UNIVERSIDADE DE LISBOA
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Departamento de Informática

RESILIENT MIDDLEWARE FOR A MULTI-ROBOT TEAM

Eric Emmanuel Pascal Vial

MESTRADO EM INFORMÁTICA

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PROJECTO

Projecto orientado pelo Prof. Doutor Mário João Barata Calha

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Thanks

I would like to thank Mário Calha for all his help and comprehension along these months. A special thank as well to FCT and LASIGE people for their useful support.

To Marisa, my beloved daughter

Resumo

Actualmente, equipas de robôs móveis intervêm em diversos contextos e ambientes onde a intervenção humana é perigosa ou mesmo impossível, podemos mencionar como exemplo a vigilância de espaços físicos, como zonas militares ou nucleares. Devido à crescente complexidade inserida nos seus sistemas, esses robôs ficam mais poderosos mas paradoxalmente mais susceptíveis a falhas de hardware e software. Além disso, a incerteza na comunicação wireless pode privá-los temporariamente do seu suporte de informação remoto. Este tipo de problema pode ser causado pelo alcance limitado do emissor wireless e pelas zonas de sombra criadas pelo terreno. Por todas essas razões, desenhar arquitecturas capazes de oferecer mais resiliência para controlo das aplicações, tornou-se um verdadeiro desafio. Este documento aborda um motor cooperativo e resiliente para equipas de robôs que lhes permite partilharem uma vista comum e lidar com novos eventos de uma forma fiável e resiliente. Este middleware tem como função estabelecer a guarda de uma qualquer zona física e detectar eventos inabituais como os intrusos. Neste ultimo caso, um robô tem que encontrar uma maneira de bloquear o intruso para o impedir de fugir. O sistema apoia-se em duas características chave, a primeira é uma camada de controlo baseado em dois sub-módulos de controlo, o payload e o wormhole, a segunda é uma arquitectura baseada em eventos que executam tarefas do payload. Em relação à camada de controlo, o payload pode ser complexo e acede à informação partilhada pelos robôs enquanto que o wormhole é confiável mas apenas utiliza a informação local. O payload utiliza uma estrutura de dados chamada "promessa" na qual fornece o deadline correspondente ao momento mais tarde onde deve enviar a próxima promessa. No caso de receber esta promessa depois do deadline, o wormhole considera que o payload falhou, toma o controlo e executa as tarefas criticas no lugar do payload. Os eventos são propagados às traves de uma estrutura em forma de alvor, da raiz até as folhas. Cada folha do alvor é um modulo que pode ser executado e produz eventos. A produção dos eventos no alvor pode ser assimilado a uma reacção em cadeia. Durante o ciclo dos eventos as traves do alvor não são possíveis, o que permite evitar as reacções não controladas e garantem assim a estabilidade do sistema. A juntar a essa arquitectura, propomos também neste documento alguns mecanismos de sincronizações resilientes, para manter uma vista coerente num mundo ou de navegação para dar ao robô a possibilidade de se mover no mundo e de encontrar o melhor caminho. Guardar uma vista homogénea do mundo é um ponto fundamental que pode não ser fácil em caso de uma reunião de dois grupos. Introduzimos três implementações de middleware, uma versão simulada usada para validar arquitectura e testar a sincronização dos algoritmos num ambiente multi-robô, uma versão móvel apontada para ser implementado em plataformas de hardware compostas por robôs móveis reais e finalmente uma versão de posição capaz de comunicar com robôs móveis, recolher informação e enviar ordens remotas.

Palavras-chave: Middleware, communicação de grupo, robôs móveis, sincronização de vista

Abstract

Nowadays, teams of mobile robots are involved in many contexts and environments where human intervention would be risky or even impossible, we can mention the surveillance of physical areas as military zones or nuclear plants. Due to increasing complexity in their embedded systems, these robots become more powerful but paradoxically more susceptible to face a hardware or software failure. What's more, unreliability in the wireless communication could deprive them temporally of their remote information support. For all these reasons, designing architectures able to offer more resilience to the control application has become a real challenge. In this document, we present a middleware architecture for the robots to share a common view and to handle new events in a safe and resilient way. The system relies on two key features, first a control layer based on two sub-modules, the payload and the wormhole, and secondly a cycle-proof event-based architecture used to run critical tasks in the payload. Regarding the control layer, the payload could be complex and has access to information shared among robots, while the wormhole is reliable but only uses local information. The wormhole controls the timely execution of the critical tasks by the payload. In case of timing failure, the wormhole takes control and runs these tasks in place of the payload. In addition to this architecture, we propose as well in this document some resilient synchronization mechanisms to maintain a coherent view of the world when two groups of robots are merging. We introduce three implementations of the middleware, a simulation version used to validate the architecture and test the synchronization algorithms in a multi-robot environment, a mobile version aimed to be ported to hardware platforms composed by real mobile robots and finally a station version able to communicate with mobiles, collect information and send remote orders.

Keywords: Middleware, group communication, mobile robot, view synchronization

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Chapter 1

Introduction

Mobile robot teams have the potential to reduce the need of human presence for complex or repetitive tasks. For most of them, the use of cooperation between robots can enhance the overall performance of the team. Achieving an efficient cooperation requires the use of complex algorithms implemented in each robot. This internal complexity in addition to the interaction issue with the environment makes the robot control system more sensitive to failures. Nowadays, building resilient control systems for mobile robots is a real challenge.

In this document, we present a middleware architecture for robots in charge of monitoring a physical area. In particular, we focus on some architecture features which improve the system resilience: A control layer based on two sub-modules the *payload* and the *wormhole* which guarantees a timely execution of critical tasks, a event-based architecture in charge of running the payload tasks and which avoids the event cycles, some synchronization mechanisms tolerant to communication failures and used to maintain a common world view for all robots especially during group merging or splitting phases and finally a dual multi-thread environment (Java and C) which communicates through *JNI*.

The project context is a cooperative surveillance application of a given area. The covered zone is a campus, a plant or any well-defined area. We assume that the world ground is flat and that each robot follows two-way routes defined in a prior map loaded at the robot startup. The surveillance aims to detect an accident or an intrusion and build a common strategy to handle properly the detected event (e.g. blocking the intruder). All robots run the same version of the middleware and are equipped with sensors, actuators and wireless devices. These devices can be hard connected to the robot or simulated through a simulation environment.

In chapter 2, we introduce some existing concepts and mechanisms we used to design the middleware. In chapter 3, we start by presenting the middleware architecture and more precisely the control layer based on the *wormhole* and *payload*. Chapter 4 addresses the task and event management and gives a focus on the module tree. In chapter 5, we discuss some test scenarios and provide a short review of the work. Finally, section 6 concludes the document.

Chapter 2

Related work and background

Robot group management covers several areas of techniques. In this chapter, we introduce concepts as the *wormhole/payload* model or the module-based approach which are key features of the middleware architecture. In section 2.3, group and view management highlights the necessity for the robot to maintain an up-to-date view of the world. The next section presents techniques to enhance the robot ability to navigate in the world. Finally in section 2.5, we describe some programming mechanisms implemented in the middleware.

2.1 Wormhole and payload model

In the vehicular domain, designing safety-critical application is essential, the work in [8], [2] or [10] presents a hybrid (synchronous and asynchronous) control model used in real-time applications. This model is based on two sub-systems, the *payload* in charge of running complex algorithms to figure out the best behaviour of each car to avoid collisions while the second sub-system, the *wormhole* is running synchronous and robust algorithms aimed to check whether the *payload* timely sends corrections to the car actuators. In case a timely timing failure is detected, the wormhole can temporally take control of the car. This technique is applicable to any domain where a safety-critical control is mandatory.

On robots, some critical tasks like the collision avoidance require for the control layer to timely send commands to the hardware layer. Algorithms used to figure out these commands might not be deterministic and their computation time may vary especially if they require network communication. The *wormhole* could check whether these commands are timely sent by the control layer which assumes the role of *payload*. If so, the *wormhole* will just forward them to the hardware layer. Otherwise, it will assume the robot's control by calculating and sending itself these commands. In this latter case, the *wormhole* would use a low-level algorithm which only involves local information. The *wormhole* will keep the control until the *payload* starts again to send commands on time. If the *payload* does not regain stability or even no longer sends any command (the *payload* may have crashed), the *wormhole* can restart the whole *payload* process.

The *payload* sends the new commands in a structure called the *promise*. Each *promise* includes a deadline which enables the *wormhole* to control the *payload*'s timeliness. For each promise, the *payload* is expected to send the next command before the current deadline is exceeded. The *wormhole* relies on three modules as shown in figure 2.1: The *Timely Timing Failure Detection* (*TTFD*) monitors the timeliness of the asynchronous *payload* process and can activate the *Safety task* to assume control. The *Control task* receives the *promise* which includes the new command and decides whether this command can be forwarded to the actuator layer. The *TTFD* sends as well control updates to the *payload* to inform it won back or lost the control. Ideally, the *payload* should use these control updates to improve its performance. In particular, it could try to real-time adjust the priority of some internal processes.

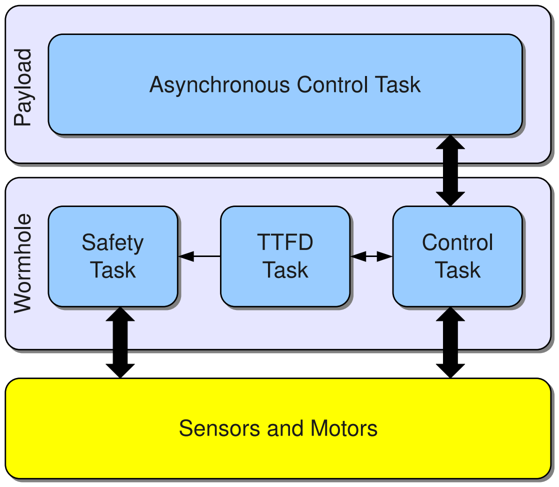


Figure 2.1: Payload and Wormhole layers

2.2 Modules and levels of competence

At the beginning of the 80's, Rodney A. Brooks [1] developed his subsumption theory based on levels of competence for robots. A lowest level of competence corresponds to a basic robot behaviour. The next levels define more complex behaviours but include the earlier levels of competence. According to Brooks, the key idea is to build a layer-based control system where each layer corresponds to a level of competence. To improve the overall competence of the system and move to the next higher level, we must add a new layer to the existing set.

Each control layer is composed by asynchronous modules which can be seen as finite state machines. As depicted in figure 2.2, the module has input and output signals. Each signal can be modified by a mechanism of suppressor and inhibitor which is based on the signal coming from another module. Some modules can work in closed loops, and thus use as input the feedback signal of other modules.

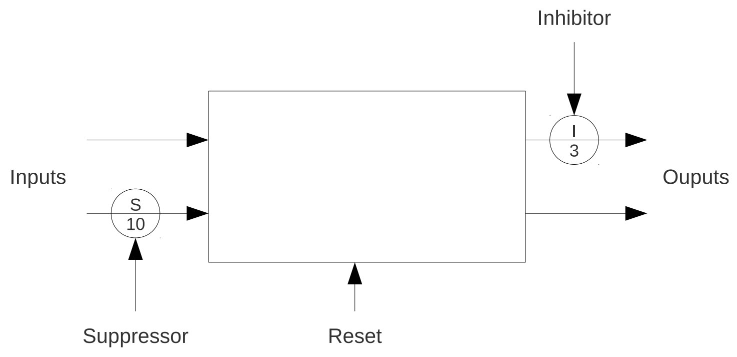


Figure 2.2: Brooks finite state machine

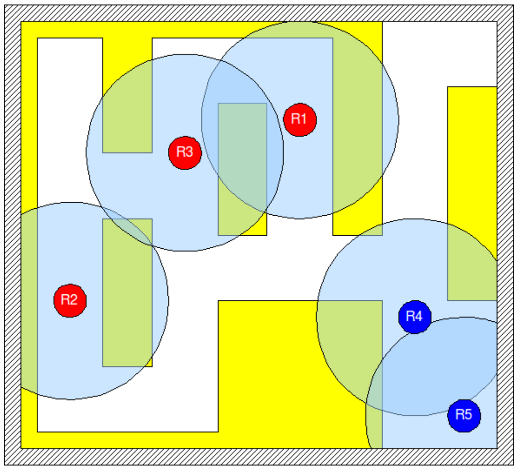
The idea to break down the control layer into various chains of small modules is powerful. However, it could lead quickly to complex architectures with a huge number of modules. As the information can circulate in cycles, the challenge is to keep the system stable and to avoid an out-of-control propagation of signals.

2.3 Group and world view

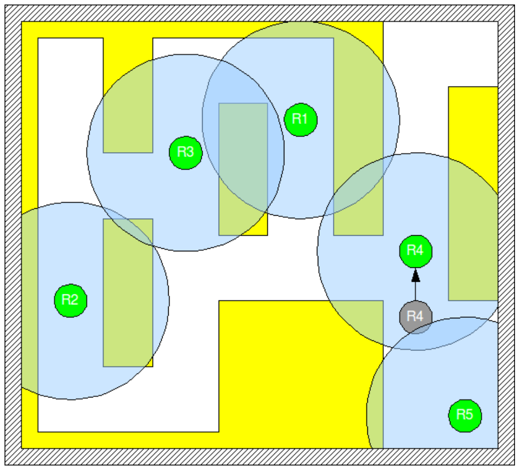
A group so called team is composed by robots which are part of the same network. They can communicate with each other and share information. A group is usually identified by a single *id*. The figure 2.3a shows two groups of robots with their network range. In figure 2.3b, the move of robot 4 leads to the union of both groups which become a single team.

The world view can be seen as the robot memory. The robot keeps information transmitted by its teammates or obtained by its local sources. The view is composed by a list of objects shared by all teammates.

Robot soccer game is an entertaining and well-known application of robot team cooperation. Actually, it shows many common points with our project like the need for all robots to real-time maintain a common view of the world. In the paper [9], the authors present an approach of view model which was successfully implemented during the 2002 RoboCup Sony competition. Due to some high latency in wireless communication, the



(a) Two isolated groups



(b) Group merging

Figure 2.3: Group merging phase

robot team does not perform any view synchronization. In order to track a dynamic object like the ball, each robot combines local information from vision sensors with shared information sent by team-mates. The robot maintains timestamps and uncertainty values for each view object, uncertainty is updated when receiving new information and grows with time.

This type of algorithm could be very efficient in high dynamic environment. However, it is based on a greedy approach in which each robot takes the most reliable information it has. Different robots can make different decisions which could become an issue as we want to build a common strategy for all robots. The other approach relies on a world view synchronization. The system maintains a shared view identical for all robots. The synchronization phase is performed when two robot groups are merging.

2.4 Localization and navigation

In the last twenty years, there has been a considerable amount of work to study mobile robot localization. Researches have been carried out focussing on two problems: computing absolute location using a priori map [7] or building incrementally this map while exploring the environment [3]. Both approaches most often rely on complex and math-oriented algorithms based on Kalman filters and maximum likelihood estimation [5]. The present document does not address this kind of problem and we assume that the robot is equipped with a localization device based for instance on GPS or RSS technologies. Given that the robot is able to locate itself in the real world, we have to find the most appropriate world model and the way to make the robot navigate through this model.

2.4.1 World model

There are two kinds of world models, either graph or cell decomposition. The second representation has many variants (adaptive cells, quadtree grid), the most simple is the regular grid based on a cell division. Each cell is a square representing a single world item. All cells have the same dimension. This world item can be a path section, a wall or an obstacle. The main advantage of such a representation is its simplicity and easy implementation. A world map can be coded in a text file where each character represents a cell.

For many calculations, a robot must be assigned to a given cell of the world model according to its real position in the world, this position is returned by the hardware devices. If we assume that the robot follows a path, the nearest path cell to the robot's current position is used to assign the cell. Since the robot could have drifted away from its path and given the lack of accuracy of the positioning device, the algorithm can use a maximum error margin. In figure 2.4a and 2.4b, cell assignment is achieved with respectively a low and high margin. In figure 2.4c, cell assignment failed due to a too large margin.

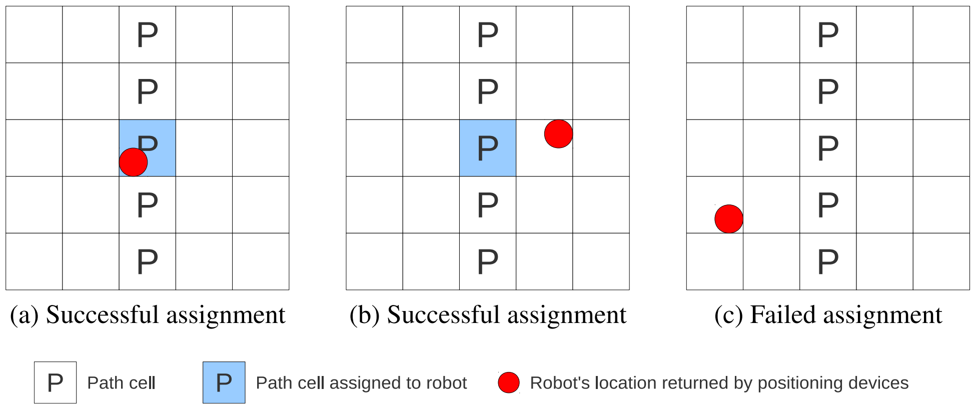

P
P
P
P
P
(a) Successful assignment
P
P
P
P
P
(b) Successful assignment
P
P
P
P
P
(c) Failed assignment
P
Path cell
P
Path cell assigned to robot
Robot's location returned by positioning devices

Figure 2.4: Example of robot cell assignments

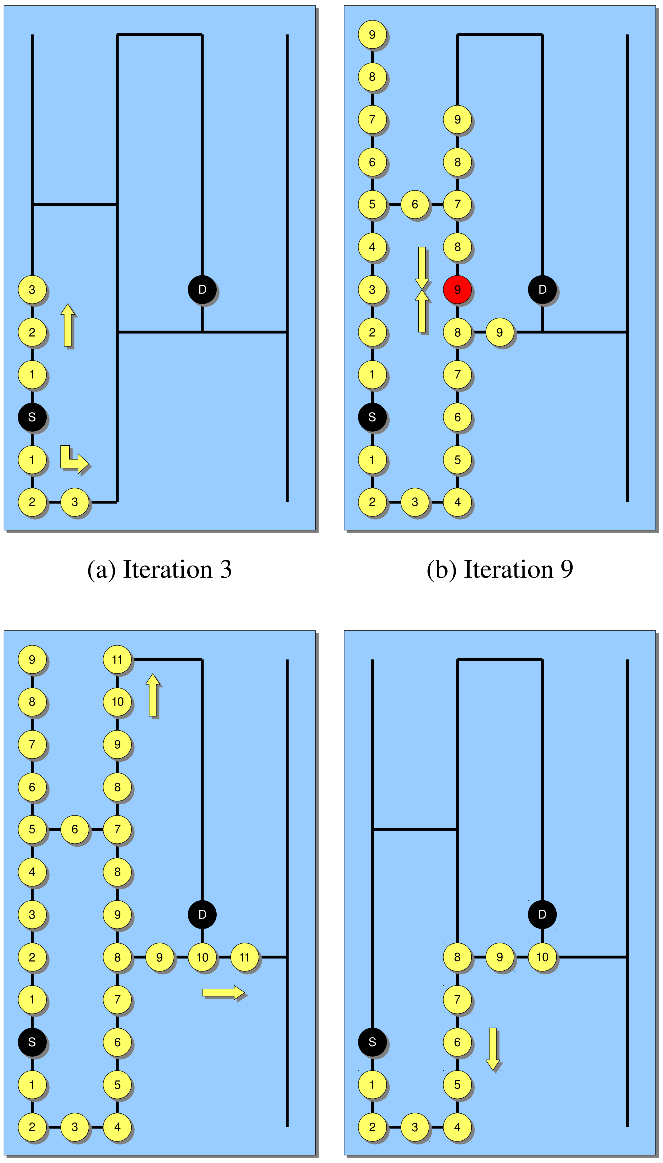
2.4.2 Wavefront-based algorithm

The way a robot team performs the surveillance of a physical area could obey many rules in order to maximize the probability of locating an intruder [6]. However, a simple strategy could be to make the robot just wander around the world and make random decisions to turn left or right at every crossing. But when a robot needs to meet another robot or block an intruder, some algorithms to calculate the better path are required. Wavefront-based path algorithms are well-suited for grid representations. In this type of algorithm, the wave is propagated from the start point towards all directions until get to the goal cell. The rules are the following:

1. Label all cells with $+\infty$ for the path sections and *-1* for the other ones. Label the start cell with *0*.

2. For every cell adjacent to the current cell, label it with an increment of the current cell distance if this new value is lower than both current distances of the adjacent cell and goal cell.

3. Continue the propagation from all cells which were updated during the previous step. Stop the algorithm when no more cells are updated.



(a) Iteration 3 (b) Iteration 9

(c) Iteration 11 (d) Gradient descent

Figure 2.5: Wavefront-based algorithm

Figure 2.5a shows an example of wave propagation with 3 iterations. In figure 2.5b, the descendant wave is stopped because of the distance of the red-circled cell *(9)*. The propagation terminates in figure 2.5c, the distance of the last updated cells is equal to the goal distance *(11)*.

Once the goal cell labelled with the best distance, we have to extract the best path using a gradient descent. First, given label of goal cell as *"x"*, we find the neighbouring grid cell labelled *"x-1"* then we mark it as a waypoint. We continue until get to the start cell labelled *0*. Figure 2.5d shows the final extracted path. In order to decrease the algorithm convergence time, dual wavefront propagation can be used from both start and goal locations.

2.5 JNI and multi-thread model

The Java Native Interface (*JNI*) enables the integration of code written in the Java programming language with code written in other languages such as C and C++. As the reader can find an abundance of basic examples, we will rather focus on the multi-thread issue which is more difficult to deal with. The figure 2.6 shows the interaction between Java and C codes. There are two types of functions implementing the *JNI* mechanisms: The C native functions called from the Java code and the Java callback methods called from the C code. Java and C codes use multi-thread environments which have to be compatible each other. That's why the choice of the multi-thread model is essential.

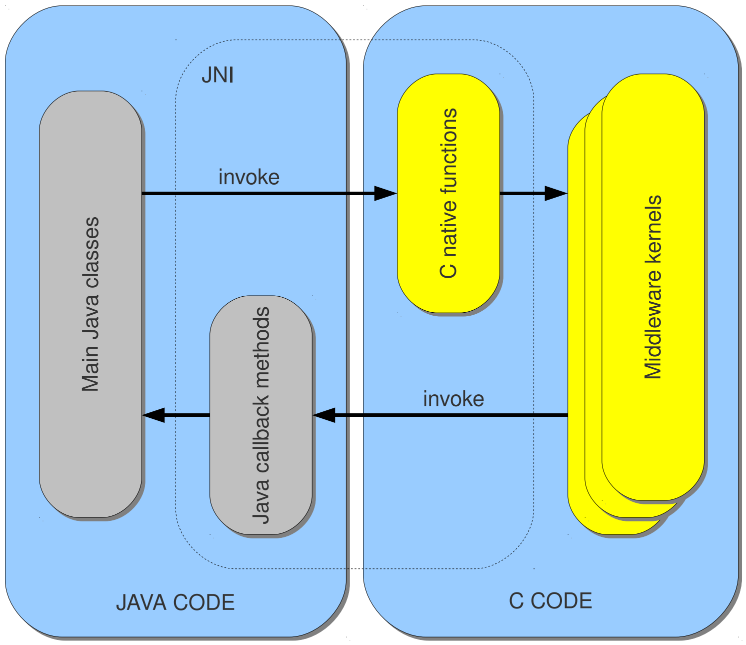


Figure 2.6: JNI architecture

Running various concurrent threads in the native C library requires to implement mutual exclusion mechanisms to avoid the simultaneous access to common resources. Actually, there are two different ways to address this issue in a native C code:

- Create some *java.lang.Thread* objects and use existing *JNI* mutex functions like *MonitorEnter* and *MonitorExit* to enter and exit from mutual exclusion zones.
- Use native thread creation and synchronization primitives like the *Posix thread* library. The mutual exclusion mechanisms are independent from *JNI*.

The first option is the safest one because we only use a single thread model which is the Java one. That way, we prevent from any compatibility issue between both thread models. The problem is that the C code becomes fully dependant of the Java implementation. Porting this C program to another platform requires to re-write large parts of the original code.

Chapter 3

Design

We start by a description of two main features of the middleware architecture: The *wormhole/payload* model and the tree-oriented architecture. Then sections 3.2 and 3.3 introduce mechanisms and algorithms to respectively maintain a coherent shared view between robots and figure out the best path in the world. Finally, the last chapter discusses the multi-thread model and *JVM* choices.

3.1 Architecture overview

An architecture overview is depicted in figure 3.1. The left side shows the middleware layer division. The *wormhole* and *payload* are the middleware basic components. The *wormhole* is placed in cut-through configuration between the *payload* and the sensor/actuator layer and does not have access to the network device. The *payload* runs all complex tasks in charge of the robot control. All tasks are triggered by events broadcasted through a module tree. An example of module tree used in the *payload* is shown in the right side of the figure. Each group of modules is dedicated to a specific task: Position update, navigation or world view management.

3.1.1 Wormhole and payload model

In a first version of the project, a special task (*watchdog*) was in charge of monitoring the critical tasks running in the middleware. Each task was supposed to be achieved before a given deadline, the latter was calculated in the same way for all tasks. The *watchdog* real-time monitored a critical task pool. All tasks that timed out were considered as blocked and were cancelled then restarted by the *watchdog*. Although this mechanism is pretty simple, it has many limitations:

- The cancellation success may depend on the task state. This point is particularly true when using some multi-thread implementations as *pthreads*. A *pthread* can only be cancelled when blocked in a *cancellation point*.

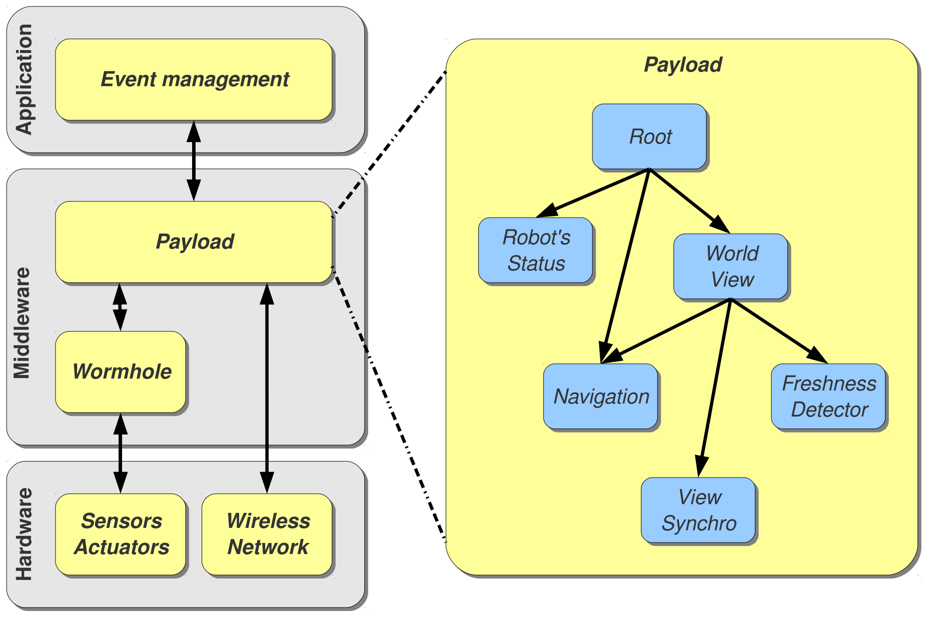


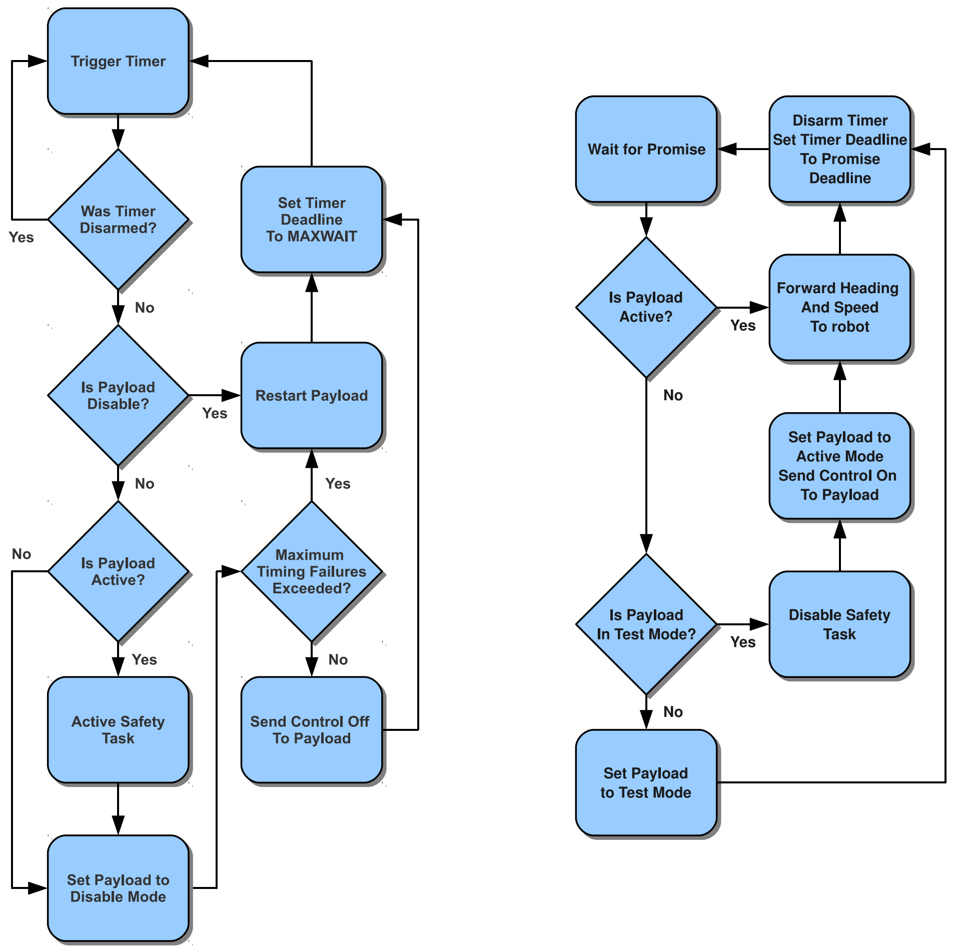
Figure 3.1: Middleware layer division and module tree

- The watchdog runs concurrently to the other tasks and thus could be affected in the same way (concurrency issue, computation delay, crash).
- The watchdog just cancels and restarts the task. When restarted, the task may redo some work and put the system in an incoherent state. Moreover, the task may fail once again and lead to a cancellation/restart cycle.

For these reasons, the *watchdog* approach was not suitable. We needed a more robust and flexible control mechanism which could run in an autonomous way and be placed in cut-through configuration between the critical task and the hardware layer. That way, this control module should be able to ignore a critical task result and take control in place of it which is exactly what the *wormhole/payload* model does.

Logical flowcharts of the *TTFD* and *Control* tasks are given in figure 3.2. The *payload* runs in three modes: *“active”* when it has the control, *“disable”* when it loses the control after the latest deadline is exceeded and finally in *“test”*, when the *wormhole* receives a timely promise while the *payload* is disabled. The *test* mode is a transition period, the *wormhole* keeps the control and waits for the *payload* to meet the current deadline before giving him back control.

There are two restart conditions for the *payload*. After setting it to *disable*, the *TTFD* task will increment a timing failure counter and will wait *MAXWAIT* milliseconds. If the failure counter is greater than a prior threshold or if no promise is received within this waiting period, the *TTFD* task will restart the *payload*. The timing failure counter is


Trigger Timer
Was Timer Disarmed?
Yes
No
Is Payload Disable?
Yes
Restart Payload
Set Timer Deadline To MAXWAIT
No
Is Payload Active?
No
Yes
Maximum Timing Failures Exceeded?
Yes
No
Active Safety Task
Send Control Off To Payload
Set Payload to Disable Mode
Wait for Promise
Disarm Timer Set Timer Deadline To Promise Deadline
Is Payload Active?
Yes
Forward Heading And Speed To robot
No
Set Payload to Active Mode Send Control On To Payload
Is Payload In Test Mode?
Yes
Disable Safety Task
No
Set Payload to Test Mode

(a) TTFD task (b) Control task

Figure 3.2: Wormhole logical flowchart

reinitialized when the *payload* wins back control. This counter allows to restart the *payload* after a given number of failures occurred in a raw but we can imagine more restart conditions as for instance, a maximum number of failures in a given period of time.

Let's see now an example of promises exchange between *payload* and *wormhole*. In figure 3.3, a first promise gets to the *wormhole* with a deadline *t1*. The second promise with deadline *t2* is sent timely to the *wormhole* before *t1*, the *payload* keeps the control. At *t2*, the *wormhole* has not received yet the next promise so it takes control and sends a control-off acknowledgement to the *payload* which is disabled. When the promise with deadline *t3* gets to the *wormhole*, the latter keeps the control and set the *payload* to the *test* mode. Finally, the *wormhole* receives the deadline *t4* on time, so it gives control back to the *payload* and sends it control-on acknowledgement.

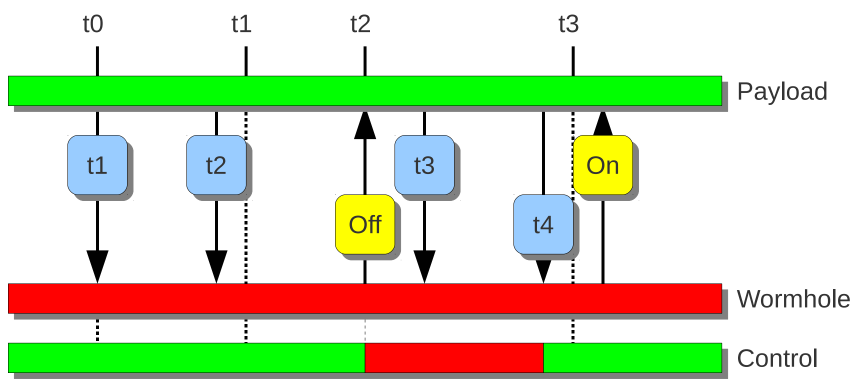


Figure 3.3: First example of control change

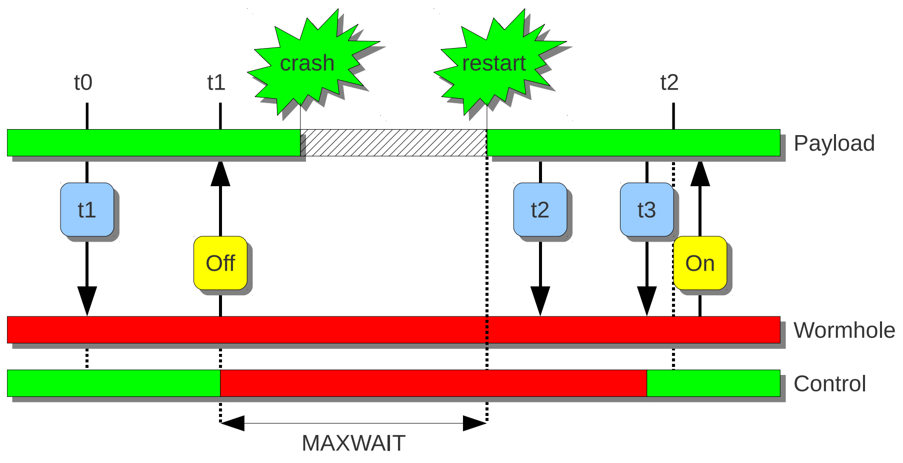


Figure 3.4: Second example of control change

In the example 3.4, we assume that the *payload* crashes after sending the second promise. At *t1*, the *wormhole* which has not received the new promise, takes control. After *MAXWAIT* milliseconds, the *wormhole* considers that the *payload* is on trouble and restarts it. The rest is similar to the previous example, the *wormhole* keeps the control until the *payload* fulfils its new promise with the deadline *t2*.

3.1.2 Tree-oriented architecture

The event-based architecture is well adapted to robot management. It allows to design a flexible and modular architecture. Indeed, we can create an event type for any robot feature and dedicate a part of the tree to handle this event. Moreover, robot hardware is composed by sensors, actuators and communication devices, each one of them can generate a special event or be triggered by this event. The *obstacle* event is an example of event which contains the distance values read from the local sensor.

This architecture is a simplified application of the subsumption theory developed by Rodney A. Brooks. The *payload* is composed by modules and groups of modules, all gathered in a tree. Each of them is in charge of managing a robot feature. A module can be seen as a process, with a short computation time, which is started by a single incoming event and can produce one or more outgoing events. The number of produced events depends on the computation result. All modules could be meshed as a graph and thus make event cycles possible. In order to avoid hazardous out-of-control cycles inside one robot or between several robots, we chose a tree-oriented module architecture.

The tree branch is composed by a group module which is the branch's root and some child modules (leaf or group) connected under the root. Unlike a leaf module, a group module does not have any computation stuff. Each module can have one or several parents. A leaf module computation is started if the incoming event can be consumed by the module. When a leaf module is triggered by a incoming event, the possible outgoing event is broadcasted from the module's parent which first broadcasted the incoming event.

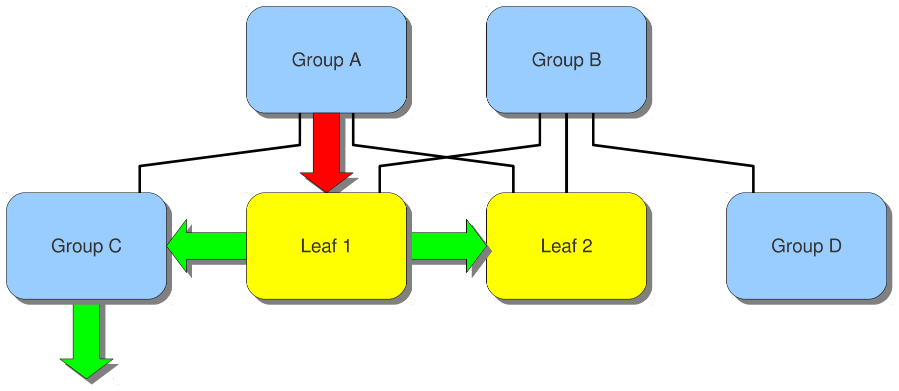


Figure 3.5: Propagation of a produced event

This mechanism is illustrated in figure 3.5: *Group A* is parent of *Group C*, *Leaf 1* and *Leaf 2*. *Group B* is parent of *Leaf 1*, *Leaf 2* and *Group D*. When the red incoming event triggers the computation of *Leaf 1*, the green outgoing event is propagated to *Group C* and *Leaf 2* but not *Group D* which is not a son of *Group A*. *Group C* will keep on broadcasting the event to its sons and so on. That way, each event is top-down broadcasted until the tree leaves. Three types of events can trigger a module execution:

- **Hard events**: They are signals generated by the robot's hardware, e.g. the robot's clock (*beat* event) or a distance sensor measure (*obstacle* event). Such events are always broadcasted from the tree's root.
- **Local soft events**: These events are produced by a module and are broadcasted through the neighbour branches (modules with same parent) and the sub-branches. Any module can produce several soft events during the same computation.
- **Remote soft events**: Instead of being broadcasted locally, they are transmitted through the wireless network and sent to all other robots. Once delivered to a given

robot, the event is broadcasted from the same branch as if it would be produced locally. This mechanism relies on two architecture properties: The module tree has the same structure for all robots which means that any path in the local tree matches the same path in a remote tree. Secondly, the path to locate the module which produced the event in the tree, is stored in the transmitted event. That way, we cannot have event cycles between robots and the remote soft events meet the same constraints as the hard and local soft events.

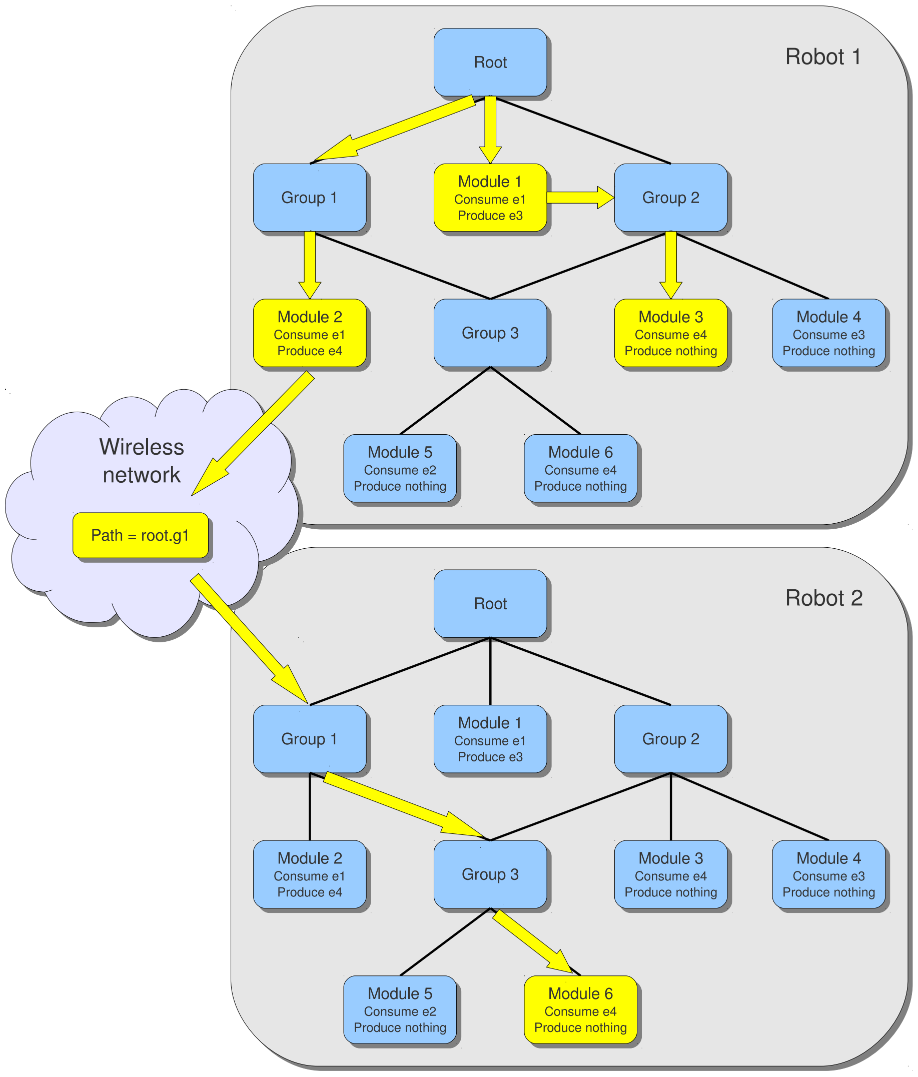


Figure 3.6: Example of event broadcast with two robots

Let's consider a group of two robots with the same module tree as depicted in figure 3.6. We assume that *e1* and *e2* are hard events, *e3* a local soft event and *e4* a remote soft event. Now, let's have a look on the started modules (in yellow in the figure) if *e1* is triggered on robot 1:

- Module 1 of Robot 1 (locally triggered by *e1*)

- Module 2 of Robot 1 (locally triggered by *e1*)
- Module 4 of Robot 1 (locally triggered by *e3*)
- Module 6 of Robot 2 (remotely triggered by *e4* with path *root.g1*.

Although module 3 can consume the *e4* event, this module is not started in robots 2 because it cannot be reached from the path *root.g1*. As a leaf module cannot start a computation and produce an outgoing event without incoming event, a cycle of event production is a chain reaction which always starts with a *hard event*.

What's more, this architecture opens the possibility of dynamically enabling or disabling a sub-branch of the module tree. When disabled, events are no longer broadcasted through this branch. The activation or disactivation can be performed by any computation module. In our project, each robot has three working modes: *Wandering*, *Searching* and *Blocking* (an intruder), each mode corresponds to a single branch of the navigation subtree. We use the branch enabling/disabling mechanism to activate the modules associated to the robot current mode.

3.2 View and group management

Given that robots can move away from each other and go beyond their wireless range, a group can be split in various sub-groups. The unreliability of the wireless network can also lead to isolate a single robot if it temporarily loses the Wi-Fi signal. As discussed in section 2.3, the synchronization of all views in this situation is not mandatory, robots could keep on exchanging information and acting according to their local knowledge of the world. But one purpose of the middleware is to provide a cooperative framework to allow robots to build common strategies. This last point implies for all robots to maintain a shared view of the world so a synchronization mechanism is necessary to consolidate the information of each group view especially when two group are merging. This mechanism involves a leader in each group, which is the robot with the lowest *id* in the group.

3.2.1 Time synchronization

In order to maintain an up-to-date world view, information requires to be timestamped. When an object is transmitted through the network, this timestamp is set by the sender just before the emission. The receiver to make use of the timestamp, must have its internal clock synchronized with the sender or know the time-lag between its clock and the sender one.

As the first solution implies to use dedicated network protocols as *NTP* to synchronize all clocks, we chose the second solution. But instead of storing as many time-lags as teammates, the robot just maintains one time-lag with its leader. The algorithm 1 details the *Object Receiver* module involved in the time synchronization phase (line 1). This module is triggered by an *Object* event received through the network. If the object comes from the leader, the algorithm calculates a mean time-lag over a number of rounds (line 9). The greater is the number of rounds and the more accurate is the time-lag calculation. If the leader has changed since the last iteration, the mean time-lag calculation is re-initialized (line 5). The *readTimestamp* function (line 12) is used to read an adjusted timestamp value. The robot state parameters are as follows:

- *myLastLeader*: Latest leader *id* the time synchronization was performed with.
- *myRoundNumber*: Number of rounds since the time synchronization initialization.
- *myLagSum*: Consolidated time-lag over $myRoundNumber$ rounds.

Algorithm 1 Time synchronization algorithm

```
1:  upon event <object | type, id, ts> do
2:      if $type = "robot" \wedge id = myLeader$ then
3:          $delta \leftarrow$ DIFFTIME($ts$)
4:          if $id \neq myLastLeader$ then
5:              $myLastLeader \leftarrow id$
6:              $myLagSum \leftarrow delta$
7:              $myRoundNumber \leftarrow 1$
8:          else if $myRoundNumber < MaxRoundNumber$ then
9:              $myLagSum \leftarrow myLagSum + delta$
10:             $myRoundNumber \leftarrow myRoundNumber + 1$
11:
12: function READTIMESTAMP(ts)
13:     $lag \leftarrow myLagSum \div myRoundNumber$
14:     return $ts - lag$
```

The time synchronization algorithm is very simple. However, the time-lag must be re-calculated at every leader change. As there is no synchronization between teammates, a robot could have started a calculation with the new leader while another robot would still use the time-lag of the old leader. During this short period of time, the timestamp calculated by a robot might be wrong which is not problematic in our case.

3.2.2 World view synchronization

We will now describe in details the synchronization algorithm used to maintain in each robot a coherent world view when two or more groups are merging. This view is composed by all dynamic objects present in the world. The first part will deal with the algorithm principles and the second part will present some synchronization scenarios.

Algorithm principles

When two groups are merging, the synchronization is performed by exchanging a *synchro* event which contains the list of all view objects except for the robots position. This latter is already exchanged through the *hello* events so including this information in a *synchro* event would be redundant. The *synchro* event is normally sent by the group leader. The *synchro* event reception is not centralized by the leader, each robot from the destination group, will handle the *synchro* event and extract the object list. The synchronization phase ends when all robots have the same leader and group id.

The basic steps below are associated to a faultless synchronization phase. By fault, we mean any event reception failure due for instance to a temporally Wi-Fi signal loss. Different fault scenarios will be discussed in the next section. Two *synchro* events are exchanged during a faultless synchronization, the first *synchro* event is always generated by the group leader with the higher id.

- *Step 1*: Leader 1 receives a *hello* event from the group leader 2.
- *Step 2*: Leader 1 broadcasts a *synchro* event through the group 2.
- *Step 3*: Robots from group 2 receive the object list and update their view.
- *Step 4*: Leader 2 broadcasts a *synchro* event through the group 1.
- *Step 5*: Robots from group 1 receive the object list and update their view.

The algorithm 2 gives the modules involved in the synchronization phase. The *Hello Receiver* module (line 1) is triggered by an *object* event which is used by a robot to broadcast its own position, the module checks out whether this event comes from another leader. The *View Synchronizer* module (line 9) is triggered by a *synchro* event, it extracts the object list and updates the local world view (line 16). Finally, the *Freshness Detector* module (line 22) is triggered by the *beat* event and removes out-of-date objects from the robot's view. The *beat* is a hard event periodically generated by the system. The robot state parameters are as follows:

- *myId*: single robot identifier.
- *myView*: view objects including team-mate positions.
- *myLeader*: current group leader identifier.
- *myGroup*: current group identifier.

Algorithm 2 View synchronization algorithm

```
upon event <object | type, id, leader, group> do
    if $type = "robot" \wedge (leader \neq myLeader \vee group \neq myGroup)$ then
        if $id = leader \wedge myId = myLeader \wedge id < myId$ then
            SYNCHRONIZATION($myLeader, leader$)
        else if $id = myLeader$ then
            SYNCHRONIZATION($myId, leader$)
            $myLeader \leftarrow myId$

upon event <synchro | leader1, leader2, objList> do
    if $myLeader = leader2$ then
        if $leader1 < myLeader$ then
            $myLeader \leftarrow leader1$
        if $myId = myLeader$ then
            SYNCHRONIZATION($myId, leader1$)
        for all $obj \in objList$ do
            trigger <object | obj.type, obj.id, obj.leader, obj.group>
        if $leader1 > leader2$ then
            $myGroup \leftarrow leader1$
        else
            $myGroup \leftarrow leader2$

upon event <beat | > do
    $updateRequired \leftarrow false$
    for all $obj \in view$ do
        if $isUptodate(obj) = false$ then
            $view \leftarrow myView - \{obj\}$
            if $obj.type = "robot" \wedge (obj.id = myLeader \vee obj.id = myGroup)$ then
                $updateRequired \leftarrow true$
    if $updateRequired = true$ then
        $updateLeader()$

procedure SYNCHRONIZATION(leader1, leader2)
    $objList \leftarrow \{\}$
    for all $obj \in myView$ do
        if $obj.type \neq "robot"$ then
            $objList \leftarrow objList + \{obj\}$
    trigger <synchro | leader1, leader2, objList>

procedure UPDATELEADER
    $myLeader \leftarrow myId$
    $myGroup \leftarrow myId$
    for all $obj \in myView$ do
        if $obj.type = "robot" \wedge obj.id < myLeader$ then
            $myLeader \leftarrow obj.id$
        if $obj.type = "robot" \wedge obj.id > myGroup$ then
            $myGroup \leftarrow obj.id$
```

Examples of synchronization scenarios

The normal synchronization phase is shown in figure 3.7 while figures 3.8 and 3.9 show various synchronization scenarios with respectively two and three different groups merging at the same time. Each group is first composed by two robots. Arrows identify events (blue for *hello* and red for *synchro* events) which are handled by robots for the synchronization phase. Other *hello* events broadcasted to periodically announce robot positions are not represented here. Each scenario is given as an example. Therefore, the number of events exchanged during a scenario could be different according to the order each event is delivered with. This statement is especially true if the number of groups merging at the same time is large.

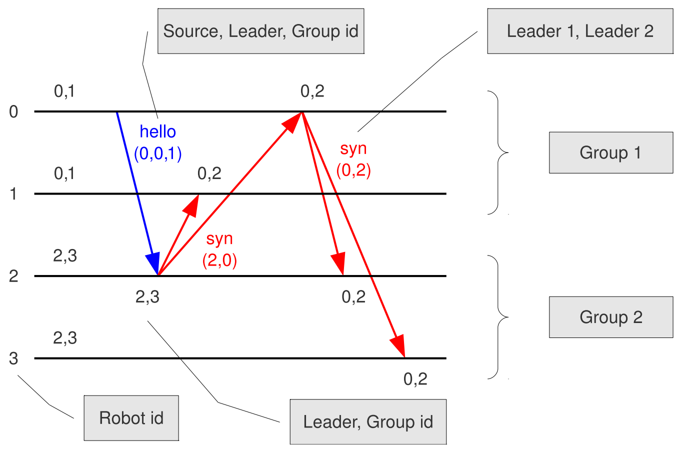
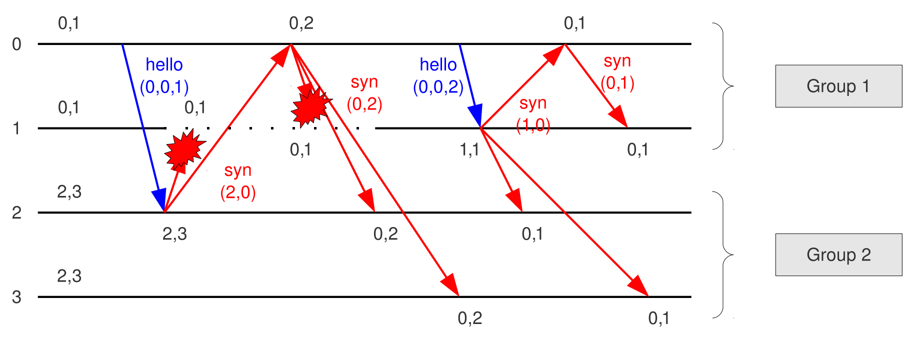


Figure 3.7: Two-group synchronization without failure

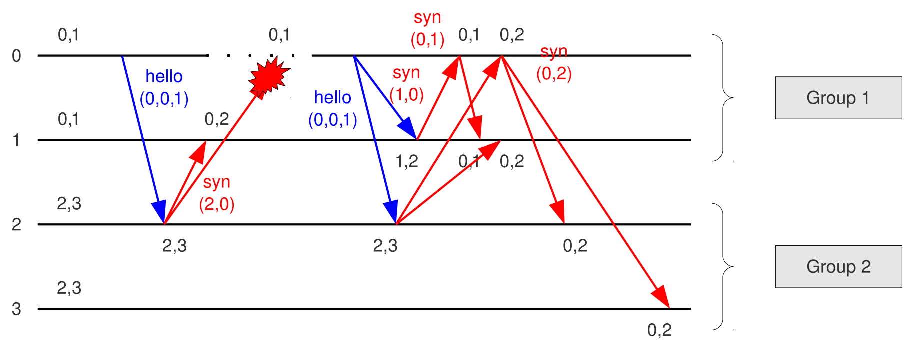
In a robot time line, couple of black values correspond respectively to the leader and group id. The *hello* event parameters are the source robot, leader and group id. Finally, the *synchro* event parameters are the source and destination leader id (*leader1* and *leader2* in the algorithm 2).

Scenarios 3.8a, 3.8b and 3.8c highlight temporally reception failures which lead the robot to broadcast extra events to achieve the synchronization. Such failures could be due to a temporary Wi-Fi signal loss. The extra event phase is initialized by the faulty robot which receives a *hello* packet from its leader. This mechanism is implemented at line 5 of the algorithm 2.

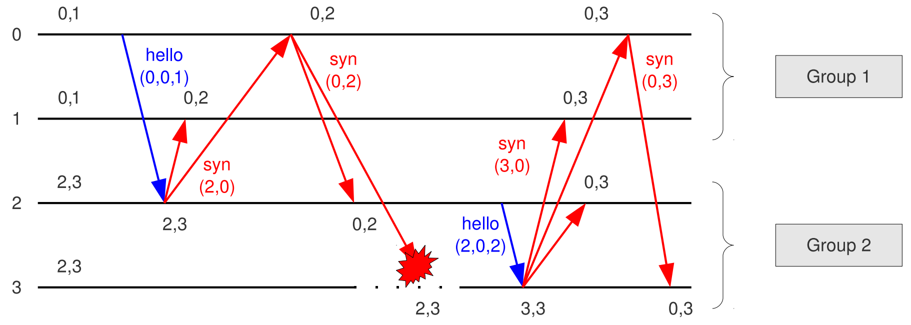
The last scenario 3.9, three groups merging at the same time, is unusual but shows the algorithm resilience. We can notice that at the end of the first “round”, the robot 3 does not have the same group id than the others (yellow-circled value). The situation gets stable after the second *hello* event.



(a) Reception failure on robot 1



(b) Reception failure on robot 0



(c) Reception failure on robot 3

Figure 3.8: Two-group synchronization with failure

This algorithm is very simple and offers resilience in signal loss situations. Nevertheless in some tricky scenarios, it could require more than one round, i.e. more than one *hello* event to stabilize itself. *Hello* events are periodically generated (according to the *beat* signal frequency), so increasing this beat signal frequency to accelerate the synchronization phase could be attractive but may on the other hand overload the wireless network and what's more, lead to some algorithm instability if this frequency is greater than half the mean round trip delay of the wireless network.

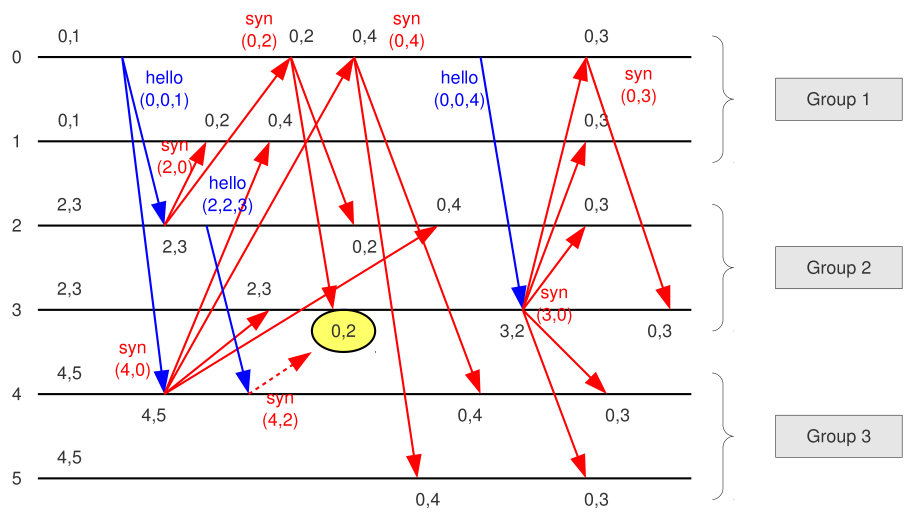
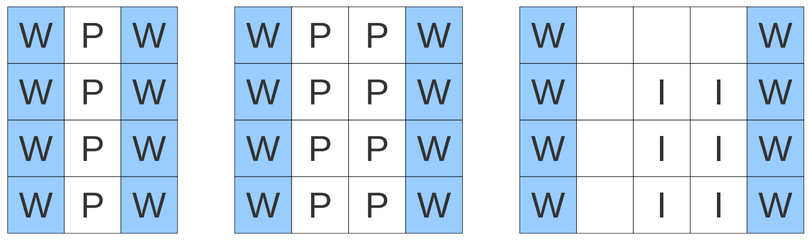


Figure 3.9: Three-group synchronization without failure

3.3 World model and navigation

We choose a simple world representation based on a regular grid (see 2.4.1). The real world is divided into regular cells, each cell represents a world item (wall, path, robot, invader). We approximately size the cell to the robot width and assume that an one-cell path does not allow two robots to pass each other (figure 3.10a). The path has to be duplicated to allow two robots to pass one another (figure 3.10b). The path is a special cell used to tag the routes the robots can take in the world. An intruder or any unusual event like a fire, larger than a cell can be split into various cells (figure 3.10c).



(a) One-cell path (b) Two-cell path (c) Large intruder zone

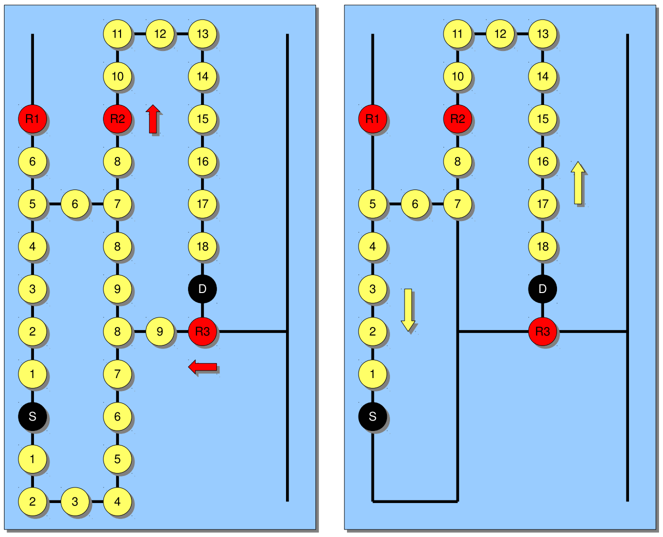
Figure 3.10: Example of cell divisions cells

Regarding the shortest path algorithm, the wavefront-based mechanism described in section 2.4.2 is simple and efficient, however it does not take into consideration the possible obstacles which could block the robot and force it to turn back especially inside an one-cell path. Table 3.1 classifies the obstacles into four categories. We propose an improved version of the algorithm in which each obstacle can affect the behaviour of the propagation wave.

Obstacle type	**Behaviour**
Intruder	Stops the propagation wave
Stopped robot	Stops the propagation wave
Robot moving in the same direction as the propagation wave	Lets the propagation wave go
Robot moving in another direction	Stops the propagation wave

Table 3.1: Propagation wave behaviours

Let's consider a world with three robots: *R1*, *R2* and *R3*. Figure 3.11a shows the path covered by the propagation wave if *R1* has stopped, *R2* is going up in the same direction as the wave and *R3* is going left in the opposite direction to the wave. Unlike *R1* and *R3*, *R2* lets the wave go, the shortest path is given in figure 3.11b after a gradient descent.



(a) Iteration 19 (b) Gradient descent

Figure 3.11: Improved wavefront-based algorithm

As robot moves can change quickly, the shortest path algorithm is computed each time the robot passes through a new cell, until it gets to the goal cell. That way, the shortest path will be updated in case another robot crosses the path or changes its direction.

Another improvement could be to associate a cost to every path cell. This cost could be set according to the ground nature (low cost for smooth ground, high cost for rocky area) and consequently to the robot's maximum speed on this ground. It could be as well associated with the distance from a identified danger like a fire. The cost would be introduced in the shortest path calculation.

3.4 Multi-thread environment and JVM

As we explained in 2.5, the choice of the multi-thread model is essential. We chose the *pthread* library because we wanted the middleware to be as independent as possible from Java and fully portable to another platform. Regarding the simulation and station versions, the multi-thread model used in the Java virtual machine (*JVM*) must be compatible with the C multi-thread model. Manipulating native threads in the middleware kernel could lead to deadlocks and crashes if the JVM implementation does not fully support a thread model that matches the native model.

Although we do not notice any crash with *Open JDK* which is supplied by default with many Linux distributions, this *JVM* version is said not to be compatible with pthreads. For these reasons, we adopted *Sun JDK 6.0* which uses internally pthreads. Moreover this framework is associated with the *Java 3D* package used in *Simbad*.

Chapter 4

Implementation

The chapter starts with a presentation of the three implementations of the middleware kernel. For each of them, we will present the interaction between the *wormhole* and the other layers. The two next sections deal with the task management respectively in the *wormhole* and *payload*. Section 4.4 focusses on the world view content and the update context. In the next section, we explore the module tree and detail the communication and navigation modules. In section 4.6, we describe some of the mechanisms we used to manage concurrency in both Java and C codes. Finally, in the last section, we address some programming issues we faced during development.

4.1 Middleware versions

The development of the middleware kernel is a large part of this project. The kernel contains the *wormhole* and *payload* modules and all the event-based architecture we defined previously. The kernel is designed to run in an autonomous way. Three types of interfaces are defined with the robot environment. For each of them, the kernel uses primitives to interact with the real or simulated environment.

- **The actuators:** The kernel can change the speed and heading of the robot.
- **The sensors:** The kernel can get the absolute Cartesian position of the robot, as well as its current speed and heading. Moreover, the kernel can read the absolute Cartesian coordinates of an obstacle situated in front of the robot.
- **The network:** The kernel can send and receive information through a wireless device. That way, it can exchange information with all teammates.

In a real environment, installing such interfaces is not a simple thing and may requires to set up intermediate equipments. In this project, we just assume that the kernel has access to this information. At this stage, we can now present the three versions of the middleware, each one involves one or various kernels:

- **Simulation**: It uses a robot simulation tool called *Simbad* which allows to easily create a 3D environment with several robots. A robot can be moved around the world using simple Java primitives. For each robot, the simulation runs a different kernel and simulates the wireless network to exchange information between all robots.
- **Mobile**: It runs a single middleware kernel and aims to be installed on a hardware platform with hard devices (actuators, sensors, network). The mobile can communicate with others mobiles or stations through the wireless network. This version is fully autonomous.
- **Station**: It is similar to the mobile as it uses a single kernel. The station runs on a fixed PC and can communicate as well with mobiles or other stations. A Java interface allows to simulate the interaction with the sensors and that way, create fake intruders. Finally, the station can send and receive *control* events which allow it to remotely control mobiles and collect information. This feature will be detailed further in this chapter.

In simulation and station versions, parts of the code are written in Java. Communication between Java and C codes is handled with the *JNI* package (Java Native Interface). The figure 4.1 depicts the three combinations of kernels.

The middleware kernel is composed by the *wormhole* and *payload* layers. As explained in section 3.1.1, both layers must be as independent as possible. We implemented each one as a single Unix process, the *pthread* library is in charge of the thread concurrency management inside a layer. Communication between both *wormhole* and *payload* is handled with *UDP* sockets. The *TCP* protocol offers a reliable delivery service but is inadequate in wireless environments. We will now enter the kernel architecture and see in details each versions:

4.1.1 Simulation version

Figure 4.2 shows the three simulated *JNI* interfaces (sensors, actuators and network) which are connected to the *wormhole* layer. In reality, only the *wormhole* kernel should compose this layer because the actuators is the only required interface. But maintaining two processes connected with *JNI* to the Java simulation would not be efficient so the *wormhole* sensor and network interfaces are just in charge of forwarding packets to the *payload*.

The *wormhole* layer shares three communication channels with the *payload* each one dedicated to a given type of information: Sensor inputs for channel 1, promises and warning for channel 2 and finally networks events for channel 3. Each channel is handled

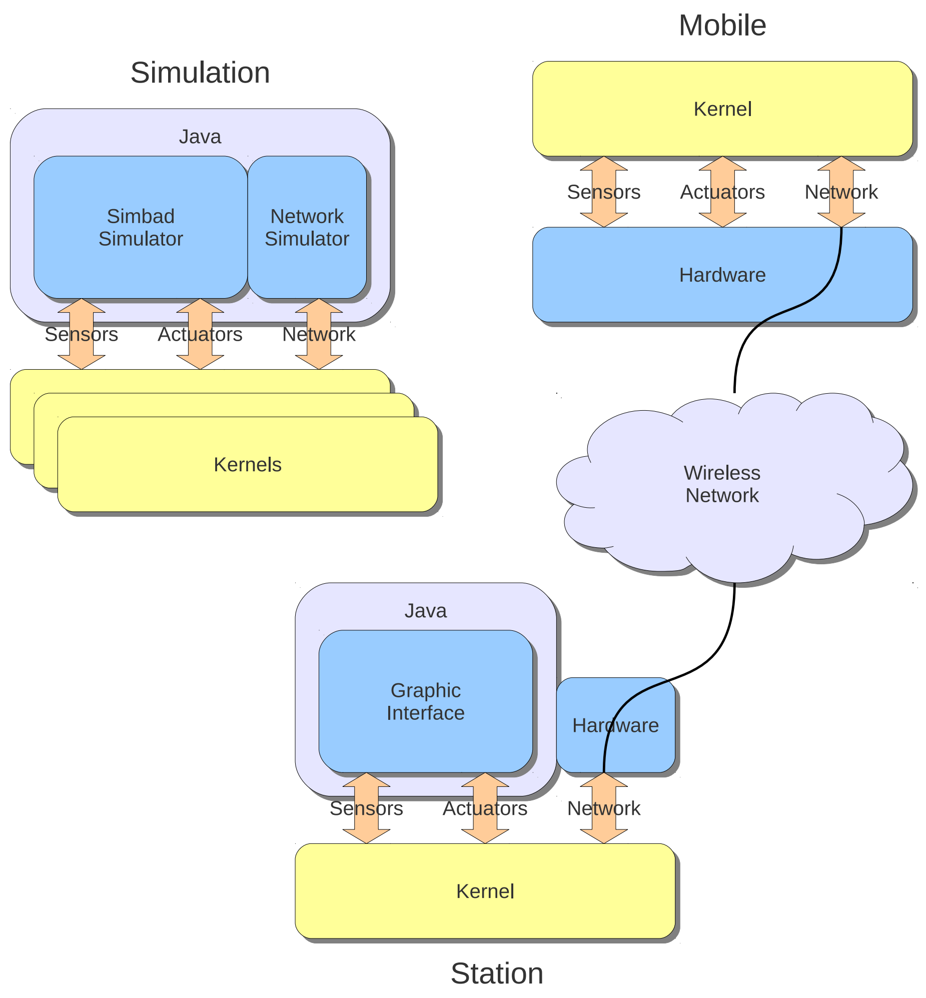


Figure 4.1: Middleware versions

with UDP sockets. Every interface corresponds to a thread listening to a given UDP port. All ports are dynamically allocated when *wormhole* and *payload* are started up. Let's remember that the simulation layer will launch as many middleware kernels (*wormhole* and *payload*) as simulated robots. Table 4.1 details the data exchanged through the three channels.

Finally, we can notice the presence of a bridge between the sensor interface and the *wormhole* kernel. As described in section 3.1.1, the *wormhole* can take control of the robot through the *safety* task. This task has to pilot the robot with a basic navigation algorithm and consequently, needs to get some information from the sensor interface.

4.1.2 Mobile version

The mobile version architecture (see figure 4.3) is quite similar to the simulation. The simulation layer and *JNI* mechanism have disappeared and have been replaced by the

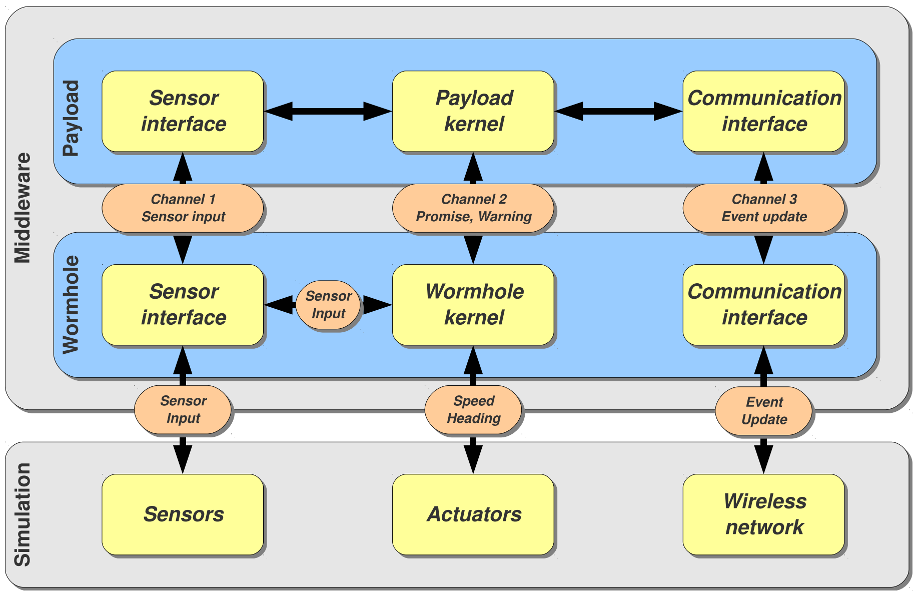


Figure 4.2: Architecture of the simulation version

Channel	Direction	Description
1	To payload	Current robot coordinates and possibly obstacle coordinates
1	To wormhole	Sensor initialization message sent at payload's start and after any sensor failure
2	To payload	Warning message to inform the payload it won or lose control
2	To wormhole	Promise including the deadline and the speed/-heading orders
3	To payload	Any events sent by the wormhole
3	To wormhole	Any events sent by the payload

Table 4.1: Simulation UDP channels

hardware layer. As the *wormhole* does not access to the network, the wireless interface is directly connected to the *payload*. As a consequence, there are only two UDP channels between *wormhole* and *payload*.

4.1.3 Station version

The station version architecture (see figure 4.4) is actually a mix between simulation and mobile versions. The sensor and actuator interfaces are simulated and connected to a *JNI* simulation layer. The Java part contains the implementation of a graphic interface used to create fake sensor information. The network interface is connected to the *payload* as for the mobile version.

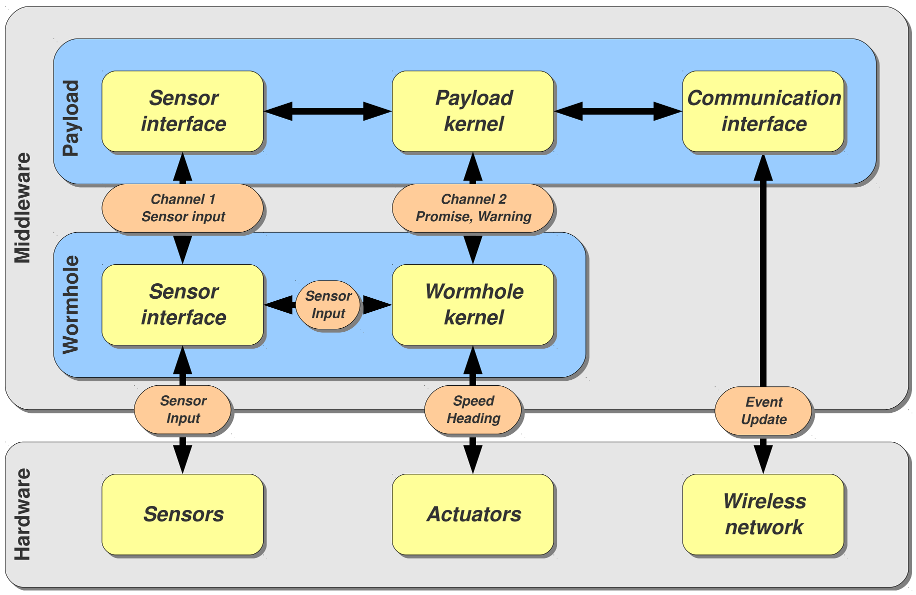


Figure 4.3: Architecture of the mobile version

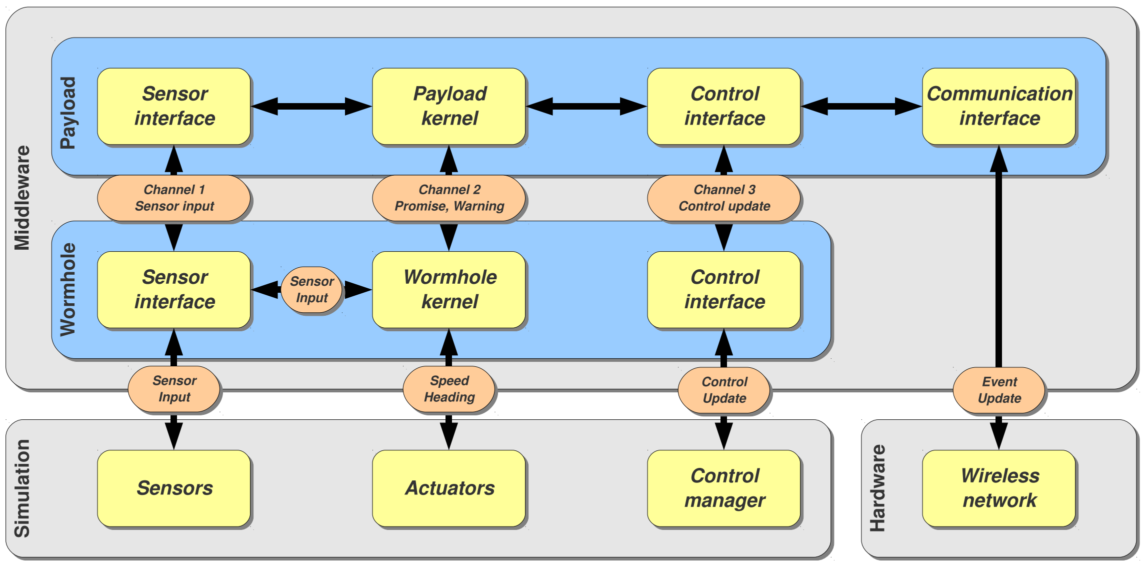


Figure 4.4: Architecture of the station version

There is a fourth communication channel used to transport *control* events. These special events will be further detailed and are exchanged between mobiles and stations. The station uses *control* events to send remote orders to mobiles or to receive state acknowledgements from them. *Control* events transit through the network so they are first delivered to the *payload*. The latter uses the control interface to forward these events until the control manager and the Java interface.

4.2 Task management in wormhole

As described in 3.1.1, the *wormhole* main components are the *Control*, *TTFD* and *Safety* tasks. Each of them corresponds to a concurrent process initialized at the wormhole's startup. The logical flowchart 3.2 gives the actions of each task.

4.3 Task and event management in payload

In this section, we will focus on the *payload* and especially the event production. Below a list of different types of events and their production context. According to the type, an event can transport some basic data which can be used by the triggered module.

- **Beat (hard event)**: this event is a pulse with a static frequency (currently 2 Hz). The pulse thread generates the *beat* event every 500 ms and broadcast it from the tree's root. This event is used by some leaf modules to perform repetitive and regular tasks.

- **Obstacle (hard event)**: This event is generated as soon as an obstacle is detected in front of a robot. The event is produced as long as the obstacle is detected and at the same frequency as the beat event. The event contains the absolute Cartesian coordinates of the obstacle.

- **Object (local and remote soft event)**: This event is the most important one. As a local soft event, it is used to update the robot local view. As a remote soft event, it is regularly sent by a robot to signal its position (*hello* events). It is used as well by a robot to broadcast an obstacle position update. The event contains all object information: coordinates, speed and heading. If the object is a robot, the *robot id*, *group id* and *leader id* are also included.

- **Synchro (remote soft event)**: It is produced during the synchronization phase between two groups (see algorithm 2). Each group leader uses it to send the content of their local view. This content can be seen as a list of concatenated *object* events.

- **Move (local soft event)**: The communication modules use this event to inform the navigation modules that the current robot's route must be recalculated. A world view update means either that some objects have moved in the world so the current best route might have been changed, or that a new intruder has been detected so a new route to get to this intruder must be found.

- **Control (hard and remote soft event)**: It is used by a station to send remote orders to the mobiles. On the other side, it is used by each mobile to send information (as view update status) to the station. This special event is a remote one because it can be broadcasted through the network but it can also be considered as hard because it is initially produced by the station graphic interface.

4.3.1 Event handling cycle

Figure 4.5 illustrates the production cycle of events which always starts with a hard event production. This first event is pushed into the event queue. Then the event dispatcher process pops it from the event queue and broadcasts it from the root of module tree. Each leaf module triggered by the event in the tree must execute its associated task. The task information (module and incoming event) are pushed into the task queue.

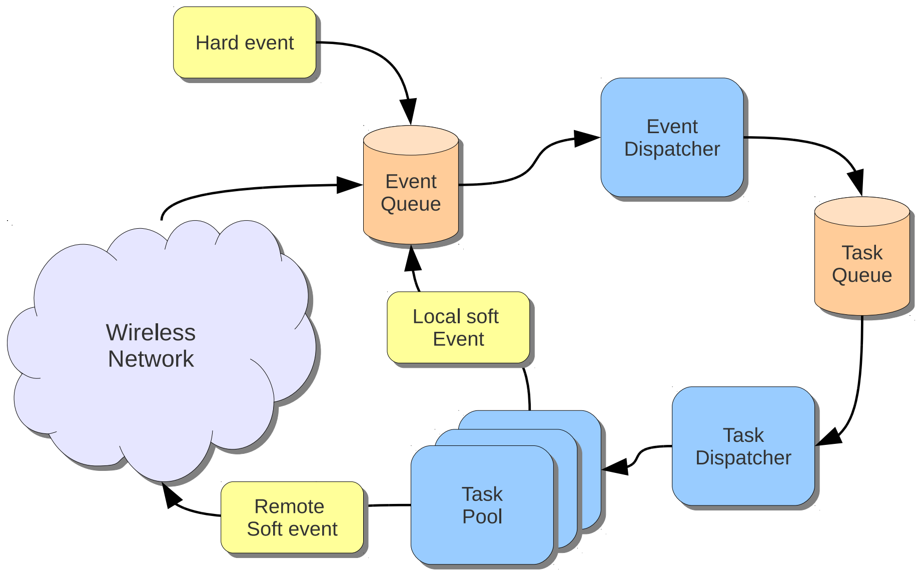


Figure 4.5: Event handling cycle

The task dispatcher pops the task from the task queue and assigns it to an available task process from the pool. This pool is a set of running process in charge of executing a module task. Each single execution can lead to the production of local and remote soft events. A local event will be pushed in the event queue but this time, the module's path in the tree is also saved in the queue. When this event is handled by the event dispatcher, the broadcast will start from this path in the tree as explained in section 3.1.2. If a remote soft event is produced, the process is similar but the event is first sent through the network to all teammates. When delivered, the event is pushed into the teammate event queue with the same path information as it would be produced locally. The cycle continues as long as the queue and task events are not empty.

4.3.2 Event and task priority

As some events are more important than others, we introduce three levels of priority (high, normal and low) in the event handling. These priority levels are used in the event and task queues (see figure 4.6). The event extraction mechanism is very basic: As long as there are some high priority events, they are popped then the turn of the normal priority and finally the low priority. This kind of priority management can lead to starvation issues and should be improved. However, the relative low rate of hard event production (every 500 ms for the beat event) makes a congestion quite improbable.

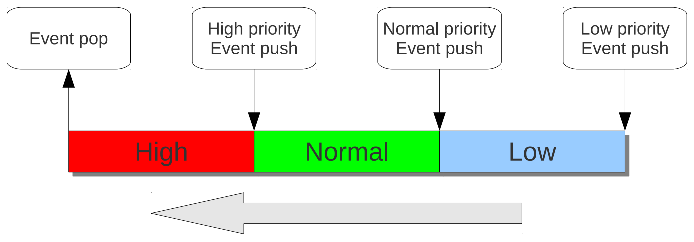


Figure 4.6: Queue and priority management

The event priority in the event queue is forwarded to the task queue with the same priority level. At this stage of the middleware development, the event priority is set as follows:

- **High priority**: Set for *obstacle* events
- **Low priority**: Set for the remote soft events
- **Normal priority**: Set for the rest of the events

The reader might be surprised that the *beat* event is not set to high priority because it is supposed to be produced at regular and accurate intervals. It's true but the *obstacle* event has a higher priority because it could trigger an obstacle avoidance procedure in the robot. Moreover, the *payload* is not synchronous and a few milliseconds late in the *beat* event production won't be serious.

4.4 World view

The view contains information transmitted by its teammates or obtained by its own sensors. The view is composed of objects which represent a robot or an intruder. The object attributes are given in table 4.2.

The *certain* attribute is quite important and is worth to be detailed. The value of this attribute changes in the course of time. When true, the object information has a great

Name	Description
Type	Object's nature i.e. Robot or Intruder
Xcoord, Ycoord	Object's Cartesian coordinates in the world
Heading, Speed	Object's heading and speed values (only available for robots)
Certain	Boolean indicating whether the information is reliable or not
Ts	Timestamp of the latest information update
Id	Object's identifier

Table 4.2: Object attributes

probability to be correct at the view reading moment. When false, the information is no longer certain but it is still maintained in the view. Actually, when an object is detected by a robot sensor, the information associated to the object is tagged as certain in the view. Later, the *certain* attribute is set to false in the following situation:

1. The current age of the information calculated from the timestamp value is greater than a given threshold called *CERTAINTY_MAX_AGE*.

2. A robot crossed the latest coordinates of the object and did not detect it at this place, which means most likely that the object has moved.

4.4.1 Robot modes

According to the view content, each robot can run in three different modes:

- **Wandering:** The world view does not contain any reference to an intruder. The robot just wanders around the world, making random decisions to turn left or right at every corner. The robot speed is constant and equal to *WANDERING_SPEED*.

- **Searching:** The world view contains one or several references to an intruder but no reference with a *certain* attribute set to true. The robot will try to locate the intruder and will figure out random destination points around the intruder's latest coordinates. The robot speed is constant and equal to *SEARCHING_SPEED* (greater than *WANDERING_SPEED*).

- **Blocking:** The world view contains at least one reference to an intruder with a *certain* attribute set to true. The robot will try to block the intruder to prevent him from running away. The robot will calculate the shortest path to get to the intruder location. The robot speed is constant and equal to *BLOCKING_SPEED* (greater than *SEARCHING_SPEED*).

4.4.2 World view update

There are basically two sources for view updates: The robot local sensors and the wireless network. Each time a robot receives an update, it will add the information into the view if it is associated to a new object (e.g. a new intruder detection) or it will update the current view object if the update timestamp is newer than the current one. All update situations are listed hereafter:

- The robot detects an intruder in front of it. After updating its own view, the robot will broadcast the update to its teammates through the network.
- The robot does not detect an intruder which is supposed to be in front of it. After updating its own view, the robot will broadcast the update to its teammates through the network.
- The robot receives an object update through the network coming from a teammate.
- The robot receives a set of object updates coming from the leader of another group (*synchro* packets) which has just merged with the robot's group.
- The age of an object is greater than a given threshold. The information is updated or removed from the view.

An object is removed from the view if its age is greater than *ROBOT_MAX_AGE* for a robot or *ROBOT_MAX_AGE* for an intruder. Both thresholds are different because a robot is supposed to broadcast regularly its position via the *hello* packets. The non reception of these packets must lead quickly to remove the robot from the view. This robot is not part any longer of the group because it faced a communication issue or passed the group Wi-Fi range.

4.5 Module tree architecture

The whole module tree is depicted in figure 4.7, it can be divided into four subsets of modules, each of them represents a branch of the tree:

- **Communication**: This subset includes all modules connected with positioning and management of the world view.
- **Self-coordination**: This part deals with all processes necessary to manage the robot in an autonomous way: mainly the collision avoidance and navigation processes.
- **Multi-robot coordination**: These modules are in charge of planning actions involving a common strategy between teammates.

- **Remote control**: This single module handles the communication between mobile and station versions and allows the station to send remote requests to the mobiles.

Actually, the multi-robot coordination subset is empty. These features have not been implemented yet. A good example is the current procedure to block a detected invader. With the self-coordination modules, the robot finds out the nearest entrance point to get to the invader then it calculates the shortest path and moves to the destination point. With a multi-cooperation, the team could run a "consensus" algorithm in order to split up and cover all available entrances. We will now detail the three sub-branches left:

4.5.1 Communication modules

The communication modules are gathered in figure 4.8. First of all, we can notice that the navigation group is connected to the communication branch. That way, the navigation modules can receive the events produced by the branch. The following modules compose the communication group:

Position freshness detector

As it consumes the beat event, this module is run at regular intervals. The current robot coordinates, speed and heading are regularly sent to the *payload* and timestamped when delivered. The *position freshness detector* checks whether this information is up-to-date or in other words the information age is greater or not than *POSITION_MAX_AGE*. If so, the module sets the robot's state to *LOST*. A lost state makes the robot freeze.

Hello sender

This event consumes as well the *beat* event and sends at regular intervals its position (coordinates, speed and heading) to all teammates through a *remote object* event. This event will be consumed by the teammate *view updater* module. This latter will be further described.

Obstacle analyser

The *obstacle* event is produced by the sensor interface in presence of an obstacle in front of the robot. The *analyser* module first ensures the robot is not lost and the obstacle coordinates does not correspond to a wall position. This last verification is made on the basis of the local world map. If both verifications are OK, the module produces a *local object* event with a object type set to *unknown* which means the robot does not know the obstacle's nature yet.

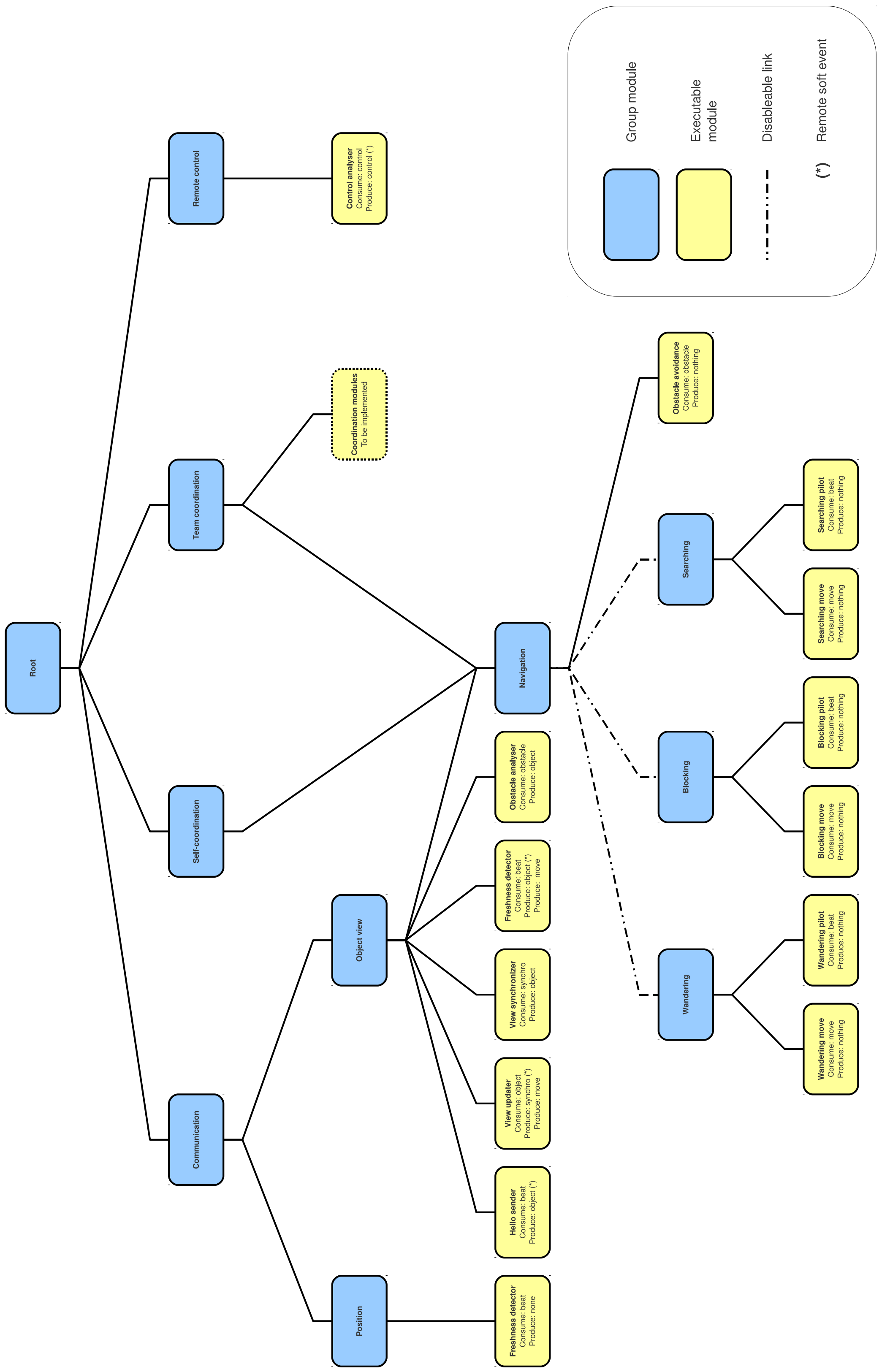


Figure 4.7: Middleware module tree

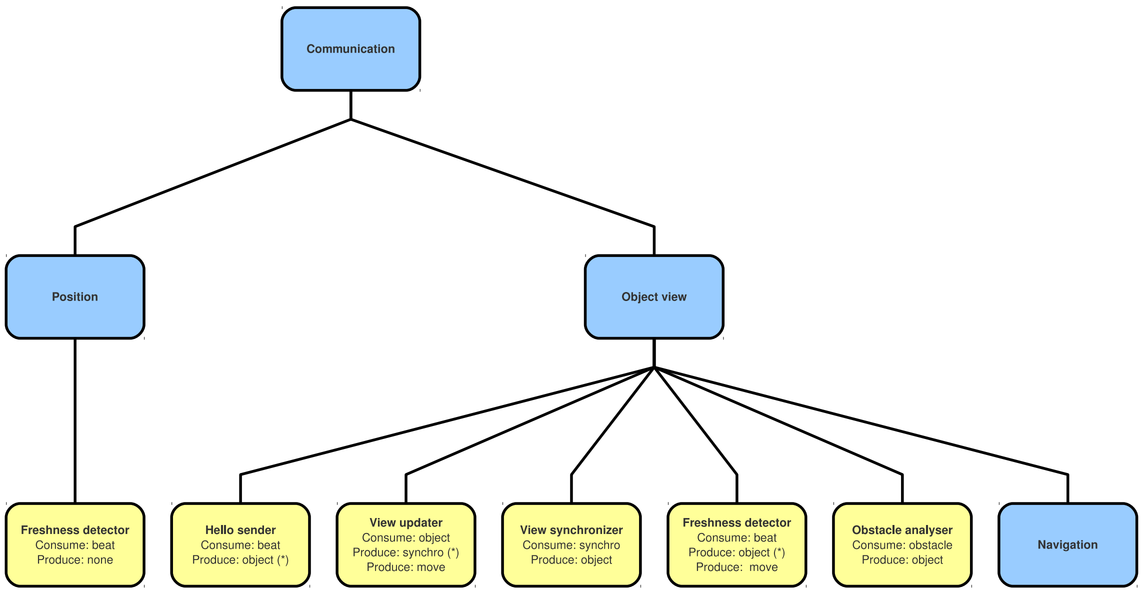


Figure 4.8: Communication modules

View updater

It's the most complex communication module because it must handle every type of *object* event (remote or local) and update the robot world view. Figure 4.9 gives the module logical flowchart. The reader can refer to the time and view synchronization definitions (see algorithms 1 and 2).

Both creation and update procedures make some tests to decide whether it is necessary to broadcast this received object to the teammates (by producing a *remote object* event). It could happen for example that the received object would be older than the matched view object so the module will broadcast the view object once again. In both creation or update, the two last actions are the robot mode verification and the *move* event production. The mode verification procedure checks whether the current robot's mode must be updated. For instance, the robot was wandering and detected a new intruder so the mode must be updated to *blocking*. Finally, the *move* event must be produced to force the navigation to recalculate the current robot route.

View synchronizer

This module handles the incoming *synchro* event which is involved in the view synchronization phase. Among all actions, this module will extract the list of objects embedded in the *synchro* event and for each of them, produce a local *object* event. For more details, the reader could refer again to the view synchronization definition (see algorithm 2).

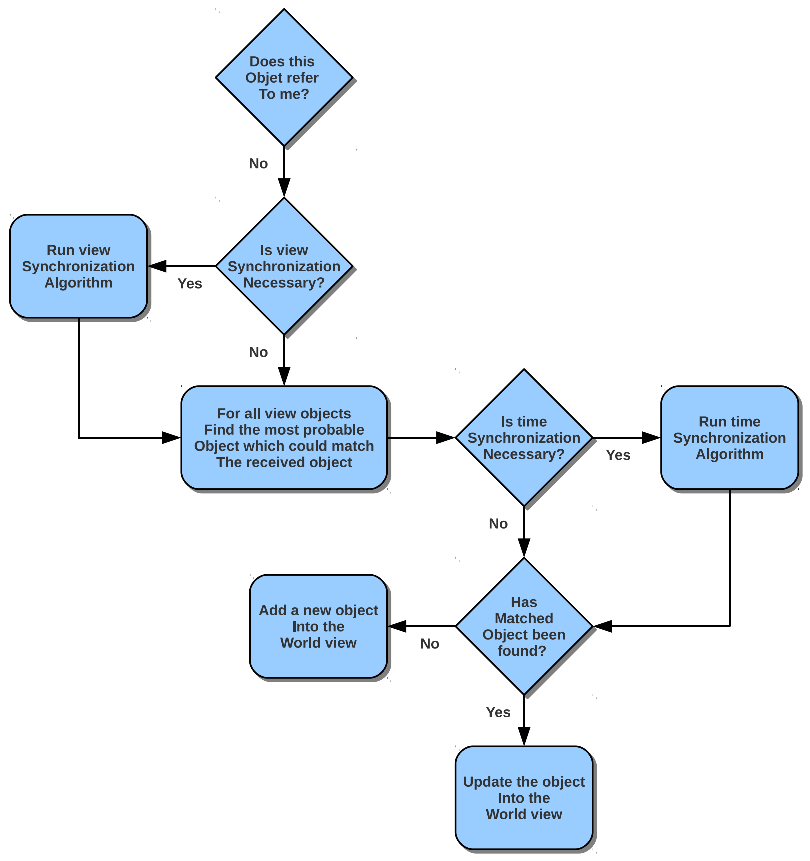

Does this Objet refer To me?
No
Is view Synchronization Necessary?
Yes
Run view Synchronization Algorithm
No
For all view objects Find the most probable Object which could match The received object
Is time Synchronization Necessary?
Yes
Run time Synchronization Algorithm
No
Has Matched Object been found?
No
Add a new object Into the World view
Yes
Update the object Into the World view

Figure 4.9: Updater module flowchart

View freshness detector

Like the *position freshness detector*, this module is executed at regular interval and scans to object view. As explained in 4.4.2, the module can remove an out-of-date object or change the *CERTAIN* attribute (e.g. if the object should be in front of the robot but it is not detected). Finally, the module terminates by the two same actions performed in section 4.5.1: The robot mode verification and the *move* event production.

4.5.2 Self-coordination modules

This branch houses the navigation modules as shown in figure 4.10. Each sub-branch: *Wandering*, *Blocking*, *Searching* is a reference to the robot current mode. Actually, only one of the three branches is enabled at the same time. When a communication module wants to update the current mode, it disables the old mode branch and enables the new one. The advantage is that an event is not broadcasted through a disabled branch, so only the modules corresponding to the current robot mode are visited.

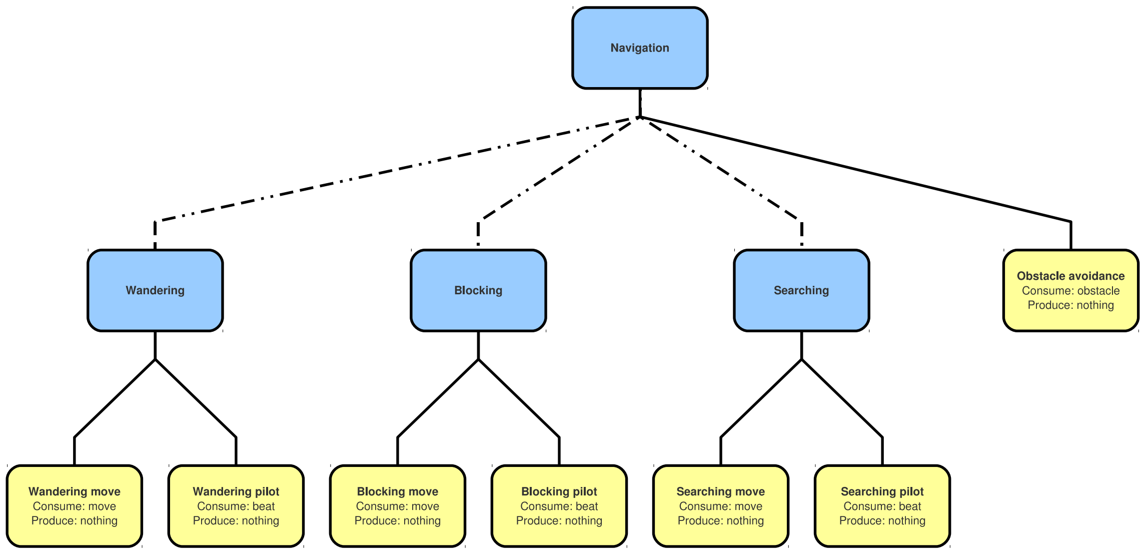


Figure 4.10: Navigation modules

Obstacle avoidance

The role of this module is to force the robot to freeze if there is a risk to collide with the obstacle. The module first calculates the angle between its own heading and the obstacle heading. If the angle is lower than $\pi/2$, the module sends new speed and heading orders to the actuators (through the promise structure) to freeze the robot.

The *obstacle avoidance* module could also produce a *move* event to force the navigation modules to recalculate the robot route and thus avoid the obstacle but all of this would introduce an additional delay before sending the new order to the actuators.

Wandering group

The *wandering* group as the two other groups, is composed by two modules. The *move* module calculates the best path to get to the *destination point* and saves the coordinates of the *next cell* in the path. The *pilot* module compares the robot current position with the *next-cell* position. If the *next cell* is not reached yet, it adjusts the robot heading value to properly head the cell (see figure 4.11). If it is reached, the *pilot* module runs a best path calculation as the *move* module does and saves a new *next-cell* position.

Regarding the *wandering* mode, there is no *destination point* because the robot makes random decisions to turn right or left at every corner, the *next-cell* position is calculated according to the random decision.

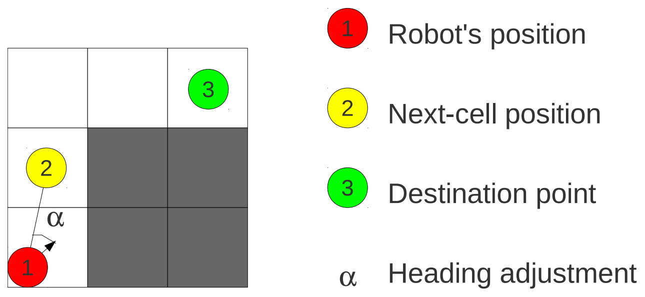


Figure 4.11: Robot heading adjustment

Blocking group

In *blocking* mode, the destination point is the coordinates of the nearest entrance point to get to the invader location. The mechanism is similar to the *wandering* navigation. The best path calculation uses the shortest path algorithm described in section 3.3.

Searching group

In *searching* mode, we are no longer sure that the invader is still at its latest position. So the robot calculates some random destination points around this latest position. Like in *blocking* mode, the shortest path algorithm is involved to figure out the best path.

4.5.3 Remote control module

The *control* event is used to exchange control information between mobiles and stations. Three subtypes of control events are already implemented but we can imagine to create more according to the needs.

- **Info request**: The station requests the world view content of all mobiles.
- **Info message**: The mobile can reply to the previous request with this message, the world view content is transmitted in the form of a text string. The mobile can also use this subtype to send any message to the station.
- **Quit request**: As mobiles version run without interaction with humans. This event can be use by a station to make all mobiles versions terminate.

4.6 Thread concurrency

We have thread concurrency in both Java and C codes. Even if Java is just dedicated to the simulation and graphic interface, we have to protect the code against concurrent access problems. To that purpose, we use *synchronized* methods and *wait/notify* protocol. We are aware that other protocols can provide improved support for concurrency as the package *java.util.concurrent* but the Java native concurrency mechanism was adequate given the project's requirements.

In C code, we use standard mutex and race conditions protocols defined in the *pthread* library. All pthreads are created as *JOINABLE* which allows the main pthread to wait for their termination using the *pthread_join* function. To manage race conditions, we use the classic primitives: *pthread_cond_wait*, *pthread_cond_timedwait*, *pthread_cond_signal* and *pthread_cond_broadcast*. *pthread_cond_timedwait* is an alternative timed condition which stays blocked until the wait time given in parameter is exceeded or an incoming signal is received. This condition is very useful to easily build timer functions because unlike the *sleep* primitive, it can be stopped at any time.

Conditions are usually used to wait for an incoming event. The signalled *pthread* will handle the event and perform a given task. Below an example of *pthread* waiting for an incoming event. The event is stored into the *events* queue, the *active* flag is true as long as the robot is active.

```
while (ctx->active) {

  // Enter mutex zone
  pthread_mutex_lock(&ctx->mutex);

  // Wait for event
  while (ctx->active && queue_isempty(&ctx->events))
    pthread_cond_wait(&ctx->cond_disp, &ctx->mutex);

  if (ctx->active) {
    // Handle the event
    ...
  }

  // Exit mutex zone
  pthread_mutex_unlock(&ctx->mutex);
}
```

Below another example with a timer function using the *pthread_cond_timedwait* primitive. We can notice that unlike the previous function, the *mutex* zone starts and ends outside the *while* loop. That way, we ensure that the function is always in a waiting state when it releases the lock. This point is important when another function which enters the mutex, tries to stop the timer.

```
// Enter mutex zone
pthread_mutex_lock(&ctx->mutex)

while (ctx->active) {

  // Initialize time
  ts.tv_sec  = ctx->payload_deadline.tv_sec;
  ts.tv_nsec = ctx->payload_deadline.tv_usec * 1000;

  // Wait for timeout or timer disarming
  int res = pthread_cond_timedwait(&ctx->cond_timer, &ctx->mutex, &ts);

  if (ctx->active == true)
    if (res == ETIMEDOUT) {
      // Timeout exceeded
      ...
    }
    else {
      // Timer stopped
      ...
    }
}
```

Regarding the module tasks, they are run by processes from the task pool in mutual exclusion zones. That means that these executions are not performed concurrently. In order to introduce real concurrency, we have to distinguish in each module task which code has to run in *mutex*. These tasks have a short computation time and most part of their code access to shared resources so making this distinction for a large part of these modules is difficult and could be inefficient. However, full concurrency is necessary to maintain the performance of the middleware and must be achieved in the future versions. The next implemented modules which will part of the cooperation sub-branch might be less dependant of shared resources.

4.7 Programming issues

This section describes some features on the code which raised some issues during the development. We will focus in particular on the *JNI* implementation with an C multi-thread environment with requires a careful code:

4.7.1 JNI Callback references

With *JNI*, when a native function is called from the Java code, two parameters are passed to the function: the *JNI* environment reference and the *JNI* object reference. Both parameters must be reused in the C code to run a callback method. Given that a native *pthread* must be able to invoke a callback method at any time, we must deal with two issues:

1. The *JNI* environment reference *(JNIEnv)* is only valid within the *pthread* which was created for the native function invocation. A new native *pthread* will be associated with a new *JNIEnv* reference. So we must find out and keep this new reference at the pthread creation.

2. There are three types of *JNI* object references *(jobject)*: *local*, *global* and *weak*. The *local* reference is created at the native function invocation and is automatically freed once the native function returns. On the other hand, *global* and *weak* references remain valid until they are freed by the programmer. In order for any native *pthread*

to call a callback method, we need to use *global* references (*weak* ones are not suitable in this case).

Let's consider two native functions: *engine_start* and *engine_stop* which are called respectively when starting and stopping a middleware kernel. The object global reference is created in *engine_start* then freed in *engine_stop*. During the middleware lifetime, the object reference is stored in the kernel context.

```
JNIEXPORT void JNICALL
Java_Robot_engine_1start(JNIEnv *env, jobject obj, jint id) {

  // Save VM pointer for callback
  (*env)->GetJavaVM(env, &jvm);

  // Create an object's global reference
  jobject global = (*env)->NewGlobalRef(env, obj);
}

JNIEXPORT void JNICALL
Java_Robot_engine_1stop(JNIEnv *env, jobject obj, jint id) {

  // Deleting the global reference
  (*env)->DeleteGlobalRef(env, global);
}
```

In *engine_start*, the *GetJavaVM* function is used to store a JVM reference which will be needful later to retrieve the JEnv reference. Let's consider now the code of a native pthread, the latter is attached to the JVM and the *JEnv* reference is initialized. Before terminating, the pthread is detached from the JVM:

```
void *engine_pthread(...) {
  JNIEnv *env = NULL;

  // Obtain JNI environment pointer
  (*jvm)->AttachCurrentThread(jvm, (void**)&env, NULL);

  // Main loop
  while (...) {
    ...
  }

  // Detach the thread from the VM
  (*jvm)->DetachCurrentThread(jvm);

  pthread_exit(NULL);
}
```

Finally, below the code of a C function invocating a callback method. The function retrieves the *JEnv* reference. In the *engine_pthread* function, we chose not to store it in the kernel context as the global object reference. When a pthread is already attached, the *AttachCurrentThread* just returns the *JEnv* reference.

```
void engine_callback(...) {
  JNIEnv *env = NULL;

  // Obtain JNI environment pointer
  (*jvm)->AttachCurrentThread(jvm, (void**)&env, NULL);
  // Get the object's class (Robot.class)
  jclass class = (*env)->GetObjectClass(env, global);

  // Get the display method identifier
  jmethodID mid = (*env)->GetMethodID(env, class, "callback", ...);

  // Call the display java method
  (*env)->CallVoidMethod(env, global, mid, ...);
}
```

The three types of native function invocation are shown in figure 4.12.

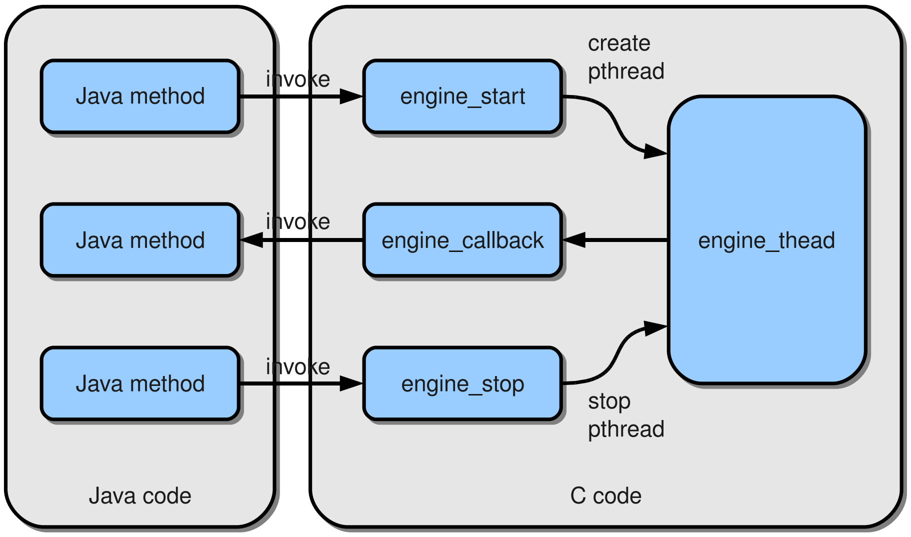


Figure 4.12: Native function invocations

4.7.2 Avoiding deadlocks between Java and C

Since the middleware was developed both in Java and C for the simulation and station versions, handling concurrency in both parts at the same time requires to be vigilant. In order to prevent various tasks from accessing simultaneously to common resources, we use classic mutual exclusion zones and race conditions. This resource management is separately performed in Java and C codes. As there is no exclusion mechanism common to both parts, there is a risk of global deadlock as depicted in figure 4.13.

Let's see an instance, we assume that a kernel function invokes in a *mutex* zone a callback method in charge to broadcast a message. This callback method which simulates the broadcast mechanism, will just send unicast messages to all teammates including the message source robot. So the method will invoke a native function to deliver the first message. This function won't handle the message because the robot is the sender but in a first version of the program, the native function checked that this message had not been received yet and broadcasted it again, calling the initial kernel function which was still blocked in the *mutex* zone which led to a deadlock. Even if the second broadcast was not

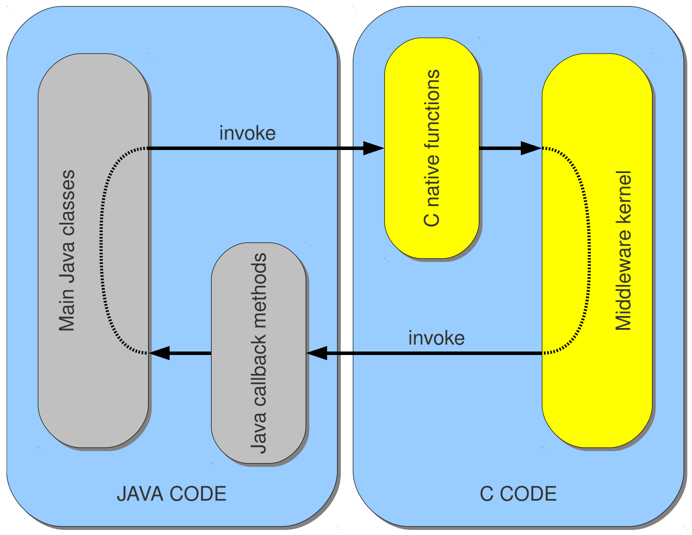


Figure 4.13: Deadlock risk between C and Java

necessary, a such deadlock was not supposed to happen.

In order to avoid such risks, we decided to ban all series of callback and native invocations from the same thread. In the case of the broadcast for example, sending and deliver actions are performed in two different threads which communicate by a *wait/notify* mechanism.

4.7.3 Memory alignment

Mobile version of the middleware aims to be running of ARM chips while station version runs on PC computers. Message exchange between payloads of both versions is handled with UDP sockets. As native mechanisms of data serialization do not exist in C, we should have ensured that all message fields were transmitted and extracted properly on each platform which required to check the data endianness for example. In a first version version of the program, we saved time by transmitting a message structure as a single bit field which led to an incorrect extraction of some message fields. The problem due to a different memory management between ARM and PC platforms, was fixed with a manual serialization of all message fields.

Chapter 5

Results and review

In this chapter, we propose two parts. First, a description of some relevant tests we carried out to validate the middleware architecture and the synchronization algorithms and secondly a short work review composed by a list of questions/responses. In this latter section, we tried to highlight the middleware limitations and propose enhancements.

5.1 Tests and results

We discuss four scenarios, three of them use the simulation version. The last scenario involves the mobile and station version in their startup phase.

5.1.1 Blocking movements

The purpose is to test the navigation algorithms in *blocking* mode, i.e. when an intruder is detected and stays frozen in front of a robot. The scenario involves five robots and one intruder. All robot paths are one-cell wide so robots cannot pass each other. The figure 5.1 shows the final Simbad screen at the end of the simulation. We will now explain what happened.

The *blue* robot first detects the intruder, the other four robots are located on the right side of the screen. Before the detection, all robots are in *wandering* mode. When the invader is detected, all modes are set to *blocking* and all robots try to get to an entrance point close to the intruder.

The *blue* robot which has detected the intruder is already on the south entrance point and stays fixed. The four other robots will eventually choose the north entrance point because the south is closed by the blue robot. As the four robots move in the same direction as the wave propagation (shortest path algorithm), none of them are considered as an obstacle so the robots keep moving.

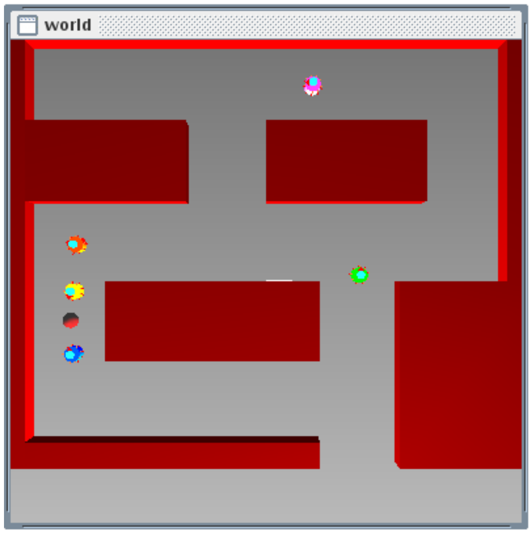


Figure 5.1: Example of blocking movements

When the *yellow* robot gets first to the north entrance point, it freezes. As soon as the *orange*, *green* and *pink* robots recalculate the best path, they consider now both *blue* and *yellow* robots as obstacle. There are no path left to get to an entrance point so the *orange*, *green* and *pink* robot freeze and stay fixed.

Conclusion: The *green* and *pink* robots stay far the invader while they had the opportunity to move closer. This is a drawback of the current navigation algorithm which could disappear if the paths would be two-cell wide. This latter case is closer to reality.

5.1.2 Payload killing

In this scenario, we want to test the *wormhole*'s behaviour on control. So we modify a little part of the simulation code to prevent the *wormhole* from reloading the *payload* in case of crash. Then we kill the *payload* process. A robot and an invader are involved in the simulation, the robot is moving towards the invader in *blocking* mode.

When the wormhole assumes the control and a destination point is set, the wormhole tries to get to this destination point with a very basic algorithm. Indeed, the wormhole chooses the nearest next cell to the destination point, no matter if the path starting from the next cell might be a dead end. As the robot was separated from the destination point with many walls, the robot was quickly unable to continue and stayed blocked in the dead end.

Conclusion: The *wormhole* navigation algorithm is deliberately very simple and limited because the *wormhole* cannot run a task with an indeterministic computation time which is the case of the wavefront-based algorithm. The wormhole is not designed to assume control during a long period of time. in a “normal” situation, the payload is supposed to quickly wormhole stability or to be restarted.

5.1.3 System stress

This scenario is designed to measure the performance of the *payload* task management when the system is stressed, i.e. when many events concurrently arrive to the event and task dispatchers. Then we perform the following actions:

1. We modify the structure of the queue to save the maximum queue size.
2. We size the pool task to a great number of running processes.
3. We create a simulation world with a great number of robots.
4. We stress the simulation with some event-consuming actions.

Test results: Pool size = 20. Robot number = 8. Stressing actions = consecutive view synchronizations. Maximum task queue size = 7/8.

Conclusion: The poor maximum size of the task queue may be explained by the low frequency of the *beat* event production (500 ms). Maybe a congestion situation could be reached with many more robots but we are limited by the simulation requirements. After the test, we set the task pool size to ten. This size is currently the same in the three middleware versions.

5.1.4 Time synchronization

This short scenario is used between a mobile version running on the ARM chip and a station version running on a PC. Both versions communicate through the network. We introduce a 0.5 sec lag between both system clocks and we start the payloads.

The station payload can be started before or after the mobile payload, the results are similar. Each time, the view synchronization phase (which is automatically performed because each robot is considered as a group) requires some extra *objects* events to converge. This behaviour is explained in section 3.2.1. The *payload* receives an *object* event with a timestamp older than its own view *object* so the payload broadcasts again it own object considering that the first broadcast failed for any reasons.

Conclusion: This behaviour is normal and not prejudicial for the robot as the synchronization phase just lasts a little more time.

5.2 Work review

Below some criticisms we could find against the current implementation and some answers we could provide:

- **Question:** The middleware architecture is based on a wormhole approach. This wormhole is supposed to meet timeliness requirements for critical task processing which required in theory to be synchronous. But the middleware including the wormhole is implemented on an Unix platform which does not meet any real-time requirements.
  Response: In a context of robot teams, the frequency to send promises to the wormhole is quite low (every 500 ms). So although the wormhole is not fully synchronous, this implementation allowed us to test and validate the global middleware architecture. The next step is to port the wormhole into a separated hardware device as the robot FPGA.

- **Question:** The view synchronization algorithm runs in the payload which is not synchronous by definition. What's more, the synchronization phase relies on the *hello* packet broadcast and may require various ”rounds” to be completed. During this period, a robot does not know whether its view is synchronized or not with its teammates.
  Response: The view synchronization algorithm is not said to be synchronous. During the convergence phase, world views can be different inside the group and some robots may take incoherent decisions with regard to the group strategy but as soon as the synchronization is completed, the robot will update its strategy.

- **Question:** The synchronization algorithm offers resilience to the system but the whole process to exchange messages is based on unreliable broadcasting through the teammates. There's no verification that a message is really delivered to the teammates.
  Response: The message sending process simulates a real broadcast network. Actually, this process relies on unicast messages. A possible improvement would be to set up an ad-hoc Wi-Fi network with native and reliable broadcast protocols.

- **Question:** The middleware kernel has been developed in a multi-thread environment but some threads as the module tasks do not run concurrently.
  Response: The module tasks have a short computation time and most part of their code access to shared resources. The concurrency introduction will be possible with the implementation of new modules less dependant to these resources.

- **Question:** The middleware is expected to offer an cooperative framework for a team of robots but the module tree does not include any cooperation modules.

Response: Building such a cooperative middleware required first to make available some basic mechanisms as the communication channels, the world shared view or the navigation algorithms. This first part is now achieved and makes possible the implementation of cooperation higher-level modules in future versions.

Chapter 6

Conclusion

In this document, we presented a middleware architecture which aims to offer more resilience to groups of mobile robots in charge of the surveillance of physical areas. This architecture relies on a control layer composed by the *wormhole* and the *payload*, an event-based structure for the *payload* task execution, some synchronization mechanisms tolerant to communication failures and finally a multi-thread environment common to Java and C.

Through the description of these features, we discussed how this architecture could guarantee the timely execution of the critical tasks and maintain a shared world view common for all teammates. On the other hand, we considered as well the current limitations of this architecture and the way we could improve it and overtake its limitations. The formal definition of the *wormhole* is a good example, the model is supposed to be fully synchronous and run on a real-time platform which is not the current situation. However, the porting of the middleware to hardware platforms and FPGA's would be a great improvement even if it would require to rewrite a large part of the current code.

The middleware module tree offers a flexible and simple way to add new modules i.e. new functionalities. In particular future improvements could lead to create cooperation modules which are missing in this implementation. The challenge will be to implement real common strategies to solve problems and one day, dynamically update the module tree by adding, moving or deleting modules. This latter point could allow the robot to acquire intelligence and share it through the team.

Appendix A

User and developper guide

In this chapter, we'll give basic requirements to install, modify or compile the middleware code. We'll start with the environment requirements and continue afterwards with the Eclipse configuration for a dual compilation (Java + C).

A.1 Linux vs Windows

All versions of the middleware were developped and tested on Linux platforms (Ubuntu 10.04 32bits). Porting these versions on *Windows* is possible but requires to find a *pthreads* implemention for this platform. Basically, there are three different solutions:

- Use a *Pthread* library for *Windows* as *Pthead Win32*.
- Use a Linux-like environment as *Cygwin* and compile sources with internal tools.
- Use a Virtual Machine as *WMware* and install *Linux* as emulated environment.

All documentation given in this chapter is intented to an *Ubuntu* user.

A.2 Sun JDK and Java 3d installation

As explained in chapter 3.4, we chose *Sun JDK 6.0* because it fully supports the *pthread* model implemented in the middleware. Below the commands on *Ubuntu* platform to install *Sun JDK 6.0* and set it up as the default *JVM*:

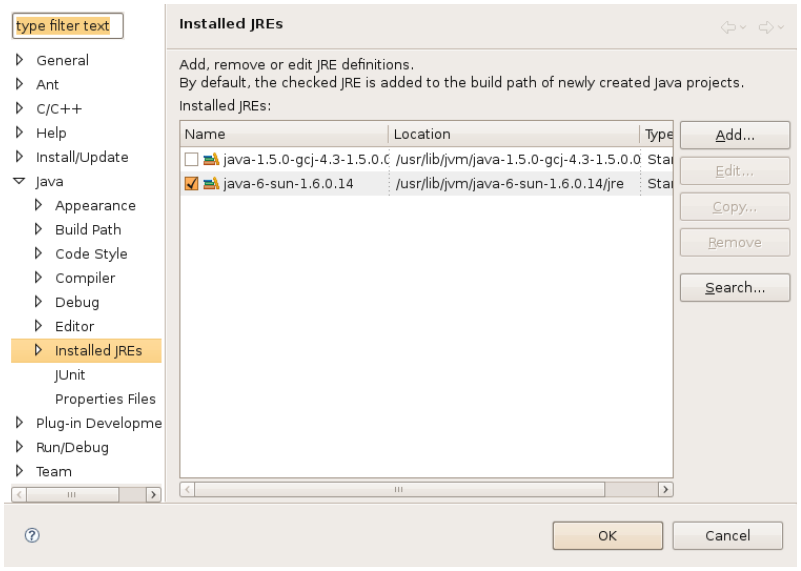
```
sudo apt-get install sun-java6-jdk
sudo update-java-alternatives -s java-6-sun
```

In order to run the *Simbad* simulation tool, the user must install a version of *Java 3d*. The software can be found on the site *java.sun.com*. These files must be installed into the *Sun JDK* file structure.

A.3 Eclipse's configuration

Eclipse supports *JNI* and allows to work on both C and Java files in the same time. Any modification in C files leads to an automatic rebuild of the C library which is very confortable. We will give hereafter the main steps to configure *Eclipse* to run the simulation version of the middleware. All screenshots come from the version 3.2 with *CDT* plug-in.

Step 1: Go to $Window \rightarrow Preferences \rightarrow InstalledJREs$ then *add new JRE*. In the JRE home directory, browse the directory which *Sun JDK 6* is installed in (*/usr/lib/jvm/java-6-sun/jre* in our system). Finally set this new JRE as the default one.



Installed JREs

Add, remove or edit JRE definitions.
By default, the checked JRE is added to the build path of newly created Java projects.
Installed JREs:

	Name	Location	Type
☐	java-1.5.0-gcj-4.3-1.5.0.0	/usr/lib/jvm/java-1.5.0-gcj-4.3-1.5.0.0	Star
☑	java-6-sun-1.6.0.14	/usr/lib/jvm/java-6-sun-1.6.0.14/jre	Star

Figure A.1: JRE setup in Eclipse

Step 2: Create a Java project: $File \rightarrow New \rightarrow Project$. You can start creating your own Java classes as normally. Then you have to modify the current project to include the C perspective and allow makefile-based compilation: $File \rightarrow New \rightarrow Other$ then *"Convert to a C/C++ Make Project"*. Choose the Java project and the C option as depicted on figure A.2.

Step 3: Create your own *makefile* and save it in the project's directory. Considering that *libfile* is the native library's name, the makefile can have the following structure:

```
CC = gcc
OBJS = file1.o file2.o ...
CFLAGS = -std=c99 -Wall
LFLAGS = -lpthread -lm

all : libfile.so

libfile.so : $(OBJS)
  gcc --shared $(OBJS) $(LFLAGS) -o libfile.so
```

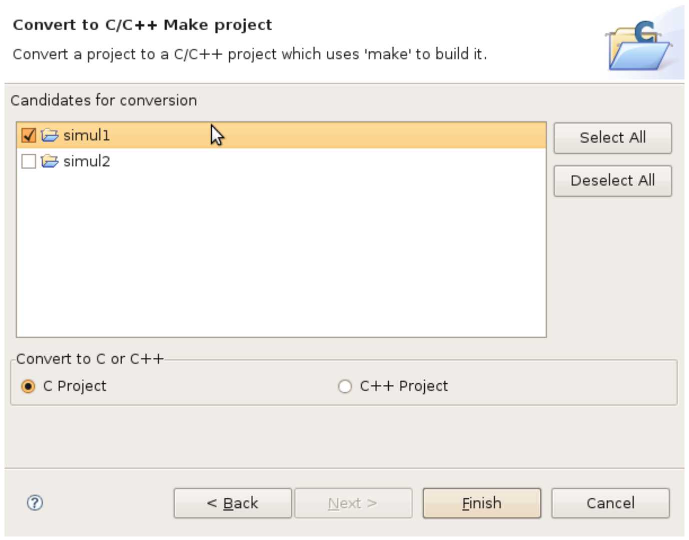

Convert to C/C++ Make project
Convert a project to a C/C++ project which uses 'make' to build it.
Candidates for conversion
simul1
simul2
Select All
Deselect All
Convert to C or C++
C Project
C++ Project
< Back
Next >
Finish
Cancel

Figure A.2: Conversion to C Make Project

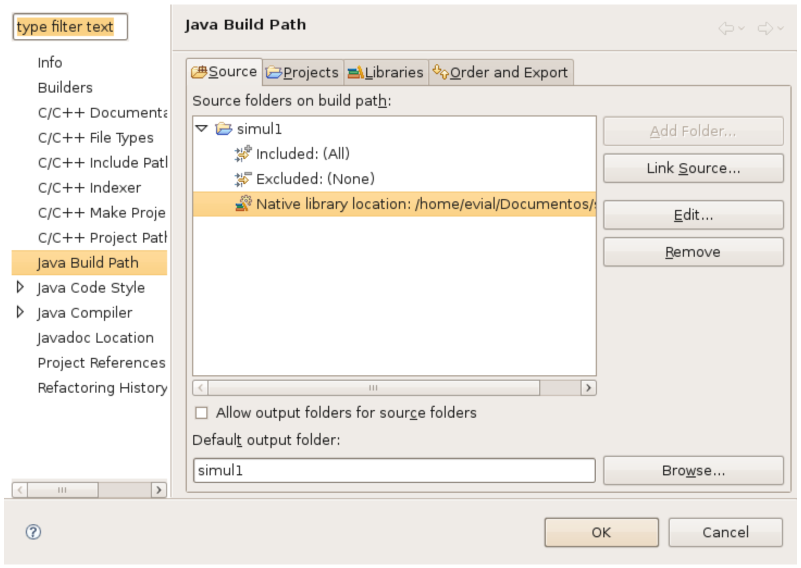
```
interface.h : package/Interface.class
  javah -o interface.h -jni package.Interface

interface.o : interface.c interface.h define.h
$(CC) $(CFLAGS) -c $<

%.o : %.c define.h
$(CC) $(CFLAGS) -c $<

clean :
  rm interface.h *.o
```

Interface.java contains the C native function signatures. We can have as many interface files as necessary. For each one, the creation of a native method header using *javah*, is required. *interface.c* must contain the implementation of the C native functions whose signatures are defined in *Interface.java*. *define.h* is a common header file and *package* the name of the single Java package. Finally, we can note that we forced the C99 version of the C compiler.

Step 4: Set up the native library path: $Project \rightarrow Properties \rightarrow JavaBuildPath$ (see figure A.3). As we use the Simbad library, the user can take the opportunity in the same menu to set up the path of the external JAR files (see figure A.4).

Step 5: Check out that the auto build option is enabled in the $Project \rightarrow Properties \rightarrow CMakeProjectmenu$ (see figure A.5).

Step 6 (optional): In order to have a more friendly environment, the user can create a filter in the left navigation window to only see the source Java and C files (see figure A.6).



Source folders on build path:

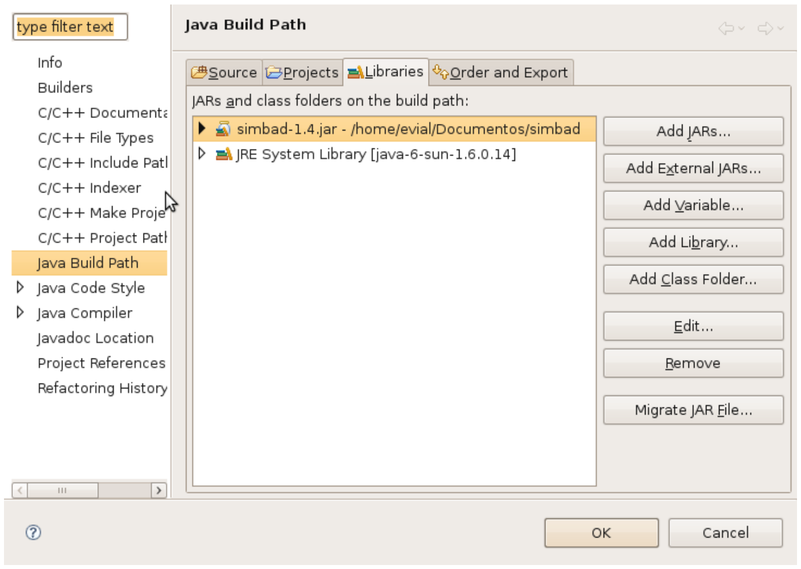
simul1
Included: (All)
Excluded: (None)
Native library location: /home/evial/Documentos/

Allow output folders for source folders

Default output folder:

simul1

Figure A.3: Native library path



JARs and class folders on the build path:

simbad-1.4.jar - /home/evial/Documentos/simbad
JRE System Library [java-6-sun-1.6.0.14]

Figure A.4: External JAR library path

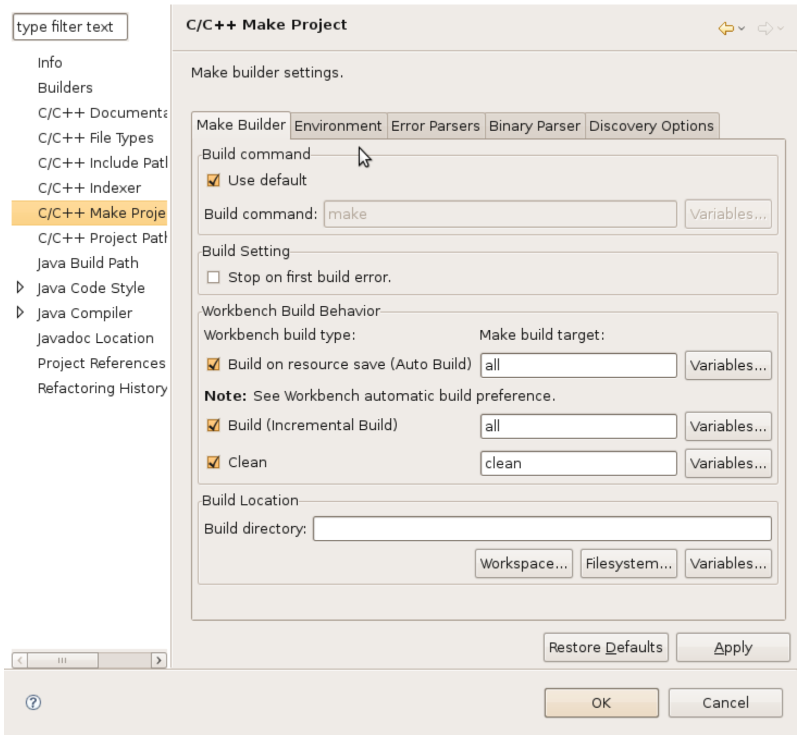
A.4 Middleware execution

This section gives the way to manually start each version of the middleware. For each of them, we'll describe the configuration files and required parameters.

Simulation version start

The simulation class execution starts the *Simbad* interface and all robot kernels (wormhole and payload). Below the start command:

```
export LD_LIBRARY_PATH=<project's-directory-path>
java engine.Simulation
```


type filter text

- Info
- Builders
- C/C++ Documenta
- C/C++ File Types
- C/C++ Include Patl
- C/C++ Indexer
- C/C++ Make Proje
- C/C++ Project Patl
- Java Build Path
- Java Code Style
- Java Compiler
- Javadoc Location
- Project References
- Refactoring History

C/C++ Make Project

Make builder settings.

Make Builder | Environment | Error Parsers | Binary Parser | Discovery Options

Build command
- [✓] Use default
- Build command: make — Variables...

Build Setting
- [ ] Stop on first build error.

Workbench Build Behavior

Workbench build type:	Make build target:	
[✓] Build on resource save (Auto Build)	all	Variables...
[✓] Build (Incremental Build)	all	Variables...
[✓] Clean	clean	Variables...

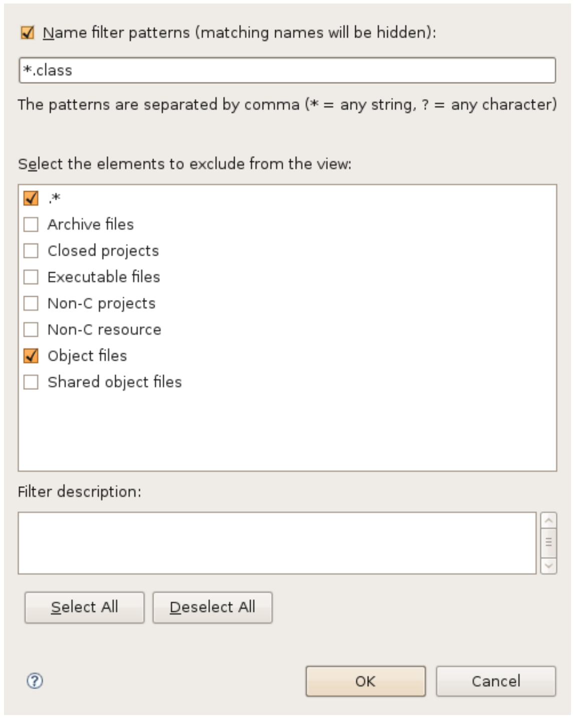
Note: See Workbench automatic build preference.

Build Location
- Build directory:
- Workspace... Filesystem... Variables...

Restore Defaults | Apply

OK | Cancel

Figure A.5: Auto-build option selection


[✓] Name filter patterns (matching names will be hidden):

*.class

The patterns are separated by comma (* = any string, ? = any character)

Select the elements to exclude from the view:

- [✓] .*
- [ ] Archive files
- [ ] Closed projects
- [ ] Executable files
- [ ] Non-C projects
- [ ] Non-C resource
- [✓] Object files
- [ ] Shared object files

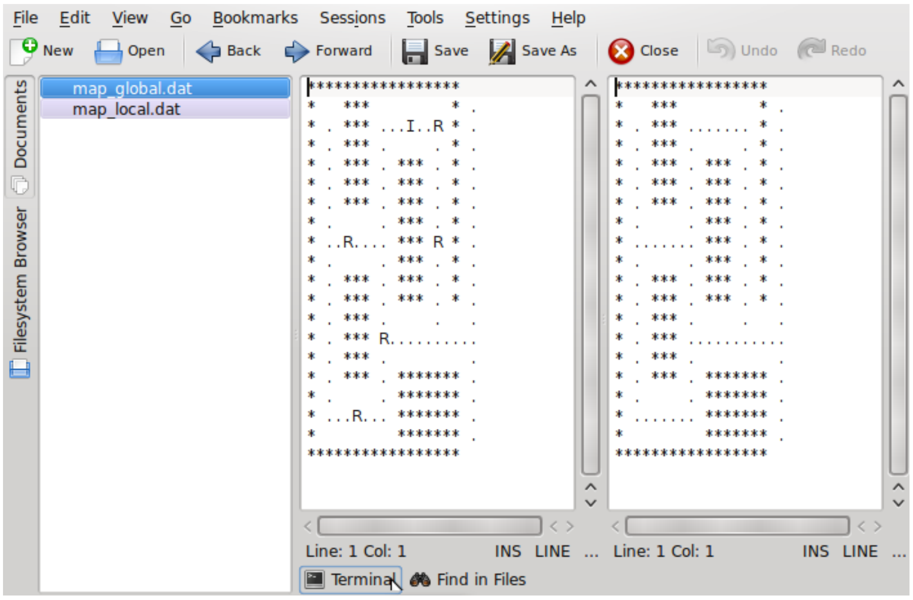
Filter description:

Select All | Deselect All

OK | Cancel

Figure A.6: Filter creation

There's no required parameter. The only configuration files are both maps files (see figure A.7). The local map is loaded by each robot kernel and gives a text representation of walls and robot paths. The global map is used by the simulation part to get all robot and invader positions. The wall and path positions must be the same as the local map.



```
*****************
*   ***         * .
* . *** ...I..R * .
* . *** .     . * .
* . *** . *** . * .
* . *** . *** . * .
* . *** . *** . * .
* .     . *** . * .
* ..R.... *** R * .
* .     . *** . * .
* . *** . *** . * .
* . *** . *** . * .
* . *** .     .   .
* . *** R..........
* . *** .         .
* . *** . ******* .
* .     . ******* .
* ...R... ******* .
*         ******* .
*****************
```

```
*****************
*   ***         * .
* . *** ....... * .
* . *** .     . * .
* . *** . *** . * .
* . *** . *** . * .
* . *** . *** . * .
* .     . *** . * .
* ....... *** . * .
* .     . *** . * .
* . *** . *** . * .
* . *** . *** . * .
* . *** .     .   .
* . *** ...........
* . *** .         .
* . *** . ******* .
* .     . ******* .
* ....... ******* .
*         ******* .
*****************
```

Figure A.7: Global and local world maps

Meaning of each text character: *'*'* for a wall position, *'.'* for a path position, *'R'* for a robot position (for global map) and *'I'* for an invader position (for global map). The *'R'* or *'I'* characters must be located on a robot path. As a design constraint, any path position must be one character apart from the map bounds and the wall positions.

Mobile version start

This version must be started on each robot hardware. Once started, the *wormhole* will run internally the *payload* process. Below the start command:

```
wormhole <id> <file1> <file2>
```

Meaning of each parameters: *id* for the robot's identifier, *file1* for the map file name and *file2* for the host file name. The host file contains a text list with all robot ip addresses. The first parameter is the robot's identifier, the second one the ip address and the third one the UDP listening port. This file must be the same for all robots, the robot's identifier given in the *wormhole* command must be part of the host file identifiers. As various UDP port numbers are assigned by the system from the listening port value, the port numbers must not be continuous. Below an example of host file content:

```
0 10.10.5.45 5000
1 10.10.5.123 5100
2 10.10.5.234 5200
3 10.10.5.45 5300
5 10.10.5.123 5400
```

As for the simulation version, the local map file must be present in the project's directory. We could imagine that some groups of robots cover different parts of the world, consequently paths defined in the each map file can be different.

Station version start

This version must be run on a fixed station, the latter will communicate with all other mobile robots and fixed stations already running. Below the start command:

```
export LD_LIBRARY_PATH=<project's-directory-path>
java engine.Station <id> <file1> <file2>
```

The parameters are the same as for a mobile execution: *id* for the robot's identifier, *file1* for the map file name and *file2* for the host file name.

Glossary

FPGA	Field-Programmable Gate Array
GPS	Global Positioning System
JDK	Java Development Kit (Sun framework)
JNI	Java Native Interface
JVM	Java Virtual Machine
Mutex	Mutual Exclusion
NTP	Network Time Protocol
RSS	Received Signal Strength
TCP	Transmission Control Protocol
TTFD	Timely Timing Failure Detection
UDP	User Datagram Protocol
Wi-Fi	Wireless Fidelity (by analogy with Hi-Fi)

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