      sum central part
      if new measure is smaller than the minimum, save new minimum;
    end if
    if the obstacle is in the left part and closer than detection distance then
      sum right part
      if new measure is smaller than the minimum, save new minimum;
    end if
  end for

calculate left mean;
calculate right mean;

  if left mean < right mean and minimum < stop distance then
    turn right
  end if
  if right mean < left mean and minimum < stop distance then
    turn left
  end if
```

The laser take measures of all the scans. When one measure is smaller than a defined distance, a counter is increased (there is one counter for each of the three areas) and if the measure is the minimum of those recorded in one area, it saves a new minimum value. When the scan has finished, it compares the values of both left and right sides. Those with a bigger counter value means that the obstacle is closer in that side. Then, if the minimum distance is smaller than the stop distance, change direction.

Results

The results of the implementation of this functions in simulation are shown in the figure 5.2. The grey traces show the path taken by the robot. It can be seen how it turns when it founds and obstacle on its way.

This algorithm is the most simple, but is the basis of the whole code. Next is to add the wall following algorithm to the code.

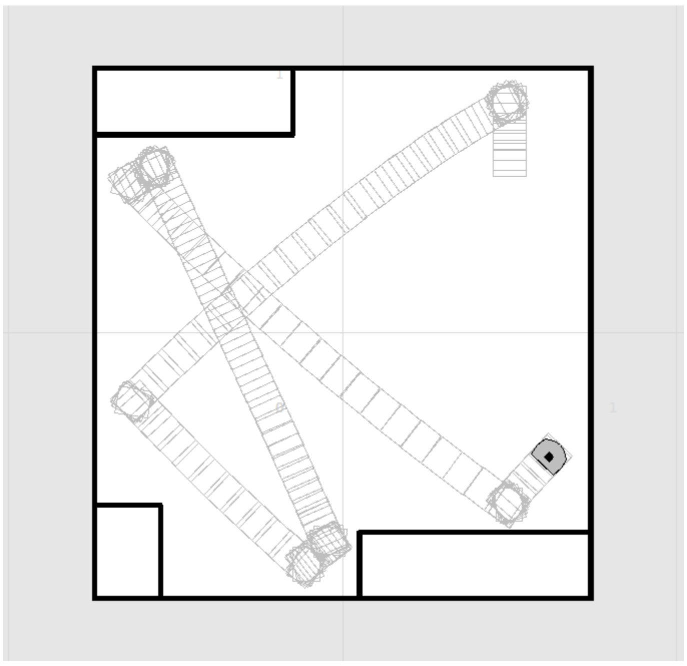


Figure 5.2: *Obstacle avoidance behaviour*

Search	The robot goes straight looking for a wall
Wall follow	Transit state. It decides which direction to turn
Left	The robot follows a wall on its left
Right	The robot follows a wall on its right

Table 5.1: *Wall following modes*

5.2.2 Wall following

The objective of this algorithm is to find a wall and follow it in a parallel way, keeping a certain constant distance to it. At the same time, the avoid obstacle will be active at the same time, avoiding the robot to crash when the wall changes its slope. The approach made for keep the constant distance to the wall is calculating the angle with respect to the wall.

The movement of the robot is based in four behaviour modes, which depends of the laser measures and the previous mode, as seen in the table 5.1

The transit between the different modes are explained in the flow diagram on figure 5.3. When the code starts running, the robot is in mode SEARCH. The motors are enabled and it starts going straight until any laser scan distance is smaller than the detection distance, which in our case and due to the fact that the program will be implemented in Khepera systems (considered as small robots) is 25 centimetres. When this happens, the robot mode changes to WALL FOLLOW, which calculates in which side it has more free space to turn, and then takes RIGHT or LEFT MODE, depending in which side of the robot is the wall to follow. Finally, if the robot loses the wall, the mode is changed to SEARCH and the process starts again.

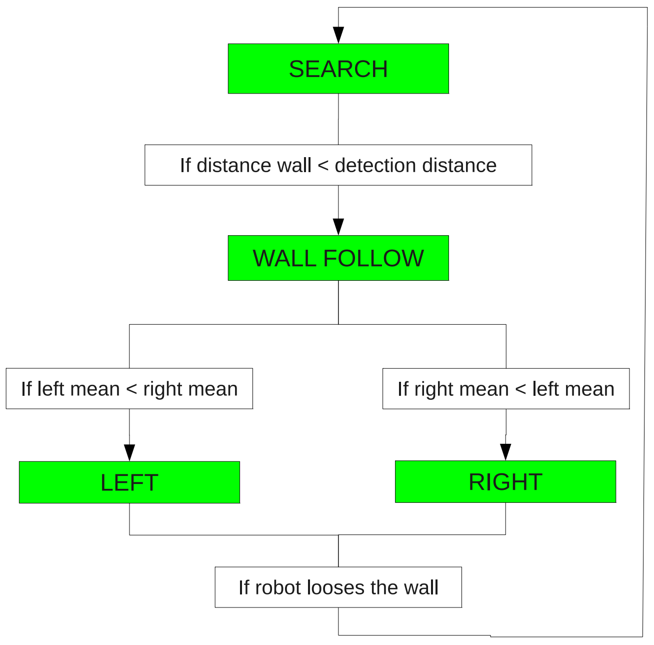

SEARCH
If distance wall < detection distance
WALL FOLLOW
If left mean < right mean
If right mean < left mean
LEFT
RIGHT
If robot looses the wall

Figure 5.3: *Robot modes flow diagram*

When the robot is in mode RIGHT or LEFT following a wall, it does it keeping a constant distance to the wall. This is achieved by tanking two points of the laser scan (two on the left or two on the right side, depending on the mode), and calculating the inclination of the wall with respect the robot, obtaining then the angle to turn.

5.2.2.1 Calculate the turn to keep a constant distance

As said before, the robot take two points on the left or on the right side. With these two points, it is possible to calculate the equation of the straight line which goes through these points:

$$y = m \cdot x + n \tag{5.1}$$

Once obtained the slope of the line (m), the orientation of the wall with respect to the robot is known, being possible to calculate the angle to turn in order to keep parallel to the wall, making m tends to 0. The scheme of figure 5.4 illustrates how the process works.

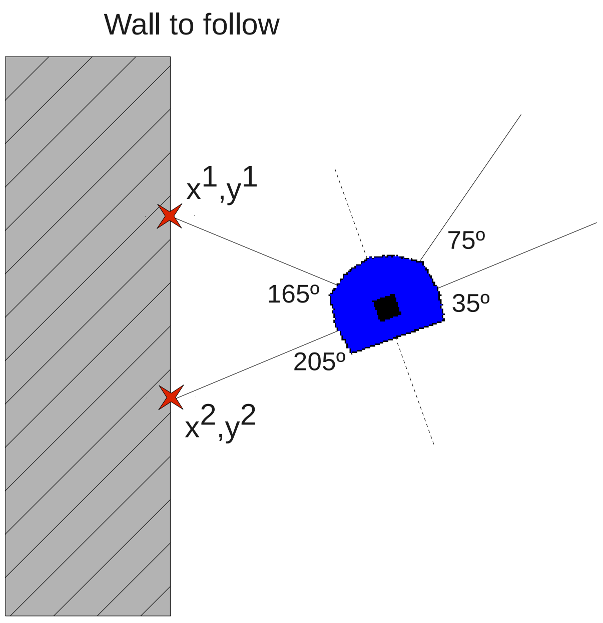


Figure 5.4: *Calculate the slope of a straight line*

When the wall is on the right side, the scans situated in the angles 35 and 75 degrees take the points, while when the wall is in the left, the scans are the ones in 165 and 205 degrees. Using simple trigonometrical relations, and using the equation of the straight line, the slope of the wall is obtained, knowing then the necessary angle to turn. The pseudo code of the whole program is the following.

```
if mode = Search then
   go straight
else
   calculate turn rate left/right
   if left mean < right mean and mode = Wall follow
      mode = Left
      calculate the slope of the straight line → turnrate
   if right mean < left mean and mode = Wall follow
      mode = Right
      calculate the slope of the straight line → turnrate
   avoid obstacles();
   if robot loses the wall
      mode = Search
end if
if the obstacle is closer than 25cm and mode = Search then
   mode = Wall follow
end if
```

5.2.3 Simulation

This section shows the result of the simulation of the code in an simulated environment. The results can be found in figure 5.5. On it, there are four snapshots in of the simulation in four different times.

Due to simulation results, we can conclude that the robot has a good response. First it searches for a wall, and when it finds it, it keeps following it without losing it. Therefore, the simplicity of the approach allows easily its use in other algorithms.

5.3 Follower robot

The next section explains the solutions adopted for the follower robot. The idea is that it detects the leader robot and follows it. The main behaviour modes of the robot are *robot following* and *obstacle avoidance*. In the same way than in chapter 5.2, this functions are implemented using the *Position2dProxie* and the *LaserProxie*, avoiding the use of any kind of communication between the robots, having then two independent systems.

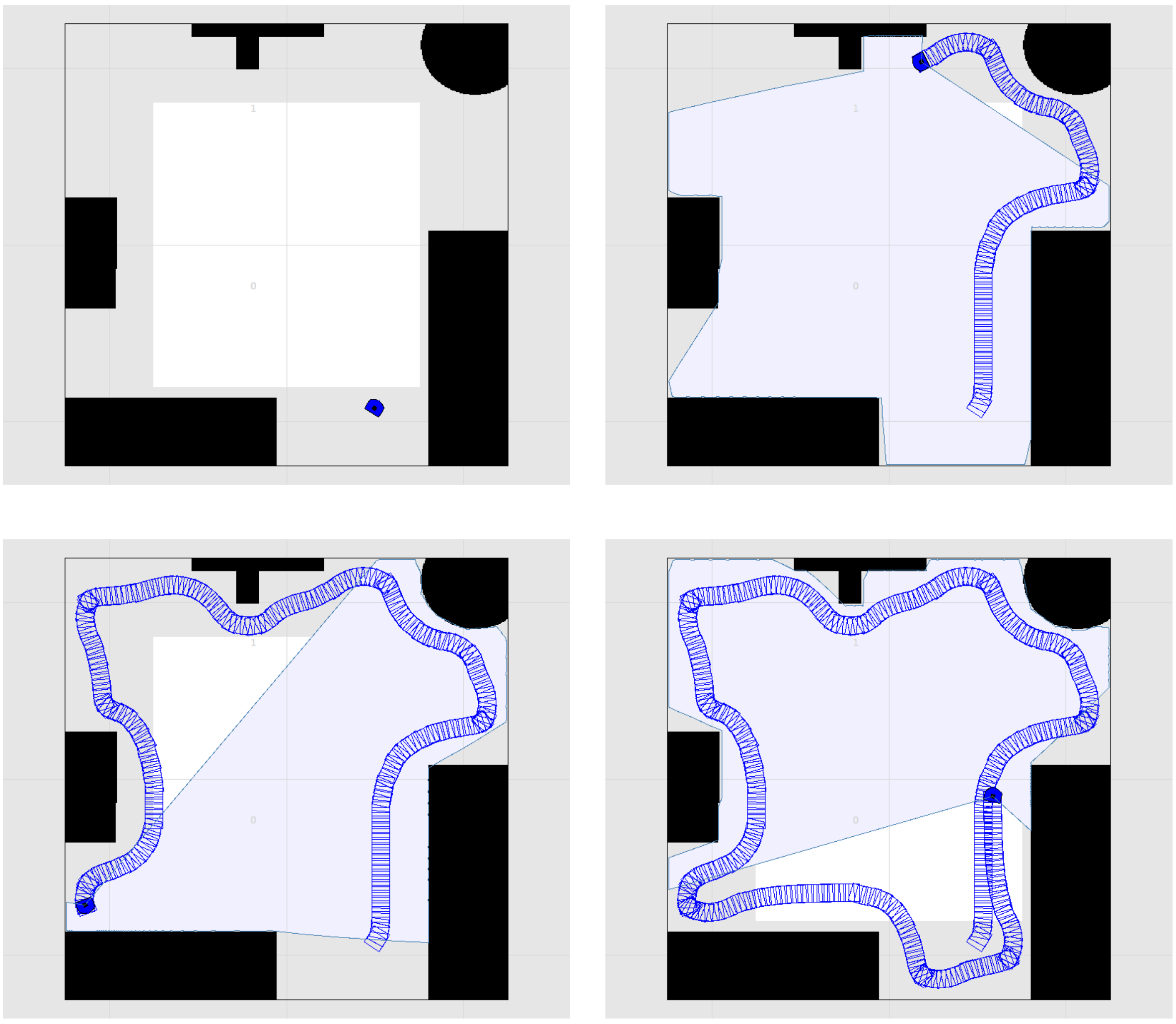


Figure 5.5: *Wall following simulation*

5.3.1 Robot following

One of the main difficulties to solve in this dissertation was how to implement a system for the follower robot to detect other robot using only a laser ranger. The idea was that they could not use any kind of communication between them, which includes *FiducialProxie*. This proxy would make the code easier and the robot response would be more accurate, but the problem is that it only exists in simulations. there are no fiducials devices for Khepera robots.

The developing of this algorithm was made through three different stages: a first approach in an environment with no walls, a second in a regular environment and a third one where the program was adapted for its implementation in a Khepera III robot.

5.3.1.1 Non-obstacles environment

The fist approach to the robot following behaviour was to create a code with the supposition that there are not obstacles in the environment. This is, if the laser detects something, that is the leader robot. The pseudo-code of this approach is the next:

```
take all laser scans
if any laser beam detects something then
  leader detected
  calculate relative angle to the leader robot
end if
if follower is facing the leader then
  turn rate = 0
else
  if robot on the right
     turn clockwise until angle difference $\simeq 0$
  if robot on the left
     turn counter clockwise until angle difference $\simeq 0$
end if
if distance to the robot > stop distance then
  go forward until distance to the robot < stop distance
end if
```

Firstly the robot scans all its laser range. If any measure is smaller than 5 meters, which is the maximum range of the robot, then the robot is detecting the leader. An average of all the scans detecting the leader is made, and then the relative angle α of the leader with respect to the front of the robot is calculated with the order *GetBearing(index)*. After it, the robot calculates its global orientation (β) with respect of the initial position using the order *GetYaw()*. A graphic explanation of both angles is made in figure 5.6. Once both angles are know, it calculates the difference between them. If the difference is $\simeq 0$, then the follower is facing the leader and the robot does not turn. On the contrary, if the angle is different, the robot starts turning right or left (depends where the robot are) until the difference is $\simeq 0$. Once the follower faces the leader, it checks the distance between them. If it is bigger than a parameter called *stop distance*, then the follower will go straight to the leader until their distance is equal or smaller than *stop distance*. All this process is inside an endless loop, being the robot taking points and measures each loop and updating the data.

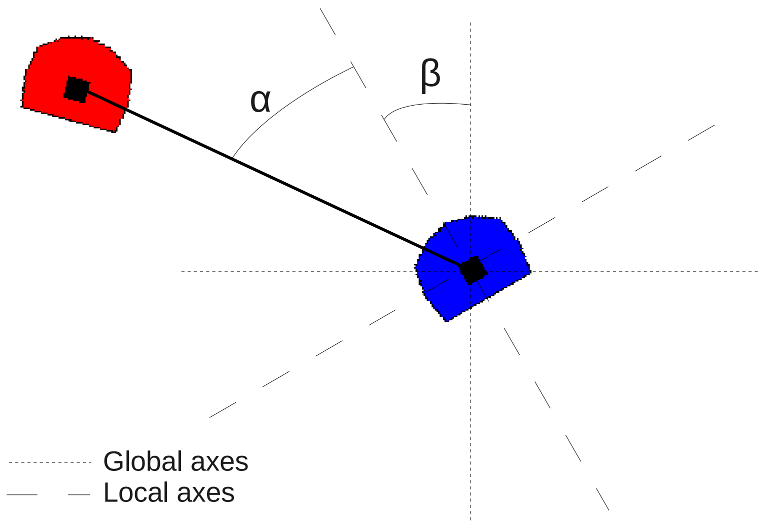


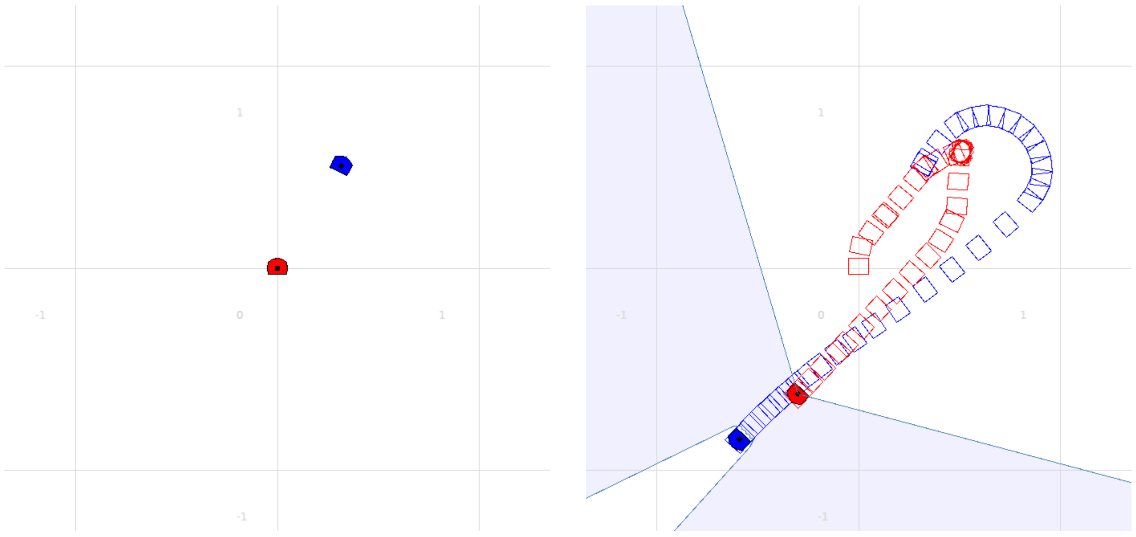
Figure 5.6: *Important global and local angles*

Simulation

The system was simulated in a world file which map has no wall nor obstacles, only two robots. The leader is moved in the scenario using *playerv* and the follower tries to find it and move to it, as seen in figure 5.7. The blue robot is the leader, while the red is the follower. At the beginning (image *a*) both robots are static, because the program is still not run. When it is run, as the leader is further than the stop distance (in this case 40 centimetres), it turns and moves until its laser measure is smaller than that value (figure *b*). As the trails made by the robots shown, when the leader is moving in the environment, the follower turns facing it and starts following it when the distance to it is smaller than the limit.

Results

The algorithm is working properly, as the robot follows the leader wherever it goes and keeps a limit distance to it for avoid any kind of collision. Nevertheless, this approach



a) System at the beginning, static b) System with the paths taken by the robots

Figure 5.7: *Simulation of the first approach*

is not useful because it does not take in account the possibility of find any other object different than the robot, while in real systems the robots will finds walls and obstacles to deal with. Anyway, it is a first approach and the basis of the next.

5.3.1.2 Environment with obstacles

In this approach, the robots move in a environment with walls and obstacles, similar than real life. The follower have to differentiate what is a wall or and obstacle and what is the leader robot to follow it. This goal has been accomplished using a movement recognition algorithm. It will work properly only with one more robot and with a static environment, so if something is moving, that is the leader robot. The pseudo code and its explanation are the following.

```
stop robot. Laser scan $\rightarrow$ save in a vector
wait one cycle
scan again $\rightarrow$ save in a different vector
compare both vectors index by index $\rightarrow$ substraction
calculate relative angle to the robot
  if in any index, any subtraction $\neq 0$ then
    something has moved $\rightarrow$ it is the leader robot
    get laser scans where the leader is $\rightarrow$ calculate average beam
  end if
  if any laser beam detects something then
    leader detected
    calculate relative angle to the leader robot
  end if
  if follower is facing the leader then
    turn rate = 0
  else
    if robot on the right
        turn clockwise until angle difference $\simeq 0$
    if robot on the left
        turn counter clockwise until angle difference $\simeq 0$
  end if
  if distance to the robot > stop distance then
    go forward until distance to the robot < stop distance
  end if
```

Before take any scan, the robot should be still, otherwise it will think all the environment is moving and will behave in a inappropriate way. The robot takes a scan and store it in a vector, then waits one cycle and takes another scan, saving it in a different vector. While the program is working normally, this process is continuous, and while two vectors and being compared, the current measure is stored for compare it with the following one in the next cycle. Then, both vectors (former and current measures) are subtracted element by element, storing it in a new vector called *diff_vectors*. If the values of the different indexes of the vectors are equal to zero, then nothing has moved in the system during the time between those two scans, and consequently the follower robot keeps still, waiting and scanning to find any movement. If any of the values of the vector *diff_vectors* is different than 0, then the leader has moved on the environment during the instant between the two scans. The follower acquires the laser scans indexes where the movement was registered and calculate the average index of them. With it, it obtains the direction the follower has to turn to face the leader. A graphic explanation is shown in figure 5.8.

Once the direction to the leader is obtained, the algorithm is the same that the developed in the first approach, explained in 5.3.1.1. The follower uses the order *GetBearing(index)* for finding its relative position with respect to the leader and also the command *GetYaw()* for calculate its angular orientation in global coordinates. For operate with them, both have to stay in the same coordinate system. Thus, the local position of the leader robot

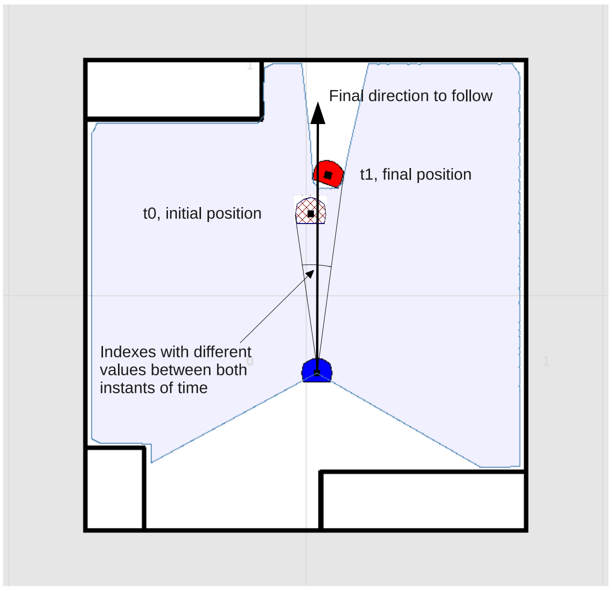

Final direction to follow
t1, final position
t0, initial position
Indexes with different values between both instants of time

Figure 5.8: *Follower robot detecting the position of the leader*

was converted into global coordinates by adding the local position angle to the last position recorded into a global counter, which provide the leader angle in global coordinates.

$$\textit{robot angle} = \overbrace{\textit{robot angle}}^{\text{last global position}} + \overbrace{\textit{lp1.GetBearing(index)}}^{\text{relative leader orientation}} \tag{5.2}$$

The commands *GetBearing* and *GetYaw()* work in a range between $[0, -\pi]$ when the angles are in the right side of the robot and between $[0, \pi]$ when the angles are in the left side (figure 5.9). So, the variable *robot angle* should be between $[-\pi, \pi]$, but due to the fact that the program is adding every time the new positions, the value could be out of the interval. In order to avoid that, the next algorithm is implemented:

$$\begin{aligned} &\textit{robot angle} = \textit{robot angle} + \textit{lp1.GetBearing(index)} \\ &\quad \textbf{if}(\textit{robot angle} < -\pi)\ \textit{robot angle} = \textit{robot angle} + 2\pi; \\ &\quad \textbf{if}(\textit{robot angle} > \pi)\ \textit{robot angle} = \textit{robot angle} - 2\pi; \end{aligned} \tag{5.3}$$

With this function, the value of the variable *robot angle* will be always inside the desired interval.

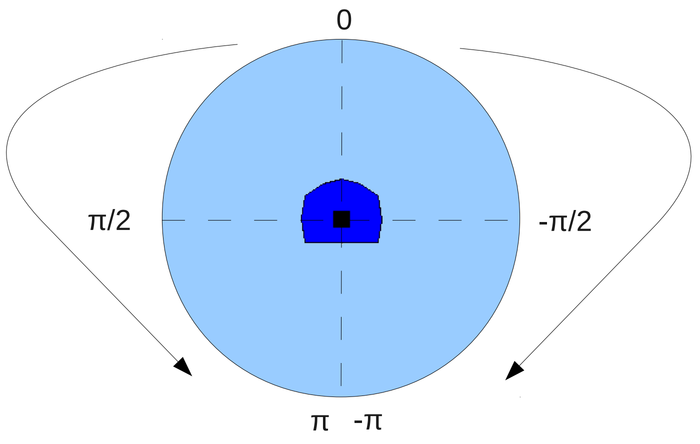


Figure 5.9: *Angle ranges*

Simulation

The program has been tried in a Stage simulation, in a bounded environment with walls. As the obstacle avoidance algorithm has not already been described, in this simulation the follower is far enough to the wall for have any problem. The leader robot is again moved using *playerv*, shown in figure 5.10.

Results

As results shown in 5.10, the follower robot follows the leader with no problem. When the leader is closer than the stop distance, the follower just turns facing the other one, without moving straight. When the leader is further, the code makes the follower walk into leader's direction.

When this code was implemented in the real Khepera robot, some functions did not work in the same way than in simulation. Then, some functions were adapted for its correct work into the physical robot, but this will be shown in section 5.3.3.

5.3.2 Obstacle avoidance

This section explains how the robot detects the walls and avoid to crash against them. The algorithm used to achieve this is very simple. As the robot will always be following the leader, in theory it will stop when the follower finds it. However, sometimes the follower can lose the leader. This could happen for some reasons. One of them is because the leader has a excessive speed and the follower is way further than the *stop distance*. As we said, the follower does not take new scans while it is moving, and goes straight just

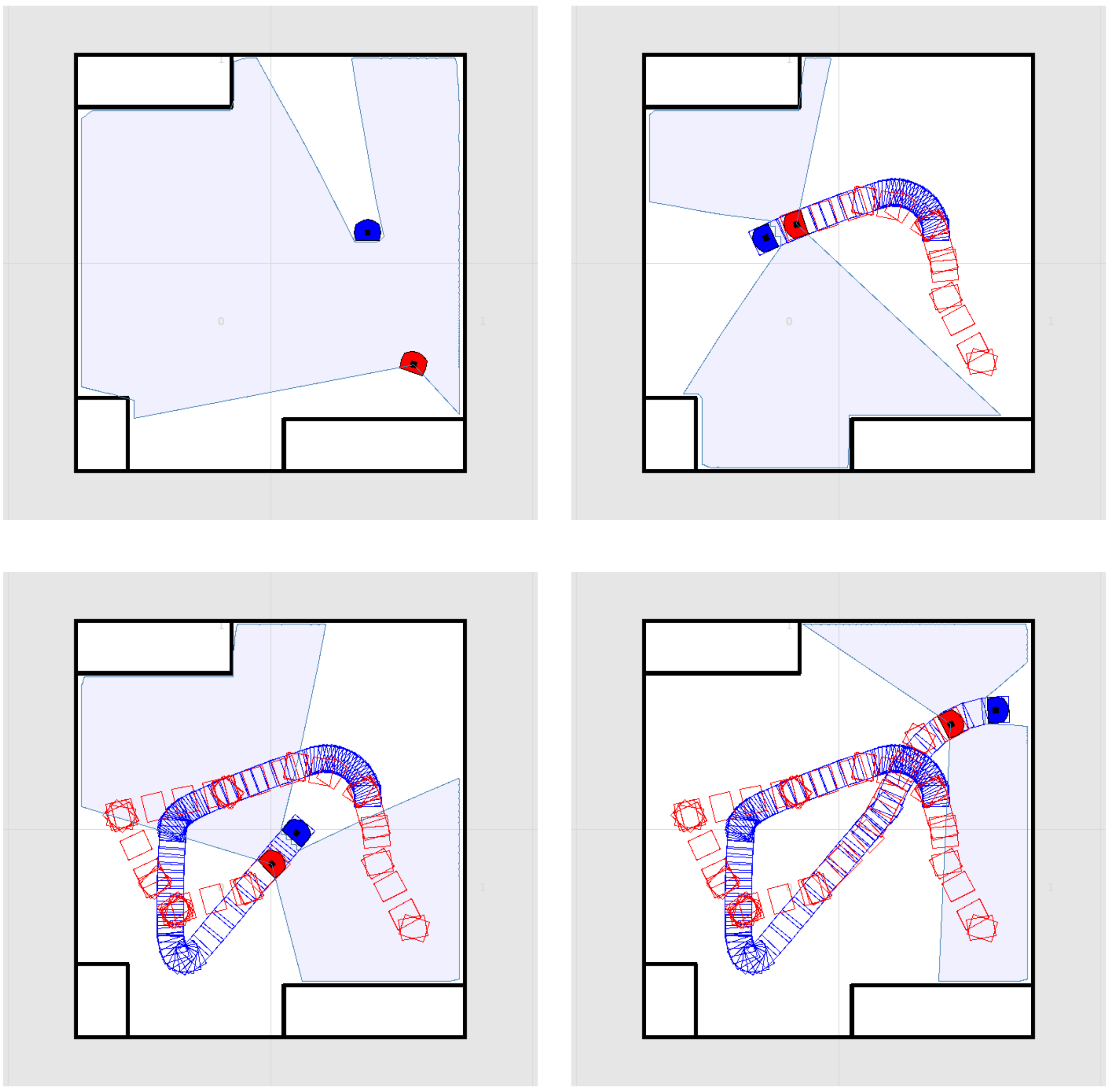


Figure 5.10: *Robot following simulation*

to the last calculated direction until it finds the other robot. So maybe, if the leader is moving too fast, when the follower arrives where the leader was supposed to stay it finds nothing and keeps going straight until it finds a wall to stop and scan the environment again looking for the leader. This problem is solved in section 5.3.3. It can also happen because of imprecisions of the robot or delays when running the code in the real Khepera III robot.

For detecting the minimum distance of the objects in front of the robot, the same function *DivideLaser* utilized for the obstacle avoidance behaviour of the leader robot is used. So basically, the robot follow this pattern:

```
once the robot direction is computed, go to it following this vector
if front minimum < stop distance then
    stop
    scan again to find the robot
else
    keep going straight until minimum distance < stop distance
end if
```

5.3.3 Code for Khepera III

As was explained in the previous section, the robot answers in a different way that it does in simulation. This happens because of the delays that appears when running the code on it, because the response time is not as ideal as in simulation. Therefore, sometimes the robot could lose the leader because it moves too fast, and then the follower would go following an erroneous path. In order to avoid that, there have been added a new series of commands, presented in the pseudo-code behind.

```
when follower is moving through last computed direction
if minimum distance > alone distance then
    keep moving 2 seconds
    stop moving
    scan again to find the robot
end if
```

The robot moves following the last computed direction. If its minimum distance is bigger than a variable called *alone distance* the robot stops and scans again. The mission of *alone distance* is to detect if the leader is in front of the follower or if it has got lost. This variable should not be small enough to be confused with *stop distance* nor big enough so that the follower detects a wall and thought it is the leader robot. In this dissertation, as the available arena in the laboratory is about one squared meter, its value is 45 centimetres.

Another different characteristic of the real Khepera robot with respect to its simulation model is the coordinate system of the *GetWay* function, which returns the global orientation of the robot with respect of the initial position. While Stage uses the coordinate system explained in the figure 5.9, whose measurements are included in the interval $[-\pi, \pi]$, the real robot uses the system of the figure 5.11.

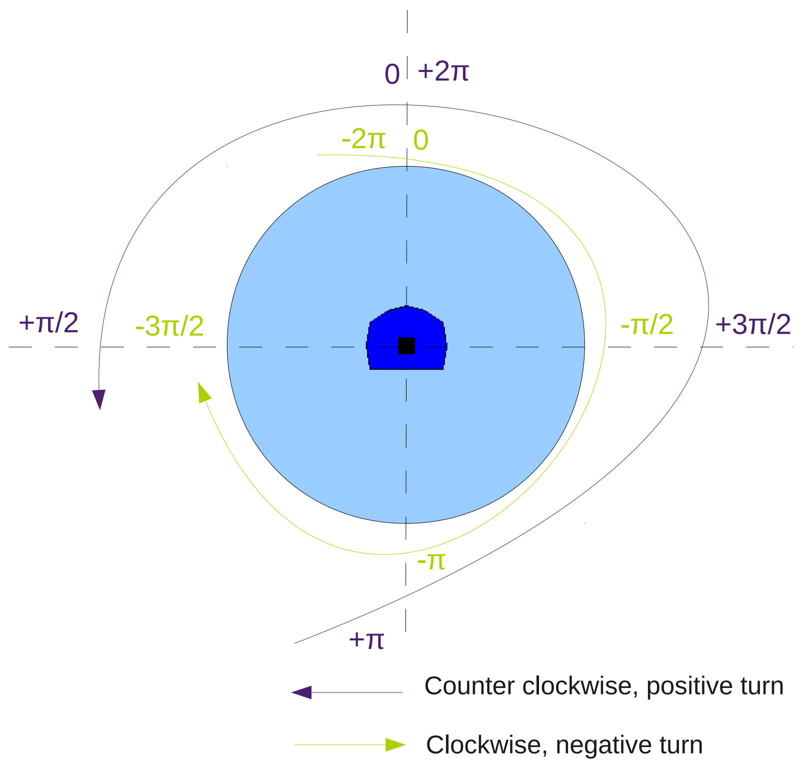


Figure 5.11: *Khepera GetYaw function coordinate system*

If the robot starts turning clockwise, the function will return negative values, and it will no change from $-\pi$ to π when it changes from the fourth to the third quadrant. Instead of it, it will be keep incrementing with negative values, and it will decrement the global counter and start return positive values when the robot turns counter clockwise. For that reason and to ensure that the data provided by the functions *GetYaw* and *GetBearing* is in the same coordinate systems, a function was developed in order to maintain the data obtained from the *GetYaw* function in the interval $[-\pi, \pi]$. This function is called *calc_yaw* and can be consulted in appendix D.

5.4 Implementation in Khepera III

Once all the explained algorithms have been tested and work in simulation, and after the adaptation of the follower robot's code, the system is ready for being implemented in the real Khepera III robots.

The process to run the code into the robots was explained at the end of chapter 2. After connect to the robot's wireless network called *Khepera_Network*, the user opens a secure shell connection (SSH) in the robot, one for the leader and one for the follower robot. Then, the configuration file is run in each robot. This file instantiates the KheperaIII driver, which supports the position interface. It also defines a laser driver for a device called *urglaser*. This file can be found in appendix A. Finally, the follower and leader codes are run in their respective hosts.

5.4.1 Results

The results of the implementation are satisfactory. The test was made in the arena that has the department in the laboratory, whose size is about $1x1$ meter. A one minute video with the robots interacting and moving in the environment can be seen in the next url:

http://vimeo.com/13212126

It can be seen how the leader is moving following a wall, maintaining a constant distance of 20 centimetres more or less with the wall. Meanwhile, the follower scans, finds the leader and follows it. There are some snapshots of the exercise in figure 5.12.

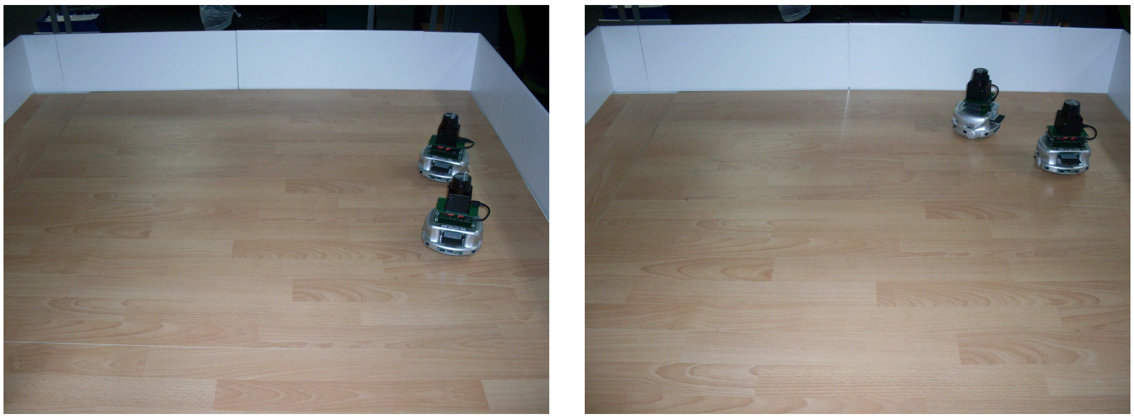


Figure 5.12: *Snapshots of the test made with the robots*

Although the response is good, the computational time of the robots is elevated, and consequently it takes sometime until the response is executed. Eventually, the follower can loose the leader and get stuck “staring” at a wall because the leader is out of the laser field of view. However, when the leader enters the laser field of view again, the follower will work properly again. Some principles of solution for this problem are purposed in section 6.2.

Chapter 6

Conclusion and further work

This chapter shows the conclusions reached after the accomplishment of the project. It should be kept in mind that the present code has been developed for its simulation in Player/Stage software, and subsequently for its implementation in Khepera III robots with the Hokuyo URG-04LX Laser. Therefore, if the user wants to use the code in different software and hardware devices, it is necessary to bear in mind that the final behaviour may be not the expected.

In addition, the use of the code in a specific Khepera system may differ from its use in a different Khepera robot. This may be due to the difference of the odometry and laser measures, an unbalanced pair of motors, ageing and deterioration of components, different computational times . . .

6.1 Conclusion

In this thesis a two-robot non-communicative system has been developed, where the first one (know as the leader) tries to find a wall and follows it maintaining a certain distance to it while avoids obstacles and the second one (know as the follower) tries to detect the leader using the laser ranger and follows it. For accomplish this, each code program has been tested first in a computer simulation to prove its correct behaviour and ensure the reliability of the system. After it, each system has been tried individually in the physical robots, and finally both have been tested in the same arena successfully.

The leader robot behaviour has been proved of being reliable, accurate and precise. Due to each cycle takes some time for the robot to compute, the program works properly for speeds smaller than 0.2 meters per second, otherwise the robot is going very fast and the processor has no time for compute and send all the information required.

The code developed for the follower robot provides a simple and easy implementation of the robot following algorithm using laser. Its accuracy is not very high because of the high computational time that the robot needs for each cycle and for the small size of the laser, which makes the detection of the leader complicated. However, it provides a first and simple approach to robot following using laser that can be the basis of further and more sophisticated algorithms.

6.2 Further work

6.2.1 Addition of more follower robots to the system

This code is made for a team composed by two robots: the leader and the follower. This is because of the supposition that any movement that the follower detects, is made by the leader. However, maybe a team with more follower robots is needed for a specific task. Then, instead of a change in a small region in the comparison vector (explained in 5.3, there would be changes in two different areas of the scan, and the robot should act in consequence. Even in this case, another algorithms should be developed to determine in which of these two directions is the leader and in which one is the other follower.

6.2.2 Accumulative errors

As was said in section 5.3.3, the order *GetWay* returns the robot global orientation in a different way than in the Stage simulation, hence the function created to keep it in a $[-\pi, \pi]$ range. Despite this feature, if the robot turns lots of time in a row in the same direction, the global counter will keep rising, accumulating consequently all the position errors, and maybe at one point, the measurements and direction vectors obtained would be wrong.

As there is a reset function in the Position proxy for this task called *ResetOdometry* but it does not work does not properly, and interesting idea could be the implementation of any kind of reset for the odometry counter. With that, each time the robot turns more than a certain value that can provide wrong measures, the orientation counter will restart again, getting rid of all the accumulate position errors.

6.2.3 Loss of the leader

In the follower robot algorithm, if the leader is further than the detection distance, the robot will stop and scan to find it again. This will work if the leader is in the field of view of the laser. However, it is possible that eventually the follower loses the leader and this was behind the field of view of the robot. In this case, the follower will keep going straight, stopping each certain period of time for make a scan again until it arrives in front of a wall and stops. The robot would not move until the leader arrives close to it again.

A possibility for avoid it could be to make any kind of counter that activates when the robot is closer than the variable *stop distance* to something (could be a wall or a robot) and the environment does not change in a period of time (then, it could only be a wall). If this happens, the robot could rotate on its own axis and making scans each 90 degrees. Thus, the follower can detect the leader again move to it.

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Appendices

Appendix A

Configuration files

A.1 Simulation *.cfg* file

Used in simulations for the second approach.

```
# load the Stage plugin simulation driver
driver
(
  name "stage"
  provides ["simulation:0" ]
  plugin "libstageplugin"

  # load the named file into the simulator
  worldfile "first.world"
)

# Create a Stage driver and attach position2d and laser interfaces
# to the model "robot1"

driver
(
  name "stage"
  provides ["6665:position2d:0" "6665:laser:0" "6665:fiducial:0"]
  model "robot1"
)

driver
(
  name "stage"
  provides ["6666:position2d:0" "6666:laser:0" "6666:fiducial:0"]
  model "robot2"
)
```

A.2 Khepera III *.cfg file*

```
# Instantiate the KheperaIII driver, which supports the position interface

driver
(
  name "KheperaIII"
  plugin "KheperaIII"
  provides ["position2d:0" "ir:0" "sonar:0" "power:0"]

  scale_factor 1

  #The wheel encoder resolution
  encoder_res 4

  #The pose of the robot in player coordinates (m, m, deg).
  position_pose [0 0 0]

  position_size [0.127 0.127]


  ir_pose_count 9

  ir_poses [-0.043 0.054 128 0
  0.019 0.071 75 0
  0.056 0.050 42 0
  0.075 0.017 13 0
  0.075 -0.017 -13 0
  0.056 -0.050 -42 0
  0.019 -0.071 -75 0
  -0.043 -0.054 -142 0
  -0.061 0 180 0
  ]

  sonar_count 5
  sonar_poses [
    0.0005 0.075 90
    0.046 0.044 45
    0.061 0 0
    0.046 -0.044 -45
    0.0005 -0.075 -90
  ]
)
driver
(
  name "urglaser"
  provides ["laser:0"]
  port "/dev/ttyACM0"

)
```

Appendix B

World file

```
# Desc: 1 pioneer robot with laser
# CVS: $Id: simple.world,v 1.63 2006/03/22 00:22:44 rtv Exp $

# size of the world in meters
size [1.5 1.6]

# set the resolution of the underlying raytrace model in meters
resolution 0.02

# set the ratio of simulation and real time
interval_sim 100 # milliseconds per update step
interval_real 100 # real-time milliseconds per update step

# configure the GUI window
window
(
  size [ 680.000 700.000 ]
  center [0 0]
  scale 0.003
)
# load a pre-defined model type from the named file
include "map.inc"

# create an instance of the pre-defined model
map
```

```
(
  color "black" #Colour of the map's frame

  polygons 4
  polygon[0].points 4
  polygon[0].point[0] [0 0]
  polygon[0].point[1] [1 0]
  polygon[0].point[2] [1 0.01]
  polygon[0].point[3] [0 0.01]

  polygon[1].points 4
  polygon[1].point[0] [0 1]
  polygon[1].point[1] [1 1]
  polygon[1].point[2] [1 0.99]
  polygon[1].point[3] [0 0.99]

  polygon[2].points 4
  polygon[2].point[0] [0 0]
  polygon[2].point[1] [0 1]
  polygon[2].point[2] [0.01 1]
  polygon[2].point[3] [0.01 0]

  polygon[3].points 4
  polygon[3].point[0] [1 0]
  polygon[3].point[1] [1 1]
  polygon[3].point[2] [0.99 1]
  polygon[3].point[3] [0.99 0]

  size [15 15]
)
##### uncomment this section to load some obstacles from the bitmap
map
(
  bitmap "./bitmaps/arena.png"
  name "map"
  size [1.5 1.6]
  border 0
)

# define a URG1-like laser scanner model, based on the built-in "laser" model
define urg_laser laser
```

```
(
  range_min 0.0
  range_max 5.0
  fov 240
  samples 685
  color "black"
  size [ 0.02 0.02 ]
)

# define an khepera-like robot model, based on the built-in "position" model
define khepera position
(
  # actual size
  size [0.08 0.1]

  # the center of rotation is offset from its center of area
  origin [0.01 0 0]

  # draw a nose on the robot so we can see which way it points
  gui_nose 1

  # estimated mass in KG
  mass 0.7

  # this polygon approximates the shape of a Khepera III
  polygons 1
  polygon[0].points 9
  polygon[0].point[0] [ -0.04   0.05  ]
  polygon[0].point[1] [ -0.01   0.055 ]
  polygon[0].point[2] [  0.02   0.05  ]
  polygon[0].point[3] [  0.035  0.025 ]
  polygon[0].point[4] [  0.04   0     ]
  polygon[0].point[5] [  0.035 -0.025 ]
  polygon[0].point[6] [  0.02  -0.05  ]
  polygon[0].point[7] [ -0.01  -0.055 ]
  polygon[0].point[8] [ -0.04  -0.05  ]

# create an instance of our "urg_laser" model
  urg_laser
  (
   # speed hack: raytrace only every 5th laser sample, interpolate the rest
   laser_sample_skip 5

   fiducialfinder( range_max 5 range_max_id 10 fov 360)
  )
)

# create some instances of our khepera robot model
khepera
(
  name "robot1"
  color "blue"
  pose [0.5 0.5 90]
fiducial_return 1
)

khepera
(
  name "robot2"
  color "red"
  pose [0 0 90]
fiducial_return 2
)
```

Appendix C

functions.h library

Some support functions

```
////////////////////////////////////////////////////////
//////////////         Functions          //////////////
//////////////      Support Library     //////////////
//////////////                            //////////////

///////////////////////////////////////////////////////////
//////////////  Function that return the     //////////////
//////////////  orientation of the robot     //////////////
//////////////  in degrees between 0-360°    //////////////
///////////////////////////////////////////////////////////

double bearing (PlayerCc::Position2dProxy &P)
{
double orientacion;

orientacion=P.GetYaw();
orientacion=RTOD(orientacion);

if (orientacion>=-90 && orientacion<=180)
   {orientacion=orientacion+90;}
if (orientacion>-180 && orientacion<-90)
   {orientacion=orientacion+450;}

return orientacion;
```

```
}

/////////////////////////////////////////////////////////////
//////////////    Function that return the       ////////////
//////////////    orientation of the other       ////////////
//////////////    robot detected with the        ////////////
////////////// laser in degrees between 0-360º  ////////////
/////////////////////////////////////////////////////////////

double bearing_laser (double obstacle_angle)
{
obstacle_angle=RTOD(obstacle_angle);

if (obstacle_angle>=-90 && obstacle_angle<=180)
   {obstacle_angle=obstacle_angle+90;}
if (obstacle_angle>-180 && obstacle_angle<-90)
   {obstacle_angle=obstacle_angle+450;}

return obstacle_angle;
}

///////////////////////////////////////////////////////////
//////////////  Function that return the     //////////////
//////////////  final orientation of robot   //////////////
///////////////////////////////////////////////////////////

double final_bearing (double angulo_giro, double orientacion_inicial)

{
double resto,orientacion_final,angulo;

if (angulo_giro<0)
                {
                if (-angulo_giro>orientacion_inicial)
                   {resto=orientacion_inicial+angulo_giro;  //sale -
                    orientacion_final=360+resto;}
                if (-angulo_giro<orientacion_inicial)
                   {orientacion_final=orientacion_inicial+angulo_giro;}
                }  //if<0
             if (angulo_giro>0)
                {
```

```
                angulo=angulo_giro+orientacion_inicial;
                if (angulo>360)
                   {resto=orientacion_inicial+angulo_giro;
                    orientacion_final=resto-360;}
                if (angulo<360)
                   {orientacion_final=angulo_giro+orientacion_inicial;}
                }   //if >0
std::cout<<"Angulo Giro: "<<angulo_giro<<std::endl;
std::cout<<"Orientacion Inicial: "<<orientacion_inicial<<std::endl;
std::cout<<"Orientacion Final: "<<orientacion_final<<std::endl;

return orientacion_final;
}
```

Appendix D

support.h library

Some support functions

```
//////////// FUNCTIONS & PARAMATERS

//////////////////////////////////
////        DEFINITIONS       ////
//////////////////////////////////

#define PI 3.14159265358979323846

enum MODE {SEARCH,WALL_FOLLOW,RIGHT,LEFT,STOP};
enum SITUACION {ALONE,ALL,VECTOR};

//ROBOT PARAMETERS
const uint VIEW = 25;          //Field of view of the robot
const uint ANGLE_DIST = 60;    //Angle from towards to the wall
const double VEL = 0.2;        //Maximal linear speed ////// 0.2
const double TURN_RATE = 30;   //Maximal wall_following turnrate
const uint K_P = 100;          //Wall_following constant used to no
                               //exceed the maximal turn_rate
const double W_F_DIST = 0.25; //Wall distance to enter in WALL_FOLLOW mode
const double DIST = 1;         //Preferred_wall_following_distance

//STATES PARAMETERS
```

```
const double WALL_DIST = 0.25;     //Distance to find the wall or obstacle
const double STOP_DIST = 0.15;     //Stop distance to avoid wall collision
const double STOP_ROT  = 25;       //Rotation speed to avoid wall collision
const double ALONE_DIST = 0.35;    //Distance to return SEARCH mode (was 2)
const double CLST_ROB = 1.5;       //If the closest robot is nearer than that
                                   //distance, it stops.

///////////////////////////////////////////////////////
////                CALCULATE RANGES               ////
////          Calculate ranges of the laser        ////
///////////////////////////////////////////////////////

void calc_range(PlayerCc::LaserProxy &L, double range[], int scans)
{
    for (int j=1;j<scans;j++)
    {
        range[j] = L.GetRange(j);
    }
}

////////////////////////////////////////////////////
////                CALCULATE YAW               ////
////    Changes the value of the robot angle    ////
////      into a [0,-pi] or [0,pi] interval     ////
////////////////////////////////////////////////////

double calc_yaw(PlayerCc::Position2dProxy &P)
{
    double n;
    int turns;
    double current_yaw = P.GetYaw();

    if (current_yaw<0) // right side
    {
        n = (-PI-current_yaw)/(2*PI);
        if (n<0) current_yaw = current_yaw;
        if (n>0)
        {
            turns = floor(n)+1;
            current_yaw = current_yaw+(turns*2*PI);
        }
    }

    if (current_yaw>0) // left side
    {
        n = (current_yaw-PI)/(2*PI);
        if (n<0) current_yaw = current_yaw;
        if (n>0)
        {
            turns = floor(n)+1;
            current_yaw = current_yaw-(turns*2*PI);
        }
    }
    return current_yaw;
}


//////////////////////////////////////////////////
////           CALCULATE FORMER RANGE          ////
//// Calculate the former ranges of the laser ////
//////////////////////////////////////////////////


void calc_former_range(double former_vector[], double range[],
double other_former_vector[], double& sum_scans, double& sum_distances,
int& count, int scans, bool detected)
{

double diff_vectors[scans];

    for (int j=1;j<scans;j++)
    {
    former_vector[j] = range[j];
        if (detected==false) diff_vectors[j] = other_former_vector[j] - range[j];
        if (detected==true)  diff_vectors[j] = range[j] - range[j];
        if ((fabs(diff_vectors[j])>0.05)&&(detected==false))
        {
            sum_scans=sum_scans+j;
            sum_distances=sum_distances+range[j];
            count++;
        }
    }
```

```
}

////////////////////////////////////////////////////////////////////
////                       FRONT DISTANCE                       ////
////  Calculates the average distance to the front of the robot ////
////                         100 scans                          ////
////////////////////////////////////////////////////////////////////

double front_distance (PlayerCc::LaserProxy &L)
{
    double SCANS;
    double sum_dist = 0, cont = 0,front_dist;

    // Loop
    SCANS = L.GetCount();
    for (int j= (SCANS/2)-100;j< (SCANS/2)+100;j++)
    {
        sum_dist = sum_dist+L.GetRange(j);
        cont++;
    }

    front_dist = sum_dist/cont;
    std::cout << "Front distance: " << front_dist << std::endl;
    std::cout << "I'm in" << std::endl;

    return front_dist;
}


/////////////////////////////////////////////////////
////              EUCLIDEAN DISTANCE             ////
//// Calculate the euclidian distance to a point ////
/////////////////////////////////////////////////////

double hip (double x, double y)
    {
        double res;
        res=sqrt(x*x + y*y);
        return res;
    }
```

```
////////////////////////////////////////
////       DEGREES TO RADIANS       ////
////    Turn degrees into radians    ////
////////////////////////////////////////

double D2R (double degree)
{
    double rad;
    rad=degree*(PI/180);
    return rad;
}

/////////////////////////////////////////
////         DEGREES TO SCANS        ////
////     Turn degrees into scans      ////
/////////////////////////////////////////

int DtoS (int degree)
{
    double scan;
    int res;
    scan=degree*685/240;

    for (uint d=1;d<685;++d)
    {
        if ((scan<=d+0.5)&&(scan>d-0.5))
        res=d; //calculate the entire part rounded
    }
    return res;
}

///////////////////////////////////////////////////////////////
////                     MAXIMUM TURN                      ////
////  Is not allowed to exceed a maximum turn given. If it  ////
//// happens the turn is fixed to the maximum value allowed ////
///////////////////////////////////////////////////////////////

double turn_max (double turn_lat, double turn_rate_max)
{
    double turn;
    turn = turn_lat;
    if (turn_lat>turn_rate_max)
    turn = turn_rate_max;
    return turn;
}

/////////////////////////////////////////////////////////////////
////                  COLLISION AVOIDANCE                    ////
////If the obstacle in front of the robot is nearer than 0.15////
////then it turn left or right depending on the previous mode////
/////////////////////////////////////////////////////////////////

void collision_avoidance( double min_dist, uint mode, double &speed, double &turn)
{
    if (min_dist < 0.15)
    {
        speed = 0;
        if (mode==LEFT) // right turn
        turn = D2R(-STOP_ROT); //STOP_ROT=30;
        if (mode==RIGHT) // left turn
        turn = D2R(STOP_ROT);
    }
}

////////////////////////////////////////////////////////////////////
////                        AVOID OBSTACLES                     ////
//// When there is an obstacle in the robot’s way, it avoids it ////
////  turning 45° left or right depending if the obstacle is on ////
////                 the right or on the left                   ////
////////////////////////////////////////////////////////////////////

void avoid_obstacles (PlayerCc::LaserProxy &L, PlayerCc::Position2dProxy &P)
//pass by reference
{
double NumScan=L.GetCount();
double minDist=1.0;
int abs;

// Loop for avoid obstacles;
for(int i=0;i<NumScan;i++)
{
    if (L.GetRange(i)<minDist && L.GetRange(i)!=0
    {
        minDist=L.GetRange(i);
        abs=i; //Save the minimum distance to the obstacle
    }

    if(minDist<0.8)         //If is closer than 0.8m it stops and turn
    {
        if (L.GetBearing(abs)<0) //If the obstacle is on its right
        P.SetCarlike(0.0, DTOR(45)); //Turn left

        else //else, the obstacle is on its left
        P.SetCarlike(0.0, DTOR(-45)); //Turn right
    }
}
}


////////////////////////////////////////////////////////////////////
////                    AVOID OBSTACLES 2                       ////
//// When there is an obstacle in the robot’s way, it avoids it ////
//// turning 45° left or right depending if the obstacle is on  ////
////          the right or on the left (smaller distance)       ////
////////////////////////////////////////////////////////////////////

void avoid_obstacles2 (PlayerCc::LaserProxy &L, PlayerCc::Position2dProxy &P)
{
double NumScan=L.GetCount();
double minDist=1.0;
int abs;

// Loop for avoid obstacles;
    for(int i=0;i<NumScan;i++)
    {
        if (L.GetRange(i)<minDist && L.GetRange(i)!=0)
        {
            minDist=L.GetRange(i);
            abs=i; //Save the minimum distance to the obstacle
        }

        if(minDist<0.2) //If is nearer than 0.8m it stops and turn
        {
            if (L.GetBearing(abs)<0) //If the obstacle is on its right
                P.SetCarlike(0.0, DTOR(45)); //Turn left
            else //else, the obstacle is on its left
                P.SetCarlike(0.0, DTOR(-45)); //Turn right
        }
    }
}

//////////////////////////////////////////////////////////////////////
////                       DIVIDE LASER                           ////
//// Separates the laser's FOV in tree parts (right, center and ////
////   left) and gives in what of those parts is the closest    ////
////             obstacle calculating different means           ////
//////////////////////////////////////////////////////////////////////

void divide_laser(PlayerCc::LaserProxy &L, double &left_mean, double &right_mean,
double &min_right, double &min_left, double &min_dist)
{
double NumScan=L.GetCount();
uint right_view=DtoS(120-VIEW), left_view=DtoS(120+VIEW); //VIEW=25;
double right_sum=0, left_sum=0;
uint i, right_count=0, left_count=0;
min_right=1; //10
min_left=1;  //10
min_dist=1;  //10
left_mean=0;
right_mean=0;

    for (i = 0; i <NumScan ; ++i)
    {
        if (L.GetRange(i)!=0)
        {
            if (i<right_view)
            {
                right_sum += L.GetRange(i);
                ++right_count;
                if (L.GetRange(i)<min_right)
                    min_right = L.GetRange(i);
            }

            if ((i>right_view)&&(i<left_view)&&(L.GetRange(i)<min_dist))
```

```
                min_dist = L.GetRange(i);

            if (i>left_view)
            {
                left_sum += L.GetRange(i);
                ++left_count;
                if (L.GetRange(i)<min_left)
                    min_left = L.GetRange(i);
            }
        }
    }

left_mean = left_sum/left_count;
right_mean = right_sum/right_count;
}

/////////////////////////////////////////////////////////////////////
////               CALCULATE straight line SLOPE                ////
//// Takes two points from an obstacle then obtains the straight ////
//// line between them and calculate it slope. With this we have ////
////                  the robot's orientation                   ////
/////////////////////////////////////////////////////////////////////

void calculate_slope (double &turn, uint mode, PlayerCc::LaserProxy &L)
{
double m, b, heading;
double x1_right, x2_right, y1_right, y2_right;
double x1_left, x2_left, y1_left, y2_left;

    if(mode==RIGHT)
    {
        x1_right=L.GetRange(DtoS(35))*cos(L.GetBearing(DtoS(35)));//+W)+X;
        y1_right=L.GetRange(DtoS(35))*sin(L.GetBearing(DtoS(35)));//+W)+Y;
        x2_right=L.GetRange(DtoS(75))*cos(L.GetBearing(DtoS(75)));//+W)+X;
        y2_right=L.GetRange(DtoS(75))*sin(L.GetBearing(DtoS(75)));//+W)+Y;

        m=(y1_right-y2_right)/(x1_right-x2_right);
        b=y1_right-m*x1_right;
        std::cout << "(" << x1_right << "," << y1_right << ")" << std::endl;
        std::cout << "(" << x2_right << "," << y2_right << ")" << std::endl;
        heading=atan(m);
        turn=heading;
    }

    if(mode==LEFT) // el modo LEFT ya va bien
    {
        x1_left=L.GetRange(DtoS(205))*cos(L.GetBearing(DtoS(205)));//+W)+X;
//1er punto: x1,y1
        y1_left=L.GetRange(DtoS(205))*sin(L.GetBearing(DtoS(205)));//+W)+Y;
        x2_left=L.GetRange(DtoS(165))*cos(L.GetBearing(DtoS(165)));//+W)+X;
//2n punto: x2,y2
        y2_left=L.GetRange(DtoS(165))*sin(L.GetBearing(DtoS(165)));//+W)+Y;

        m=(y1_left-y2_left)/(x1_left-x2_left);
        b=y1_left-m*x1_left;
        std::cout << "(" << x1_left << "," << y1_left << ")" << std::endl;
        std::cout << "(" << x2_left << "," << y2_left << ")" << std::endl;

        heading=atan(m);
        turn=heading;
    }
}

////////////////////////////////////////////////////////////////////
////                   KEEP DISTANCE TO THE WALL               ////
//// These expresions are useful for calculate the distance to  ////
////                keep the robot and the wall                ////
////////////////////////////////////////////////////////////////////

void keep_wall_distance (double &turn_left, double &turn_right,
PlayerCc::LaserProxy &L)
{
    uint on_the_right=DtoS(120-ANGLE_DIST), on_the_left=DtoS(120+ANGLE_DIST);

    turn_left = D2R(K_P*(L.GetRange(on_the_left)-WALL_DIST));
    turn_right = D2R(K_P*(L.GetRange(on_the_right)-WALL_DIST));
}


/////////////////////////////////////////////////////////////////
////                  TAKE MODE (Straight line)            ////
////  Selects the working mode calculating the slope of a   ////
```

```
////            straight line formed by two points           ////
/////////////////////////////////////////////////////////////////

void take_linear_mode(double &turn, double &speed, uint &mode,
PlayerCc::LaserProxy &L, double left_mean, double right_mean,
double min_right, double min_left, double min_dist)
{
double turn_left, turn_right;

    if (mode == SEARCH)
    {
        turn=0;
    }

    else
    {
    keep_wall_distance (turn_left, turn_right, L);

    if ((right_mean<left_mean)&&(mode==WALL_FOLLOW))
        mode=RIGHT;

    if ((left_mean<right_mean)&&(mode==WALL_FOLLOW))
        mode=LEFT;

    calculate_slope (turn, mode, L);

    if ((mode == RIGHT)&&(L.GetRange(DtoS(60))<WALL_DIST))
    {
        turn = -turn_max (turn_right,D2R(TURN_RATE));//turn = -turn_right;
    }

    if ((mode == LEFT)&&(L.GetRange(DtoS(180))<WALL_DIST))
    {
    turn = turn_max (turn_left,D2R(TURN_RATE));//turn = turn_left;
    }

    collision_avoidance (min_dist, mode, speed, turn);

    if ((min_left>ALONE_DIST) && (min_right>ALONE_DIST) && (min_dist>ALONE_DIST))
        mode = SEARCH;
    if (mode == STOP)
    {
        speed=0;
        turn=0;
    }
} ////////// close else

if (((L.GetRange(DtoS(210)) < W_F_DIST) || (L.GetRange(DtoS(30)) < W_F_DIST)
|| (min_dist < W_F_DIST)) && (mode==SEARCH) && (min_dist!=0))
    mode=WALL_FOLLOW;
}


////////////////////////////////////////////////////////////////////
////                 TAKE MODE (Wall following)                 ////
////  Selects the working mode with the wall following formule  ////
////////////////////////////////////////////////////////////////////

//The robot go forward and try to search some obstacle or wall

void take_wall_follow_mode(double &turn, double &speed, uint &mode,
PlayerCc::LaserProxy &L, double left_mean, double right_mean,
double min_right, double min_left, double min_dist)
{
double turn_left, turn_right;

    if (mode == SEARCH)
        turn=0;

    else
    {
        keep_wall_distance (turn_left, turn_right, L);

        if ((left_mean<right_mean)&&(mode==WALL_FOLLOW))
            mode = LEFT;

        if ((left_mean>right_mean)&&(mode==WALL_FOLLOW))
            mode = RIGHT;

        if (mode==LEFT)
            turn = turn_max (turn_left,D2R(TURN_RATE));//turn = turn_left;
        if (mode==RIGHT)
            turn = -turn_max (turn_right,D2R(TURN_RATE));//turn = -turn_right;

        if (min_dist < STOP_DIST)
        {
            speed = 0;
            if (left_mean<right_mean)
                turn = D2R(-STOP_ROT);

            if (left_mean>right_mean)
                turn = D2R(STOP_ROT);
        }

        if ((min_left>ALONE_DIST) && (min_right>ALONE_DIST) &&
        (min_dist>ALONE_DIST))
            mode = SEARCH;

if (mode == STOP)
        {
            speed=0;
            turn=0;
        }
    } //close else

    if ((min_dist<1)&&(mode == SEARCH)&&(min_dist!=0)&&(mode!=STOP))
        mode = WALL_FOLLOW;
}
```