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Bachelor of Science in Computer Science

A Distributed Platform for the Volunteer Execution of Workflows on a Local Area Network

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I dedicate this dissertation to my family, to all friends and classmates from high school to university. A special feeling of gratitude to my grandmother, Maria, who always encouraged me to take this master course.

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Abstract

Albatroz Engineering has developed a framework for over-head power lines inspection data acquisition and analysis, which includes hardware and software. The framework's software components include inspection data analysis and reporting tools, commonly known as PLMI2 application/platform.

In PLMI2, the analysis of over-head power line maintenance inspection data consists of a sequence of Automatic Tasks (ATs) interleaved with Manual Tasks (MTs). An AT consists of a set of algorithms that receives as input one or more datasets, processes them and returns new datasets. In turn, an MT enables human supervisors (also known as lines inspection operators) to correct, improve and validate the results of ATs. ATs run faster than MTs and in the overall work cycle, ATs take less than 10% of total processing time, but still take a few minutes. There is data flow dependency among tasks, which can be modelled with a workflow and even if MTs are omitted from this workflow, it is possible to carry the sequence of ATs, postponing MTs.

In fact, if the computing cost and waiting time are negligible, it may be advantageous to run ATs earlier in the workflow, prior to validation. To address this opportunity, Albatroz Engineering has invested in a new procedure to stream the data through all ATs fully unattended.

Considering these scenarios, it could be useful to have a system capable of detecting available workstations at a given instant and subsequently distribute the ATs to them. In this way, operators could schedule the execution of future ATs for a given inspection data, while they are performing MTs of another.

The requirements of the system to implement fall within the field Volunteer Computing Systems and we will address some of the challenges posed by these kinds of systems, namely the hosts volatility and failures. Volunteer Computing is a type of distributed computing which exploits idle CPU cycles from computing resources donated by volunteers and connected through the Internet/Intranet to compute large-scale simulations.

This thesis proposes and designs a new distributed task scheduling system in the

context of Volunteer Computing Systems, able to schedule the ATs of PLMI2 and exploit idle CPU cycles from workstations within the company's local area network (LAN) to accelerate the data analysis, being aware of data flow interdependencies.

To evaluate the proposed system, a prototype has been implemented, and the simulations results have shown that it is scalable and supports fault-tolerance of tasks execution, by employing the rescheduling mechanism.

Keywords: Volunteer Computing system, Interdependent tasks, Distributed task scheduling, Fault-tolerance, Scalability

Resumo

A Albatroz Engenharia SA desenvolveu um sistema de aquisição e análise de dados das inspeções de linhas elétricas, que inclui *hardware* e *software*. Os componentes de *software* incluem ferramentas de análise e elaboração dos relatórios das inspeções, conhecidas como PLMI2.

A análise dos dados de uma inspeção no PLMI2 consiste numa sequência de Tarefas Automáticas (TAs), intercaladas com Tarefas Manuais (TMs).

Uma TA consiste num conjunto de algoritmos que recebem como entrada um ou mais conjuntos de dados, processa-os e cria novos conjuntos de dados. Por sua vez, uma TM permite aos supervisores humanos (também conhecidos como operadores) corrigir, melhorar e validar os resultados das TAs. As TAs executam com maior rapidez do que as TMs, e no ciclo geral de processamento dos dados de uma inspeção, demoram menos de 10% do tempo total, mas ainda na ordem dos minutos. Há uma dependência no fluxo de dados entre as tarefas, que pode ser modelada como um *workflow* e se as TMs forem omitidas deste *workflow*, é também possível realizar a sequência das TAs, adiando TMs.

De facto, se o custo da computação e o tempo de espera forem desprezáveis, pode ser vantajoso executar as TAs no início do *workflow*, antes do processo de validação pelos operadores. Para abordar essa oportunidade, a Albatroz Engenharia tem investido num novo procedimento alternativo para fazer transmitir os dados entre todas as TAs totalmente autónoma.

Considerando estes cenários, seria útil dispor de um sistema capaz de detetar que as estações de trabalho estão livres num determinado instante e subsequentemente distribuir as TAs por elas. Deste modo, os operadores poderão agendar a execução das próximas TAs para um determinado conjunto de dados de uma inspeção, enquanto estão a fazer as TMs de um outro conjunto de dados.

Os requisitos do sistema a implementar enquadram-se no âmbito dos Sistemas de Computação Voluntária (SCV) e vamos abordar alguns dos desafios impostos por esses tipos de sistemas. Computação Voluntária é um tipo de computação distribuída que

tira partido de ciclos livres dos recursos de computação doados por voluntários (i.e., os proprietários dos recursos) e que estão ligados através da Internet ou Intranet para a computação de simulações de grande escala. Pretendemos desenvolver um novo sistema de escalonamento de tarefas no contexto dos SCV, capaz de agendar as TAs do PLMI2 e explorar os ciclos livres de CPU das estações de trabalho presentes na rede local da empresa (i.e., na LAN) para acelerar a análise dos dados, tendo em consideração as suas interdependências.

Esta tese propõe e desenha um novo sistema de agendamento distribuído de tarefas no contexto da Computação Voluntária, capaz de agendar as TAs do PLMI2 e explorar os ciclos livres de CPU das estações de trabalho dentro da LAN, para executar essas tarefas, tendo em consideração os requisitos definidos pela Albatroz Engenharia.

Para avaliar o sistema proposto, foi implementado um protótipo e os resultados das simulações mostram que este é escalável e suporta tolerância a falhas na execução das tarefas, recorrendo a um mecanismo de reescalonamento das tarefas.

Palavras-chave: Computação Voluntária, Interdependências entre tarefas, Sistema de escalonamento distribuído de tarefas, Tolerância a falhas, Escalabilidade

Contents

List of Figures

List of Tables

List of Algorithms

Listings

1

Introduction

This thesis fits in an enterprise environment, emerging as a real need of Albatroz Engineering, a private company dedicated to research, development and innovation in fields such as robotics, aeronautics, software, etc. (see J.Gomes Mota [1] for more details). This company was founded in February 2006 when Gomes Mota and Alberto Vale conceived the Power Line Maintenance Inspection (PLMI) system, which is an innovative, integrated, real time, full-featured airborne solution for over-head lines inspection [2].

Since then, Albatroz Engineering has developed a comprehensive framework for overhead power lines inspection data acquisition and analysis [3], that includes hardware (sensors for data acquisition) and software tools. The framework's software components include inspection data analysis and reporting tools, commonly known as PLMI FrontEnd v2.0, abbreviated PLMI2, and one of its main features is the classification of points of interest (PoIs) detected during over-head power line inspections. A point of interest represents an entity (such as a tower, or a tree branch dangerously close to the electrical wires) detected either by a human operator or by an automatic process during a session of data acquisition.

In PLMI2, the analysis of over-head power line maintenance inspection data comprises a sequence of automatic tasks (ATs) followed by manual tasks (MTs). An AT consists of a set of algorithms that receives as input one or more datasets, processes them and returns new datasets. In turn, an MT enables human supervisors (also known as lines inspection operators) to correct, improve and validate the results of ATs.

Figure 1.1 depicts the usual workflow for the processing of inspection data. A workflow can be modelled as a Directed Acyclic Graph (DAG), where each node represents a task and an edge between two nodes means the data dependency between two tasks.

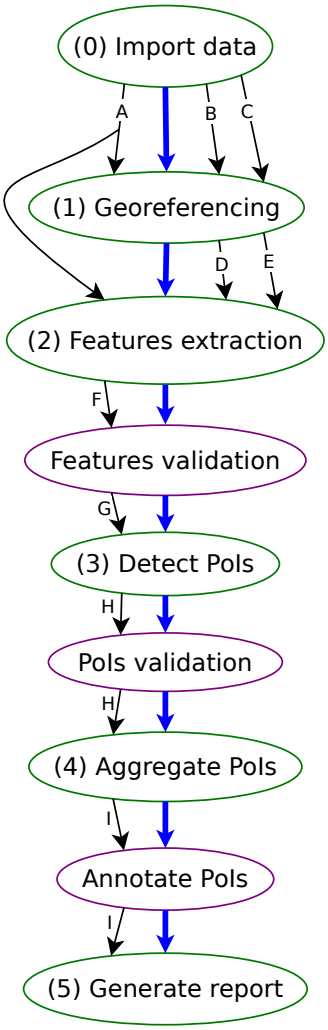


Figure 1.1: A workflow with ATs and MTs intertwined. ATs are outlined with the green colour and MTs with purple.

The data flow dependency is represented by the labelled arrows while the workflow itself by the blue arrows (the thicker ones). Note that a task may depend on one or more outputs of another, being this determined by the number of edges between them. For instance, the AT *Features extraction* depends on one output of *Import data* (A) and on two of *Georeferencing* (D and E). The labels A, B, C, and so on, represent the identifiers of output datasets generated in database when a task is executed. The only manual task which may generate a new dataset on database is the *Features validation*. The remaining ones just make changes on existing datasets.

Briefly, for any processing of an inspection data, there are at least the following tasks organized according to a waterfall model:

0 (**automatic**) Import inspection data (sensors' data and video) to a centralized database server;

1 (**automatic**) Geo-referencing of imported data and returning the results to the database

server. This task consists in merging acquired data from three sensors, i.e., GPS, IMU[1] and LiDAR[2];

2 (**automatic**) Features extraction or classification, which is the process of finding power lines, towers, vegetation, buildings, ground, roads and water;

- (**manual**) Features validation, i.e., the validation of extracted features from the previous task;

3 (**automatic**) Detection of Points of Interest;

- (**manual**) Validation of Points of Interest;

4 (**automatic**) Aggregate Points of Interest according to relevance and maintenance criteria;

- (**manual**) Add annotations to Points of Interest;

5 (**automatic**) Generate the inspection analysis report files.

For the first AT, the data to be imported is stored in a local workstation (where the PLMI2 is installed) or else in some location within the company's Local Area Network (LAN). For the remainder ATs and MTs, the input data is available from the database server. All tasks are performed in a workstation where the PLMI2 application is already installed, and each one of them retrieves data from a central server and stores the subsequent results in this same server.

The PLMI2 application is the main entry point to the system, i.e., it is the tool from where the analysis of inspection data is triggered, when an operator requests the execution of the first AT. PLMI2 provides for the processing of the inspection data; for a very rich and complete visualization of the power line and surrounding environment [3], by combining data from different sensors; and for the generation of inspections' report files.

On the other hand, the database server is very simple, i.e., it does not do any complex processing. It simply provides a database service to store the large data volumes processed by PLMI2 applications. The system architecture is illustrated in Figure 1.2.

1.1 Motivation

Automatic tasks run faster than manual tasks. In the overall work cycle, ATs take less than 10% of total processing time. Each AT takes from 1 to 15 minutes to complete its execution and they are intertwined with MTs. Therefore, the lines inspection operators wait during the execution of ATs but not too much to make it useful to leave the computer unattended to carry other duties.

[1] http://en.wikipedia.org/wiki/Inertial_measurement_unit
[2] http://en.wikipedia.org/wiki/LIDAR

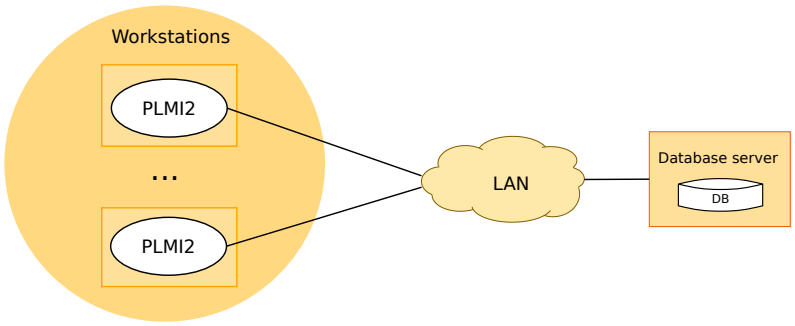


Figure 1.2: A general view of the current system architecture.

Currently, the PLMI2 enables an operator to request the execution of ATs in several ways. Some restrictions apply, such as *Import data* must be the first to be executed and all MTs should be performed before the *Generate report* due to the final inspection's report quality. Figures 1.1 (already presented) and 1.3 depict two different ways to perform the analysis of an inspection data.

Even if MTs are omitted from the workflow, it is possible to carry the sequence of ATs, although with a significant amount of errors. Nevertheless, the quality control tools embedded in PLMI2 highlight these errors which may contribute to a more efficient human validation. In conclusion, if the computing cost and waiting time are negligible it may be advantageous to run ATs earlier in the waterfall stream, prior to validation on the upstream. The configuration depicted in Figure 1.3 takes this approach to the extreme performing all automated tasks before manual tasks.

Moreover, even if one maintains the current waterfall model, it may be advantageous to allocate optimal computing resources to execute ATs instead of investing in top performing computers for every human operator since the validation tasks do not benefit from the additional computing power and a modest CPU is sufficient.

To address this opportunity, Albatroz Engineering has invested in a new procedure to stream the data through all ATs fully unattended. Depending on the type of power line, this produces between 10% and 70% of correct results before human validation and correction.

1.2 Problem Description

Taking into consideration the scenarios described in the previous section, it may be useful to have a system capable to distribute ATs among the available hosts within the company's Local Area Network (LAN). In this way the lines inspection operators could request the scheduling of next tasks for a given inspection data analysis, to be executed on available hosts, while they are performing manual tasks of another inspection data.

Briefly, the aim of Albatroz Engineering is to have a system that allows the scheduling

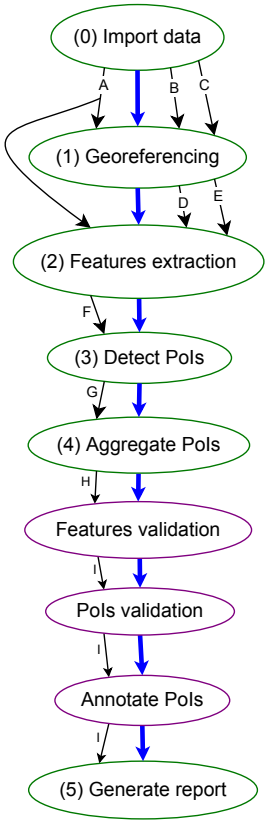


Figure 1.3: Another possible way to structure the workflow with the MTs on the upstream.

of all possible combinations of ATs for any inspection data analysis, either during daytime or night-time, by exploiting idle CPU cycles from the workers' workstations within the LAN and consequently minimizing the time that lines inspection operators wait for ATs results to be available

It is necessary to design and implement a system able to detect that the hosts are available at a given instant and subsequently distribute the automatic tasks to them. In addition to the task's execution, this system should be aware of their inter-dependencies, as explained in Section 1.1. Moreover, operators may want to prioritize the execution of tasks of a workflow relatively to tasks of another workflows. Therefore, when an operator requests the execution of a task, the system may execute it immediately or not, according to its priority and the number of other tasks that are waiting to be executed.

Computing resources should be able to execute ATs, either in a batch processing mode (which will be useful, for instance, during night-time because the company has several hosts that are stopped overnight), or in a screensaver-like mode, which will exploit idle CPU cycles from computing resources during lunch hours, meetings, etc., to accelerate the inspection data analysis.

These requirements lead us to design and implement a system which falls within the field of Volunteer Computing Systems (VCSs), defined in Section 1.3, which addresses

some of the challenges posed by these systems, such as hosts volatility (i.e., a host may join and leave the system any time it wants) and heterogeneity, i.e., hosts have different operating systems, CPU type, RAM size, etc.

1.3 Context

Volunteer Computing (VC) is a type of distributed computing in which computer owners (i.e., the volunteers) provide their computing resources, such as idle CPU cycles, storage and Internet bandwidth, for scientific projects, which use these resources to distribute the computing of large-scale processes, such as simulations. The term *volunteer computing* was introduced by Luis F. G. Sarmenta in his Ph.D. thesis in 2001 [4]. The first VC project was the Great Internet Mersenne Prime Search (GIMPS) [5], which searches for Mersenne prime numbers and began in 1996. One year later, in 1997 the Distributed.net was founded, which is a general-purpose distributed computing project where thousands of users around the world donate the power of their personal computers to academic research and public-interest projects [6]. The SETI@home [7], since its release in 1999, has demonstrated the great potential of VC. SETI@home is an Internet-based public VC project with the purpose of analysing radio signals, searching for signs of extraterrestrial intelligence [8].

One of the main advantages of volunteer computing over traditional solutions based on supercomputers is the fact that it is not expensive. However, the development of VC projects needs to address some problems and challenges in order to provide high-throughput computing. The big challenge in Volunteer Computing Systems (VCSs) is the scheduling of work-units in highly dynamic environment composed of multiple heterogeneous computers, as stated in [9]; and the common problem to address in these systems is the distributed resources management [10].

On the first viewpoint, one might sense that VC is restricted only to systems where computing resources are located in the scope of the Internet, but not necessarily, since people within an organization (i.e., within a LAN) can also volunteer their workstations during idle time, in the same way as Internet users volunteer theirs. Indeed, an important aspect emphasized by L. Sarmenta in [11], is that volunteer computing can be used not only for building a wide area network (WAN) of parallel computing more powerful than a supercomputer but it also can be employed even for small scale environments, such as companies or institutions, to exploit the power of workstations to provide similar solutions like a supercomputer.

Unlike common existing VC projects on which the resource providers are located in the scope of the Internet [12], the scope of the system to be developed is LAN-based, i.e., it may have many producers (submission hosts) of tasks, all workstations are potential producers and consumers (execution hosts), and the VC resources are only those connected by the company's LAN, meaning that some of them can be fully dedicated to execute automatic tasks and others may not. Thus, it is not relevant to address the challenges

related with reliability (e.g., trying to protect the system against malicious volunteers) as identified and discussed in [4].

The resources in the company's LAN are heterogeneous (e.g., operating system, CPU, memory, availability, volatility, etc.) and the degree of their volatility is very high during the day (when needed, some of them keep running during the night), meaning that the system should address these problems because the heterogeneity may delay the overall tasks execution time and/or make the scheduling decisions more difficult.

We intend to implement a system with the following features:

1. A distributed execution system and decentralized;
2. Execution of workflows of tasks;
3. Volunteer Computing-based;
4. Directed to the LANs;
5. Resilient to the nodes failures (fail-stop model, not Byzantine failures);

Volunteer Computing systems for the Internet, such as SETI@home [7] or those systems based on BOINC middleware [13], are resilient to the failures, take into account hosts heterogeneity, volatility, etc., but they are all centralized.

Systems based on Desktop Grid Computing (DGC), which is a type of distributed system that uses computing, network, and storage resources of idle desktop PCs distributed over multiple LANs or the Internet [14], are volunteer-based, operate within a LAN or interconnect LANs but we have not found none of them which has simultaneously all features that the system we propose should have.

At the moment of this writing, the Condor [12, 15, 16], which is a DGC system that manages clusters of desktop workstations, supports execution of dependent or independent jobs/tasks, provides supporting for fault-tolerance, addresses challenges such as resources volatility, heterogeneity, etc., is directed either to LAN or Internet, is the only system that supports the majority of features provided by our proposed system, but its current release has some limitations [3] on jobs which use checkpointing as mechanism for the fault-tolerance supporting and it relies on a single central manager.

For example, the system proposed in [17] follows a peer-to-peer scheduling architecture, takes into account the hosts' heterogeneity when it makes scheduling decisions and harvests night-time idle cycles from desktop computers distributed geographically in different time zones over the Internet, but does not consider tasks with dependencies.

The system presented in [18] follows a peer-to-peer based Volunteer Computing architecture, i.e., a decentralized scheduling model, but does not support fault-tolerance.

Entropia [19] is a DGC system directed to LAN or Internet, which addresses a number of challenging issues, such as fault-tolerance supporting, scalability, robustness, etc., but does not consider the scheduling of tasks/jobs containing dependencies.

[3] http://research.cs.wisc.edu/htcondor/manual/v8.1/1_4Current_Limitations.html

Regarding distributed scheduling algorithms in the context of Volunteer Computing, currently, it may be found research works such as:

- For example, [20] is a fully distributed scheduling algorithm which takes into consideration several issues, such as scheduling interdependent tasks of DAG and exploits idle CPU cycles, but it lacks of fault-tolerance supporting of task execution;
- The decentralized scheduling algorithm *CoAllocation* proposed in [21], for scheduling tasks having dependencies in Grid environments, which tries to achieve the load-balancing in terms of number of tasks scheduled in each computing resource, yields good results, but lacks of the fault-tolerance supporting.

1.4 Solution

We developed a new task scheduling system in the context of Volunteer Computing Systems, able to schedule simulated automatic tasks of PLMI2 and exploit the idle CPU cycles from hosts within Albatroz Engineering's LAN to accelerate the data analysis, being aware of their inter-dependencies and priorities. These tasks are executed by the company's computing resources either in a batch processing mode or in a screensaver-like mode. This system follows a distributed scheduling architecture, on which each scheduler may have either the role of server and/or client; which does not rely on the process of computing resources discovery such as pull and push modes (defined later in Subsection 2.2.2) because all schedulers are supposed to have the same set of tasks and when a scheduler's host becomes idle it just asks other servers if it can start executing a given task.

The main challenges of this thesis are:

- Dealing with the data flow dependency among tasks, i.e., how to represent that an automatic task depends on the results of other tasks which have not finished yet their executions, meaning that an AT should only start its execution once its dependable tasks have processed the data on which it depends on. In other words, tasks are organized in an assembly-like manner, where the output of a task is fed to following tasks;
- Dealing with the computing resources volatility, i.e., they may join or leave the system unexpectedly;
- The implementation of a distributed system with fault-tolerance supporting.

1.5 Contributions

The main contributions of this thesis are:

- The design of a system fully distributed, able to meet the requirements defined by Albatroz Engineering, namely the scheduling of tasks of a workflow within a LAN following a Volunteer Computing model;
- Implementation of a prototype of the proposed system;
- Evaluation of the system scalability and its ability for fault-tolerance supporting;
- Evaluation of the average waiting time by a task, i.e., the time since it becomes ready to be executed until the system starts executing it and the average completion time of a workflow.

1.6 Document Organization

This document has six chapters organized as follows:

- Chapter 1 introduces us to the problem, its motivations and challenges.
- Chapter 2 discusses what is a job scheduling system, what are the common scheduling architectures employed, how the computing resources are discovered and finally presents the related works from state-of-the-art.
- In Chapter 3, we present the system requirements, the communication protocols among its entities, the algorithms for achieving the distributed scheduling and its architecture.
- Chapter 4 explains in details how a system prototype was implemented.
- In Chapter 5, we describe how it was developed a simulation framework to automatically test the prototype and we present the results obtained by evaluating it with different test configurations. We also provide an evaluation of the requirements satisfaction by our developed prototype.
- In Chapter 6, we present the overall conclusions of this thesis, the goals that were met and we propose the future work needed to improve the implemented prototype.

2

State of the Art

This chapter briefly presents a literature overview of existing job scheduling systems, in which we define and discuss several issues related to this field of study. Concretely, we present the common architectures employed by existing scheduling systems, their advantages and disadvantages taking into consideration the requirements of a given job scheduling problem. We also talk about the scheduling for Volunteer Computing, its main challenges and problems. Furthermore, this chapter presents some of close related works from state-of-the-art, namely the scheduling in Peer-to-Peer systems. Finally, this chapter ends with a brief discussion about the scheduling systems and what are the mechanisms that our system will employ.

2.1 Introduction

The scheduling problem is not new in the field of distributed computing systems. It has been a subject of study for more than two decades; hence, several solutions to solve this problem in an effective way have been proposed in the field of Artificial Intelligence, often based on genetic algorithms and heuristic search strategies [9, 22, 23, 24]. A considerable number of researches have been done in order to categorize the field [4, 10, 12, 25] and several systems addressing this problem have been implemented in real-world scenarios [7, 11, 15, 26, 27].

The remainder of this chapter is organized as follows. Section 2.2 gives an overview of what a scheduling system is about and how it works. Section 2.3 provides basic characteristics of scheduling in the context of Volunteer Computing Systems and overviews existing policies. Related works concerning the scheduling in peer-to-peer systems are

Sate	Description
Submitted	The job was submitted to the scheduler and is waiting in the job queue for its turn to be processed, according to its type, priority and resources it needs, then going to Ready state.
Ready	The job is waiting in the ready job queue to be assigned to the execution host.
Scheduled	The job was dispatched to the execution host.
Running	The job is being executed.
Suspended	The job was interrupted, either explicitly by a user through an external command or the job suspended itself waiting for some condition to allow it to proceed.
Cancelled	The job was cancelled (e.g., by a user).
Aborted	The job was aborted due to an internal system error.
Terminated	The job has finished execution.

Table 2.1: Description of job state.

presented in Section 2.4. Section 2.5 presents two related works concerning the scheduling of tasks with dependencies and provides references to more related works. Finally, a general discussion about what techniques will be applied by our system is presented in Section 2.6

2.2 Job Scheduling System

This section gives a general overview of what a scheduling system is about and how it works in the context of distributed computing systems.

Job scheduling is defined as the process of mapping jobs for execution into available computing resources. The concept of **job** is not clearly defined in state-of-the-art, thus in the context of this research we will define it has being a unit of computational work to be performed. Some research papers [21, 28] consider that it can be split in many small tasks, but in our case we will consider a job as being the same as a **task**, and these terms may be used interchangeably. A **resource** will be considered as any computer in the LAN with minimum required features to run a job.

The scheduler has the responsibility of selecting resources and scheduling jobs in such a way that user and application requirements are met, in terms of global execution time (throughput), cost of used resources and response time. Generally, a job can have the states shown in Figure 2.1 and described in Table 2.1. The provided diagram is similar to those diagrams of state transition of a process, found in many classical operating systems'

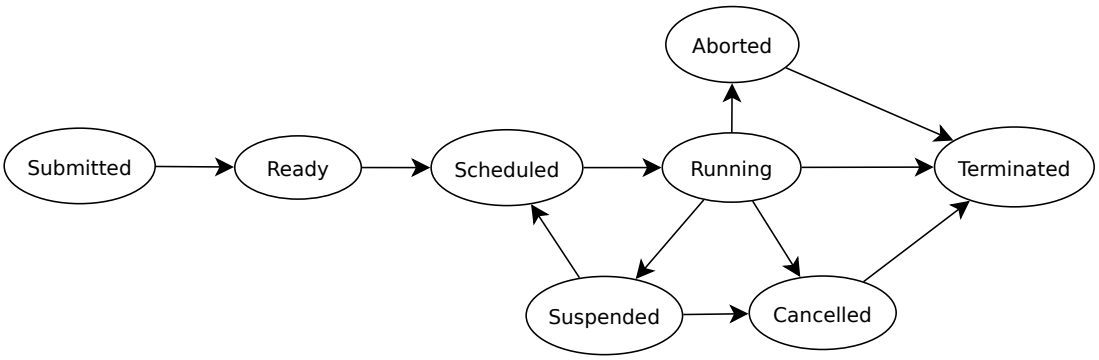


Figure 2.1: The states of a job.

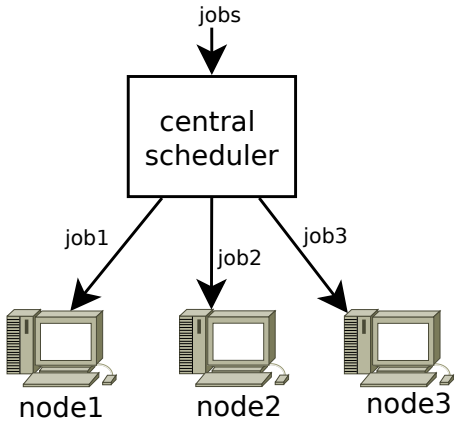


Figure 2.2: Centralized scheduling architecture. Adapted from Li *et al*. [36].

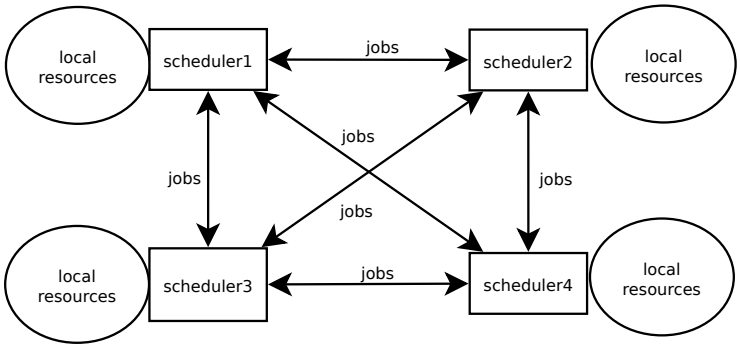
books, for example in [29, 30, 31], or found in [32, 33, 34]. Note that a job goes into Submitted, Suspended or Cancelled state by a user's action while the remainder transitions are triggered by the scheduling system.

2.2.1 Scheduling Architectures

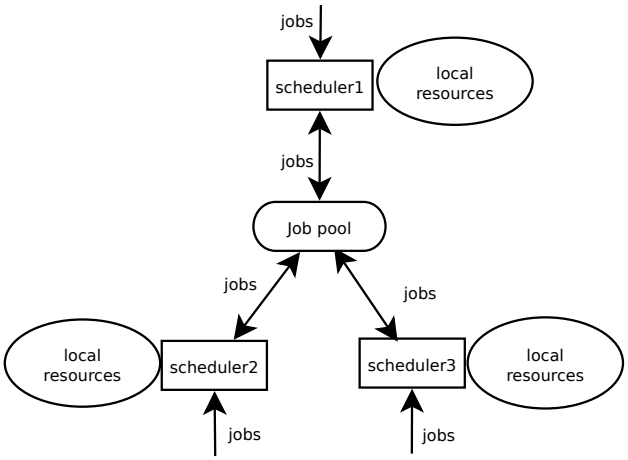
When designing and developing a scheduling system, the designers should consider the following architectures according to where and how the scheduling decision is made. There are three proposed architectures [12, 35], centralized, distributed and hierarchical, which are detailed below.

Centralized scheduling: In this architecture, there is only one scheduler that is responsible for making all decisions, i.e., how to select a job and to which resource it will be scheduled. This approach is illustrated in Figure 2.2.

Distributed scheduling: In this architecture, multiple processes cooperate with each other for making scheduling decisions. The communication type between schedulers



(a) Distributed scheduling with direct communication between schedulers.



(b) Distributed scheduling with indirect communication between schedulers via job pool.

Figure 2.3: Distributed scheduling architectures. Adapted from Li *et al*. [36].

can be divided in two sub-types [36], namely (1) **direct communication** and (2) **indirect communication via job pool**. In (1) each scheduling process features a list of it peers to whom it can communicate with. When it cannot schedule a given job locally then it sends the job to other schedulers as shown in Figure 2.3(a), whereas in (2), illustrated in Figure 2.3(b), when a job cannot be locally scheduled, then it is placed on a job pool to be scheduled by other and therefore the schedulers' policies should ensure that all submitted jobs to the job pool eventually will be executed.

Hierarchical scheduling: In this approach, jobs are submitted to a central node, which dispatches them to local schedulers, whereas each local scheduler submits jobs to its computing resources. Figure 2.4 depicts this approach.

In Table 2.2, we summarize the advantages and disadvantages of each scheduling architecture.

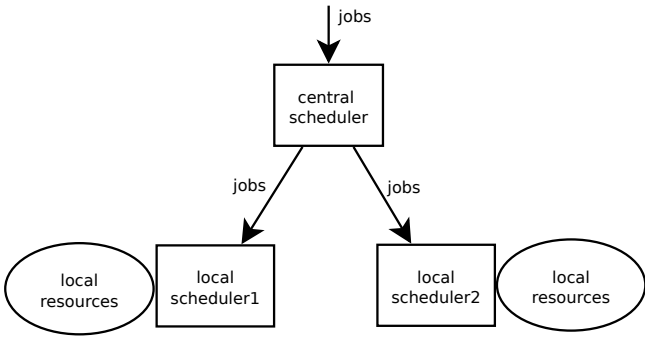


Figure 2.4: Hierarchical scheduling architecture. Adapted from Li *et al.* [36].

Architecture	Advantages	Disadvantages
Centralized	- Makes better scheduling decisions because the scheduler has access to all information about all resources.	- Single point of failure; - Does not scale well with the increasing of number of resources.
Distributed	- Scalable; - Can offer better fault tolerance and reliability.	- The lack of a global scheduler, that knows all system information, may lead to sub-optimal scheduling decisions.
Hierarchical	- Global scheduler and local scheduler can have different policies in selecting jobs or resources.	- The central scheduler can have scalability and communication bottlenecks because it is a single instance to which all jobs are firstly submitted.

Table 2.2: A summary of advantages and disadvantages of centralized, distributed and hierarchical scheduling.

2.2.2 Resource Discovery

The resource discovery consists in finding suitable resources from an available set of them, for executing jobs. The information that is passed from resources to the scheduler are CPU speed and current load, available memory, etc. The resource discovery might be performed by three models, i.e., the pull model, push and push-pull, as proposed by Li *et al.* [36].

The pull model: A daemon process associated with the scheduler is responsible for requesting/pulling state information from resources. Figure 2.5 depicts this model.

The push model: In this model, the process of resource discovery is started by resources themselves, i.e., each resource has a local daemon that collects and pushes state information to the scheduler, which receives and stores it in a database for later retrieving by the

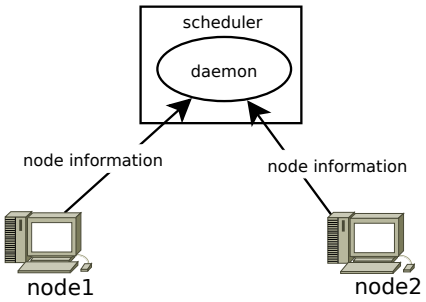


Figure 2.5: The pull model for resource discovery. Adapted from Li *et al*. [36].

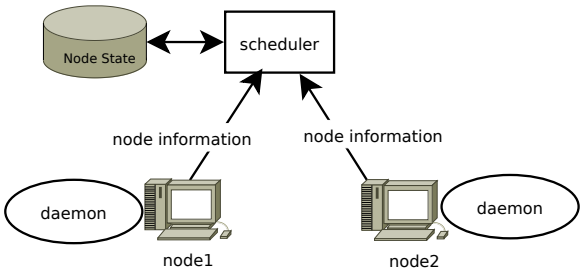


Figure 2.6: The push model for resource discovery. Adapted from Li *et al*. [36].

scheduling algorithm. Figure 2.6 illustrates this model.

The push-pull model: This model is a combination of pull and push strategies, i.e., there is a daemon process in the central scheduler, who pulls information from **aggregators**, and there are daemons in nodes/resources whom collect and push state information to the daemon process of a known aggregator, which is responsible for aggregating information from a set of resources and replying queries from the scheduler. This strategy for resource discovery is shown in Figure 2.7.

Resource discovery in distributed scheduling: Note that, the previously described resource discovery mechanisms apply not only to the centralized but also to distributed scheduling. But usually in decentralized environments the discovery is accomplished by a central entity (e.g., the Grid Peer Information Service in [37]), which itself can be implemented either as centralized or decentralized. The latter case might be more challenging because it is necessary to keep all its replicas coherent.

2.2.3 Job Scheduling Policy

The process of selecting the next job from a queue to be scheduled is accomplished by using a dedicated algorithm named **scheduling policy**.

In the context of scheduling in distributed computing systems, a **policy** is defined as an algorithm that determines to which resources a job is assigned [12], that is, how it should choose a job for execution from its available set of jobs and how it should pick

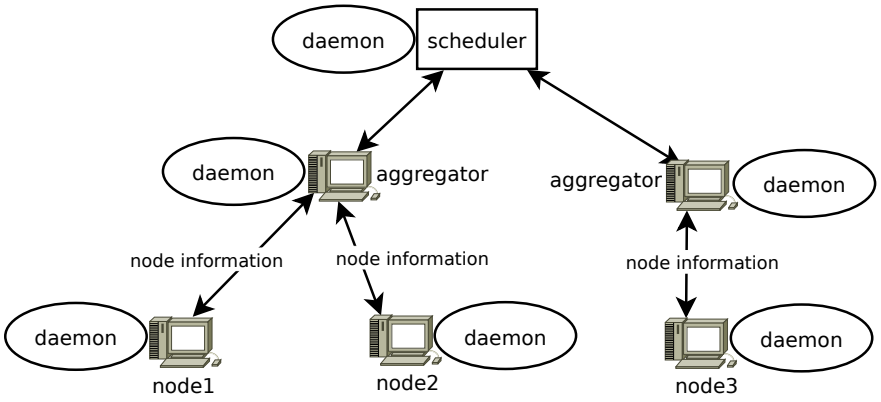


Figure 2.7: The push-pull model for resource discovery. Adapted from Li *et al*. [36].

up one resource to execute the chosen job, from an available set of resources. Or even more concrete, what is the matching job-resource that would minimize the overall jobs execution time.

The problem of mapping jobs into distributed resources in a way that minimizes the **makespan** (the total execution time), has shown to be NP-complete, by a reduction from the Minimum Multiprocessor Scheduling [38]. What can be done is to find sub-optimal solutions by using strategies based on heuristic search.

Choi *et al*. [12] classified the scheduling policy in three approaches, i.e., simple, model-based and heuristic-based.

Simple approach The common and simple strategy [12, 39] consists in selecting jobs or resources with the First Come First Serve (FCFS) method, which can be implemented with a well-known data structure, the FIFO (First In First Out) queue, or a random approach, which is implement by techniques of random numbers generation.

Model-based This approach is divided in three main categories, namely deterministic, probabilistic or economy model.

In **deterministic model**, jobs or resources are selected according to a predefined structure or topology of their organization, that is, how the jobs or resources are interconnected with each other. The common structures or topologies are the queue, stack, graph and the ring. In comparison, in **probabilistic model**, jobs or resources are selected according to probability theory (e.g., using the Markov model as applied in [40]).

Heuristic-based In this approach, jobs or resources are selected by **ranking** (i.e., ranks and then chooses the best one), **matching** (i.e., chooses the best one according to evaluation functions) and/or **exclusion** (i.e., excludes resources according to a given criteria and then chooses the best one among survivors).

There are other scheduling policies that were not mentioned above, which are those based on priority of jobs. Examples are **pre-emptive scheduling**, which lets a pending high-priority job to take resources away from an executing job of lower priority, and **shortest job first (SJF)**, in which the next job to be scheduled is the one that has minimum estimated completion time (ECT); if two jobs have the same ECT then FCFS is applied.

A well-known problem of priority-based scheduling is **starvation**, i.e., a job that is ready to run can never be scheduled because high-priority jobs are always selected first even when they arrive after that job. A solution to solve this problem is to apply **ageing**, which is a technique of gradually increasing the priority of jobs that wait in the system for a long time [31].

2.2.4 Job Dispatching

It is the process of assigning the execution of next job to run on the selected resource. It can also be performed according to the pull and push modes [36], described as follows:

Pull mode: The resources pull jobs from scheduler when they go into idle time and then the scheduler assigns jobs to them according to its scheduling policy. This mode is suitable for those systems where resources are **volatile**, i.e., **non-dedicated** [12, 41].

Push mode: The scheduler starts the scheduling process when jobs are submitted to its queue, that is, it pushes jobs to resources according to its scheduling policy. The push mode can be suitable for systems whose the probability of a resource being in idle state is very low (in this case, the resources are called **dedicated resources** as defined in [12, 41]).

An example of a scheduling system that employs similar mechanisms is the Condor [15]. It allocates resources for job dispatching by employing a matchmaking mechanism. This mechanism is based upon notion that jobs and resources advertise themselves in **classified advertising** (abbreviated ClassAds), which include their characteristics and requirements, then each pair job-resource that matches is created.

2.3 Job scheduling in Volunteer Computing Systems

The job scheduling in VCSs has several common characteristics with Grid scheduling, but in VCSs it should be taken into consideration that the resource providers are not reliable; VC resources are dynamic (they can join and leave the system at any time), either due to the poor network bandwidth or intentionally by theirs providers; and the resources are highly heterogeneous [12]. The reliability is related with the fact that VC resources may return maliciously incorrect result [42] and they are faulty, which requires the implementation of result validation and fault tolerance mechanisms.

Fault tolerance: It is a common non-functional requirement found in many computing systems, which enables a system to work properly even if some of its part fails [43]. In the context this work, it can be considered as a quality attribute that tolerates resource failures and volatility. The rescheduling, checkpoint-restart, replication of tasks, etc., are the common applied techniques for leading with these failures [12]. For the **rescheduling technique**, if a scheduler detects a resource failure then it reassigns the failed task to another resource. For the **checkpoint-restart**, the scheduler restarts the failed task from the checkpoint in another resource. For the **replication**, a scheduler replicates a task on multiple resources, to allow a resource to mask the failure of another.

Load balancing: In the context of VCSs, this property attempts to balance the computation load among computing resources present in the system. Normally, the system's lightly loaded nodes cooperate to remove the work in heavily loaded node by exchanging information (periodically or on demand) about their characteristics and current CPU load. This property can be accomplished by applying the pull mode for the work *stealing* or the push mode for the load distribution.

2.3.1 Scheduling

Recently, many scheduling policies based on heuristics (e.g., HEFT, min-min, max-min, and so on [44]) have been proposed in the context of VCSs because the problem of optimal mapping of tasks to resources is NP-complete as already mentioned previously, thus these heuristics try to find sub-optimal mapping.

The pull approach (presented in Subsection 2.2.4) is the common dispatching mode employed by the VCSs, i.e., when volunteers go into idle state then they contact a VC job scheduler, requesting for the jobs for the execution. As an example, the BOINC's local scheduling [45] employs this mode. BOINC (Berkeley Open Infrastructure for Network Computing) is an open source middleware system for VCSs [13] used in several VC projects (e.g., SETI@home [7], FightAIDS@home [27], Folding@home [26], etc.).

As stated by Estrada *et al.* in [9], existing job dispatching policies in VC projects can be classified in two classes, i.e., naive and knowledge-based. Examples of **naive** approaches are FCFS, the random allocation and the locality assignment in which jobs are assigned preferentially to volunteers that already have necessary data to accomplish the execution. In contrast, **knowledge-based** approach takes into account the historical behaviour of the volunteers when assign jobs to them.

In contrast to the manually designed scheduling policies, which are limited to the specific projects, or to those randomly generated, Estrada *et al*. [9] in their research entitled *A Distributed Evolutionary Method to Design Scheduling Policies for Volunteer Computing*, proposed an evolutionary method to automatically generate scheduling policies based on the volunteers' behaviour, when the computing resources request the jobs for execution.

This method includes a genetic algorithm in which the representation of individuals, fitness function, and genetic operators are tailored to get effective policies that are project-independent, minimize errors, and maximize throughput in VC projects. However, some input values to the algorithm are manually introduced and they intend to automate this process in future work.

In [43], Lee *et al.* addressed the problem of robust task scheduling in VCSs by proposing two heuristics, which identifies best task-resource matches in terms of makespan and robustness. Generally, the **robustness** is defined as the capacity to function properly in variable conditions. As the context of the research was VCSs, the definition of robustness was narrowed down to the ability to ensure the quality of a schedule in spite of a certain degree of performance fluctuations, such as inaccurate estimative of task completion time and resource performance degradation. For a given schedule, both proposed algorithms, *RMAX* and *RMXMN*, aim to reschedule it, if a new task-resource match improves the robustness without increasing the makespan.

Extensive set of experiments allowed to conclude that the robustness of output schedules is improved by maximizing either the total or minimum relative delay time over all allocated VC resources.

2.4 Peer-to-Peer Approach to Scheduling

This section overviews two related works concerning the scheduling in P2P[1] systems. The reason why we are presenting these systems, is because we intend to developed a distributed job scheduling where each node can provide both client and server functionalities.

Cao *et al*. [37] in their research entitled *A Peer-to-Peer Approach to Task Scheduling* proposed a P2P approach which employs the distributed scheduling architecture to lessen the load of intermediate server by letting the peers to cooperate among them to make scheduling decisions using their own scheduling policies. Each scheduler running on a peer follows a generic architecture which authors denominated PGS (P2P Grid Scheduler) and jobs are firstly submitted to the local scheduler where they originated. Each peer interacts with GPIS for collecting information about other peers and making scheduling decisions. Once a scheduler has decided to/from which peer it should dispatch/request jobs, then starts to interact directly with it through **Peer Communication** component.

The system relies on a Grid Peer Information Service (GPIS) based on Grid Information Service (GIS[2]). The GPIS provides information about peers in the system and it is a meta-data infrastructure that enhances existing GIS in Grid middleware. As the authors stated, in Grid environment the GIS gets outdated very quickly, because nodes are freely

[1]The term **peer-to-peer** (P2P) refers to a class of systems and applications that employ distributed resources to perform a function in a decentralized manner [46].

[2]GIS is a software component, either centralized or distributed, that maintains information about services, computing resources in computational grid, etc., and makes that information available when inquired [47].

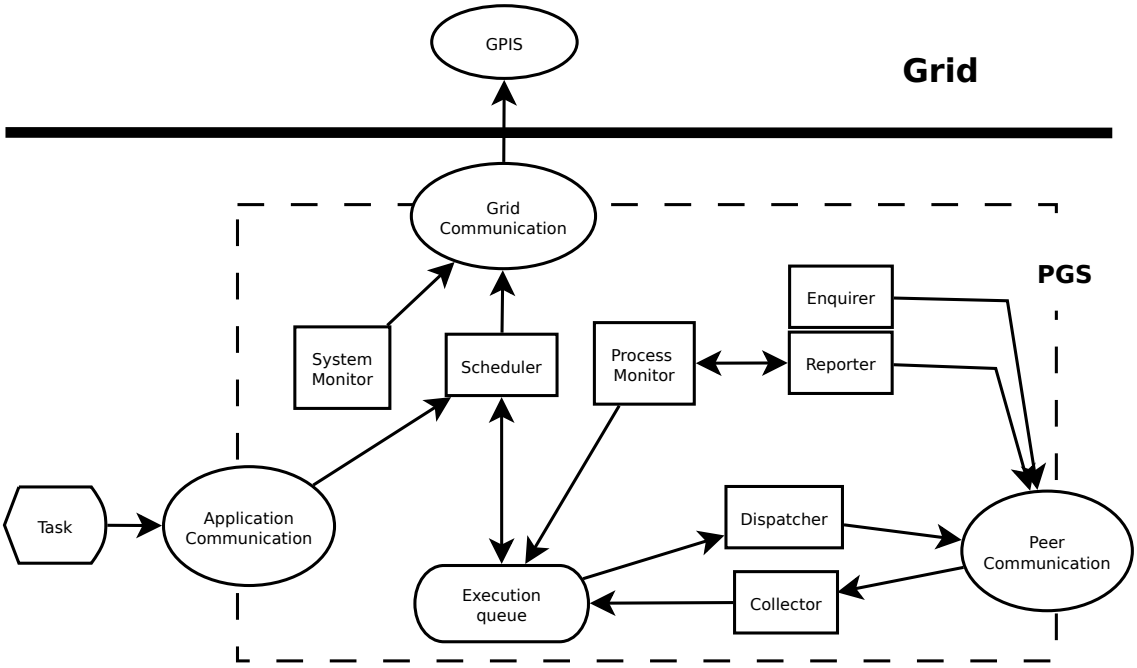


Figure 2.8: The architecture of PGS. Adapted from Cao *et al*. [37].

to join and leave at any time, and due to possible system failures. Figure 2.8 illustrates the PGS architecture installed on every peer. The components that compose the PGS are the following:

Grid Communication It is a communication interface between GPIS and PGS's components to allow a peer to query information about other peers kept by GPIS.

Application Communication It is an interface to enables user to provide resource details, to edit GPIS and specify scheduling policies.

System Monitor It is responsible for gathering quality information (either periodically or on the demand) about a peer (i.e., CPU load, available RAM, etc.) and translating it into readable format to be used in resource selection process.

Scheduler The component responsible for scheduling tasks of submitted jobs, by requesting a group of peers from the GPIS and consulting the System Monitor to get peer information, and according to the scheduling policy it decides if a task will be executed locally or remotely.

Dispatcher It is responsible for dispatching tasks of a job to other peers when peer is busy.

Collector It is responsible for requesting tasks from other peers when the peer go into idle time.

Process Monitor The component responsible for monitoring the tasks that are being executed locally.

Reporter It is responsible for gathering the tasks' status from **Process Monitor** when inquired by other peers.

Enquirer The component responsible for requesting tasks' status information from remote peers.

The process of scheduling in PGS is composed by peers registration in GPIS, task scheduling and task execution. The task scheduling is divided in task capturing and task dispatching. Task capturing uses push mode, whereas task dispatching employs pull mode.

The proposed architecture was implemented and the performed experiments allowed to conclude that combination of push and pull modes for task dispatching achieved faster convergence in speedup than only push mode.

Zhao *et al.* [18] proposed a system named *PPVC: A P2P Volunteer Computing System*, for job scheduling, in which volunteers are organized as a P2P network, i.e., there is no central server and every volunteer has the same functionality.

In order to use several computers in the network, a job should be able to be recursively separable into small sub-jobs. When a peer receives a job, he splits it in $N + 1$ sub-jobs, where N is the number of its neighbours that are free. One sub-job is executed locally and remaining will be sent to N free neighbours. A job is split until not possible to be split any more or if a peer has no available neighbour. When a peer completes the execution of a job, the result is sent to its parent to be collected and merged with other results. The system supports the dynamic joining and leaving of peers, by self-reorganization of its grid.

The authors implemented the PPVC using Java platform and the case of study was N-Queen problem. The experiments were conducted by using three computers and the results shown that the efficiency in terms of system's response time with three peers, for 14-Queen was 87.5%, 15-Queen was 88.1% and 16-Queen was 89.9%, respectively.

2.5 Scheduling of Interdependent Tasks

Relatively to scheduling tasks with dependencies, it was found that they can be modelled with a Directed Acyclic Graph (DAG) [21, 23, 43, 48, 49, 50, 51, 52], where each node represents a task, the data dependency between two tasks is represented by an edge and in some cases a weight on an edge represents the cost in terms of time to transfer information (e.g., data, code, etc.) from one task to another.

Blythe *et al.* [50] proposed two classes of resources allocation algorithms: task-based approach (TBA) and workflow-based approach (WBA). The jobs/tasks in a workflow have well-defined dependencies of required input data to allow the computing. TBA greedily assigns each ready to run task to a resource regarding only the information about that task, i.e., it only reasons about the tasks that are ready to run at any given time instant, whereas WBA searches for an efficient allocation of entire workflow, and may revise the allocation of a task based on subsequent tasks. The performed simulations allowed the authors to conclude that both approaches are suitable for computing-intensive workflows but WBA is more suitable for data-intensive workflows because it decreases the time to transfer data from one task to another.

Moise *et al.* [21] proposed a scheduling algorithm named **CoAllocation**, for scheduling tasks having dependencies, which is a decentralized, dynamic and optimal mechanism for job scheduling in Grid environments. CoAllocation consists in allocating tasks having dependencies, in which the main purpose consists in generating schedules in efficient way, in terms of load balancing among computing resources and minimum time for execution of tasks. Tasks and computing resources are described by using the XML format.

A set of tasks is represented with a weighted DAG, in which each node represents a task and the dependency between two tasks is represented by an edge. A weight on edge means the cost in terms of time to transfer information between two tasks and a weight on a node is the cost in terms of time to execute a task.

The CoAllocation algorithm involves two types of entities, called broker and agent, defined as follows:

Broker This entity is responsible for receiving an XML file containing tasks' dependencies from a user, clustering of tasks and distributing each formed cluster to each agent.

Agent It is an entity responsible for managing a set of local computing resources.

The CoAllocation algorithm comprises three phases, which are described below:

Task clustering This phase consists in creating a DAG of sub-DAGs of tasks having dependencies, on which each a sub-DAG is connected to another if there is a dependency between one of its tasks and another tasks of other sub-DAG.

Dynamic scheduling inside a cluster (i.e., a sub-DAG) It consists in scheduling tasks to an agent's local computing resources.

Dynamic scheduling of clusters It is the final scheduling, that will be done by the broker, of the DAG of clusters based on the dependencies between them.

The proposed algorithm was tested and experimental results have shown that load balancing goal was met. However, the authors did not specify if their implementation of

the broker is centralized or distributed, i.e., if the broker is centralized then it is a single point of failure.

2.6 Discussion

Throughout the previous sections, we have presented what is a job scheduling system, how it works in the context of distributed systems and particularly in the context of Volunteer Computing Systems. We also presented what are the challenges and problems raised by these kinds of systems.

Since we intend to develop a distributed task scheduling where each node may have the role of task producers, by submitting workflows for execution, and task consumers, by donating CPU cycles, then the distributed scheduling architecture with direct communication (presented in Subsection 2.2.1) better fills our requirements, in comparison with centralized or hierarchical scheduling. The scheduling policy which will be employed is the priority-based FCFS.

The inter-dependencies between ATs may be modelled with a DAG and the system will schedule only ready-to-run tasks, i.e., the tasks that satisfy all required conditions to be scheduled.

To automatically ensure the load balancing property, the pull mode, defined on Subsection 2.2.4, will be applied by resources for requesting jobs when their CPUs come into idle state. Also, the push mode may be applied when first jobs are submitted to the system. The fault tolerance mechanism will be the reassignment, explained in Section 2.3.

3

The Distributed Execution Platform

This chapter describes the requirements that the system to implement must satisfy, by exploiting idle CPU cycles of existing computing resources within the company's LAN, to execute automatic tasks of PLMI2 application, taking into account the well-defined dependencies among them. We also define the overall system architecture and establish the communication protocols among its several entities, in order to support the scheduling of the computation in the distributed environment.

3.1 Requirements

Albatroz Engineering aims to have a workflow execution engine able to schedule the automatic tasks from the PLMI2 application among the multiple desktops available in the local network, according to a volunteer-based work distribution strategy. This system should be efficient, scalable, and at the same time, resilient to both network and node failures.

For instance, suppose that one operator requests the scheduling of four tasks to be executed by a server located in a given host and subsequently this host is turned off. Then, if there is at least one another server located in other host, the system should ensure that these tasks will be executed.

Actually, the company has between twenty and thirty hosts available for data processing, and usually only between five and ten hosts are used by lines inspection operators to process inspections' data. The company's PLMI2 application does not support fault-tolerance of tasks execution. For instance, if an operator requests the execution of four tasks with dependencies and immediately he turns off his workstation then all four tasks will be lost because the tasks are executed only by a single host, that is, by the host where

ID	Description	Priority
FR1	It must be built a distributed system able to exploit idle computing time from workstations, to schedule and execute automatic tasks of PLMI2 application.	MUST
FR2	It must be possible to establish the well-defined dependencies among tasks.	MUST
FR3	It must be possible to distinguish an interactive from batch task.	MUST
FR4	Enable a client application to request the scheduling, cancelling and subscription of task execution.	MUST
FR5	Design and implement User Interfaces for client applications.	SHOULD

Table 3.1: List of functional requirements

they were generated. The company would like to have a system where operators can request the executions of tasks on a host and if this submission host is busy (e.g., its CPU is highly loaded) then those tasks can be executed by one of another hosts located in the local area network (LAN). In this way, the time that lines inspection operators wait for AT results to be available, could be minimized.

The aim is to install a server application in every workstation, even if the latter is not dedicated to process the inspection data because a server is supposed to exploit only idle cycles from hosts' CPUs to execute the tasks and also it is supposed to not decrease the host performance given that the user may be using the workstation to carry other duties. However, in case of a server located in the submission host, if a task has a high priority then it should be executed there (if there is no other task currently being executed by it), even if its CPU load is not low because in such case the operator wants to get the task's results immediately.

Taking into consideration these scenarios, we propose a new distributed task scheduling system where each node may have the role of producer and consumer. Coming to details, this means that a node may generate tasks to be executed by the remainder nodes, or, when idle, contribute with its computing resources to the Volunteer Computing, becoming a consumer.

To meet such requirements, we opt for a distributed scheduling architecture with direct communication (already presented in Section 2.2.1) in comparison with the centralized or hierarchical scheduling, since it may provide scalability, better fault-tolerance mechanisms and load-balancing among schedulers/servers.

Concretely, we summarize these requirements as functional and non-functional, presented in Table 3.1 and Table 3.2, respectively, according to the MoSCoW[1] prioritisation method.

3.2 Overall Architecture

The general overview of the system's architecture that we propose is shown in Figure 3.1, where all hosts are interconnected by the company's LAN, on which the role of each component is defined as follows:

[1] https://en.wikipedia.org/wiki/MoSCoW_method

ID	Description	Priority
NFR1	The system should be efficient and scalable, i.e., it only provides added value if its global execution time is less than of the existing solution.	MUST
NFR2	Fault-tolerance of task execution – the failure of a server-node should not cause the system to behave incorrectly.	MUST
NFR3	Non-intrusive – the performance of the workstation where a server is running, should not be lower if it is not running a task. The server should be lightweight when not running a task.	SHOULD
NFR4	Heterogeneity – the system should work in the LAN which has heterogeneous workstations (different CPUs, RAM, operating systems, etc.).	SHOULD

Table 3.2: List of non-functional requirements

client-application This component represents a generic client-application, that is, it may be either a command-line client (e.g., Telnet) or Graphical User Interface (GUI) clients. Firstly, it should be able to request a **server-node** (local or remote) to schedule the execution of a task. Secondly, it must be able to request the cancellation of a running task and also subscribe its interest in getting a given task's progress. Moreover, it may also run in the same host (local) as the **server-node**, as illustrated in Figure 3.1, i.e., the cases where *ca* (client-application) and *sn* (server-node) are inside the same rectangle shape. Local means that the server and client are running in the same host, and remote in different hosts.

server-node This component is responsible for making scheduling decisions, such as task dispatching by communicating with other servers/schedulers. The selected node for executing a given task (t) launches the executable of t and opens a communication channel between both to monitor the evolution of the t's execution. Another responsibility of a server-node, is to report, to interested parties, the progress of the task currently in execution. It should be stated that a server-node may support connections with multiple client-applications at the same time and it is not required to be connected with any client-application.

Database server This component stores the results generated by the execution of a task by a server-node. A result is a dataset generated by a task and it is identified by a database relation primary key.

task It represents the execution an automatic task of PLMI2 application. The PLMI2 tasks were, up to now, integral parts of PLMI2, and now for the purposes of this system they have to be independent applications. Therefore, when a task is started/launched by a **server-node** then it may read input datasets from the **Database server** and should generate output datasets in this same database.

Upon the completion of a task t, the hosting server-node is responsible for assigning the identifiers of output datasets to all tasks whose inputs depend on the outputs of t.

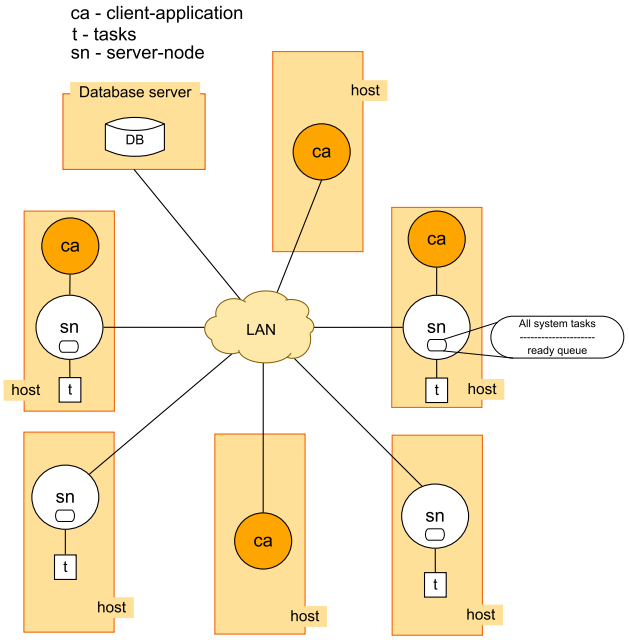


Figure 3.1: A general view of proposed system architecture.

The devised architecture comprises three distinct entities, i.e., the client-application, the server-node and the running task. In order for these to communicate, protocols have to be established.

Due to the lack of a centralized entity in the system architecture, it is in fact a distributed protocol among server-nodes, and in order to meet this requirement it is necessary to have distributed algorithms for ensuring that all nodes will have a consistent view of the system's state.

Therefore, all system components should agree on the protocols defined here, in such a way that each one of them can understand each other and cooperate to achieve the common goal, which is the execution all the scheduled tasks.

The communication among the system's entities is achieved by exchanging messages and a message may contain several pieces of information. For instance, when a server-node receives a message from another server-node or from a client-application, then it triggers an appropriate action to process the received message and according to the kind of the message it makes some local decisions and may change its state, and additionally it may reply back to the message sender.

In the remainder of this chapter, we begin by explaining how tasks are uniquely identified during their lifetimes and the content of a task, in Section 3.3. In Section 3.4 to 3.6 we, respectively, specify the communication protocol between a client-application and a server-node, between a server-node and a running task and the protocol among server-nodes.

3.3 Task Identification and Contents

A task needs to be uniquely identified during its lifetime in the system. The best way we found to do this was by using the Universally Unique Identifier (UUID) specified by IETF RFC 4122 [53], which allows the generation of unique identifiers, across space and time, in distributed environments without a centralized coordinator.

A task has the following properties:

1. A Universally Unique Identifier (UUID);
2. The associated executable file name;
3. The number of input datasets required to be assigned for it to become a *Ready* task;
4. The identifier of the client-application's host which ordered its execution;
5. A state, which may be *Submitted*, *Ready*, *Running*, *Terminated* or *Cancelled*;
6. A priority, which can be *low* or *interactive*. The priority *interactive* is privileged over the *low*;
7. A timestamp registering when it was submitted to the system;
8. The hostname of the server-node which scheduled it;
9. The hostname of the server-node where it is running, if its state equals *Running*;
10. The required identifiers of input datasets;
11. The identifiers of output datasets.

3.4 Communication: Client-application $\leftrightarrow$ Server-node

In this section we describe the interaction protocol between a client-application and server-node, for each operation offered by the system to client-applications, i.e., the scheduling of a task, cancellation of a task execution and, subscription of interest in getting the progress and state of a task. For these three operations, the interaction follows a request reply-reply pattern that is always initiated by the client. Additionally, the server, periodically sends the progress of the tasks over which the client has revealed its interest.

This communication protocol consists of seven kinds of messages, described in Table 3.3. In case of the SCHEDULE message, when a client-application requests the scheduling of task t_y which has an input i that depends on the nth output of a task t_x then it should send the argument

$$-a\ task\_uuid\_x\ nth\_output\_x$$

to inform the server-node how to assign the required identifier of output dataset (the nth output) to i, when t_x terminates the execution.

Message	Parameters	Description
SCHEDULE	task_exec_name priority [-p path_to_raw_files] [-a task_uuid_1 nth_output_1] ... [-a task_uuid_n nth_output_n] [-x parameters_file]	Allows a client-application to request a server-node to schedule the execution of an automatic task.
SUBSCRIBE	task_uuid_1 ... task_uuid_n	Allows a client to subscribe its interest in getting the progress and state of a set of tasks.
CANCEL	task_uuid	Allows a client to request a server to cancel the execution of a task.
SCHEDULED	task_uuid	A server-node notifies a client-application that a given task was scheduled.
SUBSCRIBED	task_uuid_1 ... task_uuid_n	A server notifies a client that its subscription to a given set of tasks was registered successfully.
CANCELLED	task_uuid	A server notifies a client that a given task was cancelled.
PROGRESS	task_uuid percentage_of_work_performed state	A server sends the progress of a running task to all clients that subscribed this task.
ERROR	message	A server-node notifies a client-application that its request was not successfully processed.

Table 3.3: Format of the messages exchanged between a client-application and server-node.

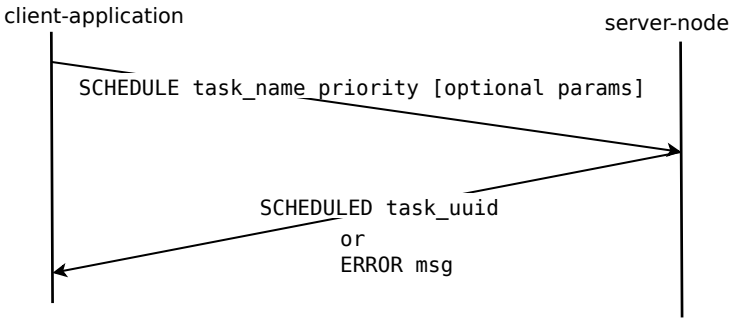


Figure 3.2: Schedule an automatic task (client-application ↔ server-node).

The options of the SCHEDULE message are:

$-a$ Indicates one of arguments of t_y. An argument is composed by the UUID of a task t_x on which t_y depends on and the nth output of t_x.

$-x$ Indicates that a parameter file (an XML) was provided.

$-p$ Indicates that a file system path or a location within the LAN containing the raw data files was provided.

Just to illustrate how it works, suppose that a client-application ca wants to schedule an automatic task t. Then this protocol enables ca able to pass only the required arguments to t.

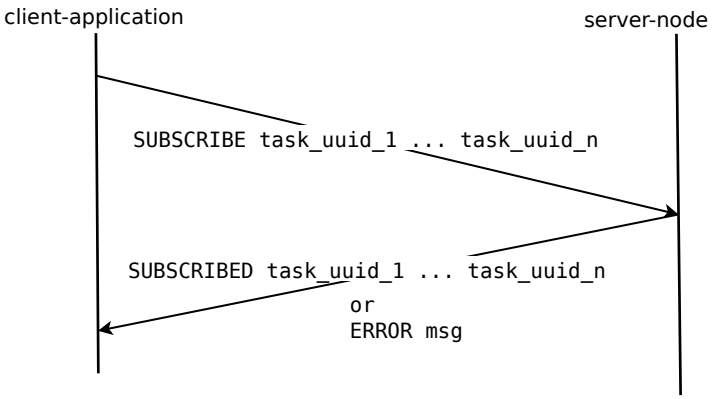


Figure 3.3: Subscribing interest in getting the progress and state of a set of tasks (client-application ↔ server-node).

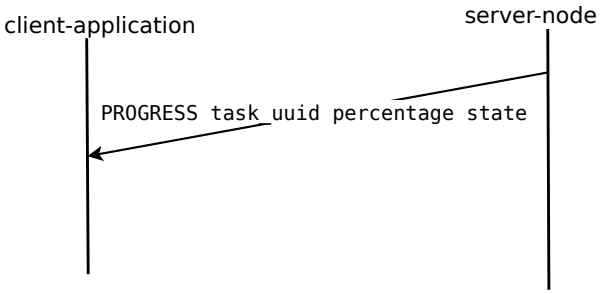


Figure 3.4: Progress reporting (server-node → client-application).

The protocol for enabling a client-application to request the scheduling of a task is illustrated in Figure 3.2, on which any argument inside a square brackets means optional. If the server-node was able to schedule the task then it generates and sends the task unique identifier to the client. Else, it replies with an error message describing why it was not possible to schedule the task.

Figure 3.3 depicts the interaction protocol for a client-application to request its subscription in getting the progress and state of a set of tasks, identified by $task\_uuid\_1$ until $task\_uuid\_n$. If the server-node has processed its request successfully then it confirms. Else, if it has found some error while processing the request then it sends an error message describing what happened.

Figure 3.4 shows the interaction protocol, in which a server-node sends the progress and sate of a given task identified by $task\_uuid$ to a client-application, being the latter previously subscribed its interest in $task\_uuid$.

Finally, this section ends with Figure 3.5, which illustrates the protocol for a client-application to request the cancellation of a given task, identified by $task\_uuid$. If the server has cancelled the task then it confirms the cancellation to the client-application. Otherwise, it notifies the client with an error message explaining what happened.

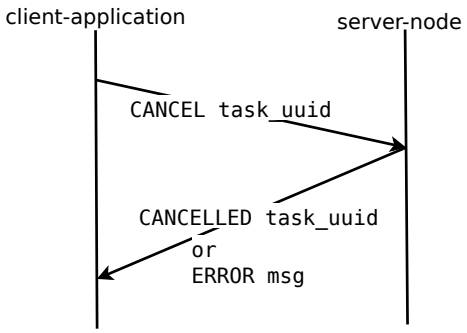


Figure 3.5: Cancelling the execution of a task (client-application ↔ server-node).

Message	Parameters	Description
PROGRESS	percentage_of_work_performed	A running task sends its local server the current progress of a running task.
CANCEL		A server requests a running task to cancel the execution of a task.
TERMINATED	id-dataset-1 ... id-dataset-n	A task notifies a server that it has completed its the execution, where the id-dataset-n is the nth identifier of output dataset generated on database by the task execution.
CANCELLED		A task notifies the server that it has cancelled its execution.
ERROR	message	Message sent from a running task to the server-node, if some error has happened while it was processing the latter's request.

Table 3.4: Format of the messages exchanged between a server-node and a running task.

3.5 Communication: Server-node ↔ Running Task

The communication between a server-node and a running task may be initiated by either entities. Server-node initiated communication has the sole purpose of cancelling the execution of the task, whilst task initiated communication has the purpose of reporting the task's execution progress.

Table 3.4 presents the format of messages exchanged between a server-node and a running task. The messages that not have any parameter, means that either it is not required or else the only parameter needed is the identification of the message sender (e.g., its IP address), which we assume that is extracted/retrieved by the message receiver.

The protocol for a running task to report its progress to the server-node is depicted in Figure 3.6. The protocol for a running task to report the final results of its execution to the server-node is presented in Figure 3.7. The protocol for a server-node to request a running task to cancel its execution is shown in Figure 3.8.

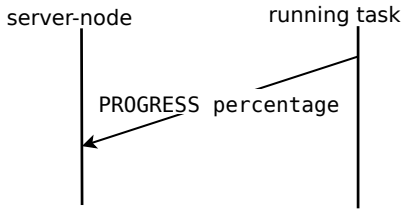


Figure 3.6: Progress reporting (running task → server-node).

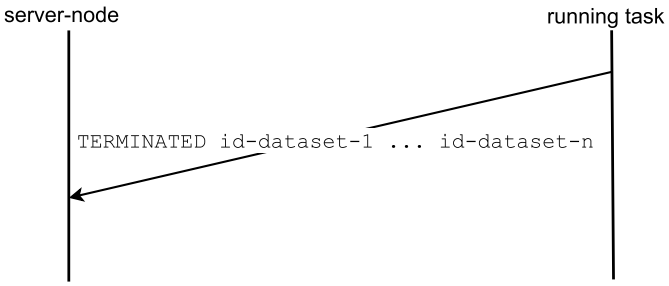


Figure 3.7: Reporting the final results of a task (running task → server-node)

3.6 Communication: Server-node ↔ Server-node

Every server-node has a local state, mainly composed by two data structures: a map storing all tasks currently under the system's supervision and the queue of ready-to-run tasks. Given that the system is purely distributed, the server-nodes have to coordinate themselves in order to ensure that each of one of them has a consistent view of this state. However, we do not want to impose a strong consistency model that requires a synchronization among server-nodes for every operation performed on these data structures. Accordingly, we opt for a more relaxed approach with eventual consistency properties. As such, each server-node will update its state, based on the type and contents of the messages that it receives. When an inconsistency is detected by a server-node, then it appeals to a special server-node, which we denominate *master*, to deliver it the most recent state of the data structures.

In the next two subsections, we provide a comprehensive explanation of two distributed algorithms run by every server-node, namely the master election and the distributed scheduling algorithms. The communication model for these two algorithms, as well as the almost communication in the system, is based on the 1 to N approach, on top of a broadcasting protocol, instead of request-reply model. The motivation is to avoid, as much as possible, synchronization points among server-nodes.

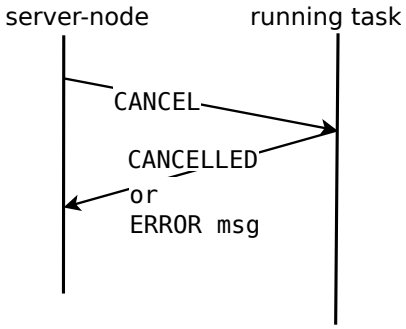


Figure 3.8: Cancelling the execution of a task (server-node ↔ running task)

3.6.1 Master Election

Firstly, we have to state that our system does not have a master by default; it is elected by a consensus algorithm among server-nodes, i.e., the nodes that belong to the system at the time of the election.

Every server-node has a reputation assigned, which indicates how many times it has failed, terminated or crashed. This information is used to elect the current master - the greater is the number of times a server-node has failed, the lower is its reputation. This reputation is initialized with basis on a number loaded from a stable configuration file, whenever the node starts running. It is also decremented each time the node re-joins the system because we assume that it is recovering from a failure/crash. In the first time that a node starts up its reputation is not decremented.

This approach is similar to the Elect Lower Epoch presented in the book entitled *Introduction to Reliable and Secure Distributed Programming* on page 77 [54], where the leader (in our case the master) is the process that has failed fewer times.

The need for a special node to act as the delivery of the system's state to the new joining nodes, or send a given task to a node when requested, came from the fact that if was any node to perform these operations, may be it would not have the recent system's state. The master is elected as being mainly the older node in system. Therefore, its probability of having the most recent system's state is greater than or equals to the other nodes.

For the definition of master election protocol, the format of the messages presented in Table 3.5 are added to the system. Some of the messages do not have parameters because in such cases they are either not required or the only parameter needed is the identifier of message sender (e.g., the IP address), and we assume that the receiver is able to extract this identifier when it receives a message.

The master election is presented in Algorithm 3.1 and it works as follows. Upon the reception of a START_NEW_MASTER_ELECTION message, by the procedure on reception of SNME(...), on a server-node from one of its counterparts notifying that they must elect a new master then it makes its candidacy by broadcasting the TRY_TO_BE_MASTER

Message	Parameters	Description
WHO_IS_MASTER		Used by a new server when it comes into the system, for asking other server-nodes for the master-server's information.
START_NEW_MASTER_ELECTION		A server-node notifies other servers that they should start a new master-server election.
TRY_TO_BE_MASTER	my_reputation local_map.size timestamp	A server proposes its proposal to be the master-server on an election.
NEW_MASTER		The master-server sends its information to a server when asked or to all servers when it wins an election.

Table 3.5: Format of the messages used in the master election.

message (line 6) to all. A candidacy is composed by the node's reputation, the number of tasks on its local map and a timestamp registering when the candidacy was generated. Within a given waiting time-window (line 7) of 10 seconds, whenever a server-node receives a candidacy from another server then he inserts it in a priority queue of candidacies ordered by candidacy's timestamp (see the procedure on reception of TTBM(...)). The algorithm stores the received candidacies in a priority queue ordered by the candidacy's generation timestamp on its candidate because we want a server to process these candidacies by their emissions' order. When this time-window finishes then it processes all received candidacies.

A server wins the election if its own candidacy is better than those ones received, meaning that if it has the highest reputation, or in case of a tie, if the number of tasks on its map is greater than the remainder candidacies, or in case of a new tie, then if its candidacy's timestamp is older than the remainder candidacies, or again in case of a new tie, then if its host name is alphabetically lower than the remainder ones.

At the end of the algorithm, if the server has won the election then it broadcasts a message to all nodes notifying the winning. Else, if it has lost then it will receive the new master information.

In Figure 3.9 is shown an example of an interaction protocol in which the server-node labelled as $sn1$ wins the election, supposing that it has the highest reputation. The TASKS_TRANSFER message that appears in this figure is later introduced in Section 3.6.3.

3.6.1.1 Fault-tolerance

Our system aims to provide the supporting for fault-tolerance at server-node and network level. Taking this aspect into consideration and the fact that a master is one of server-nodes, then the system should support fault-tolerance for it.

Algorithm 3.1: Master Election

```
Data: // Required variables.
1  bool Did_I_Win_The_Election;// Whether this server has won the election or not.
2  int my_reputation;// The server reputation loaded from a stable configuration file.
3  string my_hostname;// The name of the server's host.
4  bool Am_I_Master;// Whether this server is the master or not.
5  time my_TTBM_timestamp;
6  map<uuid, task> local_map;
7  priority_queue<TRY_TO_BE_MASTER_Request>TRY_TO_BE_MASTER_requests_queue;
```

Procedure on reception of TTBM(TRY_TO_BE_MASTER reputation map_size timestamp)

```
8  1 TRY_TO_BE_MASTER_requests_queue.push(TRY_TO_BE_MASTER_Request(timestamp,
     peer_hostname, reputation, map_size));
```

Procedure on reception of SNME(START_NEW_MASTER_ELECTION)

```
9  1 trigger elect master();
```

Procedure elect master()

```
1  begin
2      Did_I_Win_The_Election ← true;
3      TRY_TO_BE_MASTER_Request req ← null;
4      Am_I_Master ← false;
5      my_TTBM_timestamp ← time();
6      broadcast TRY_TO_BE_MASTER my_reputation local_map.size timestamp;
7      wait for a given time-window for another servers to make their candidacies;
       // Process TRY_TO_BE_MASTER messages received from other servers/peers.
8      while not TRY_TO_BE_MASTER_requests_queue.empty() do
9          req ← TRY_TO_BE_MASTER_requests_queue.pop();
10         if req.reputation > my_reputation then
11             Did_I_Win_The_Election ← false;
10 12      else if req.reputation = my_reputation then
13             if req.map_size = local_map.size() then
14                 if req.TTBM_timestamp < my_TTBM_timestamp then // Did the peer send
                   TRY_TO_BE_MASTER first than me?
15                     Did_I_Win_The_Election ← false;
16                 else if req.TTBM_timestamp = my_TTBM_timestamp then
17                     if req.peer_hostname < my_hostname then
18                         Did_I_Win_The_Election ← false;
19     if Did_I_Win_The_Election then
20         Am_I_Master ← true;
21         broadcast NEW_MASTER; // Notify the peers that this server is the new
           master.
```

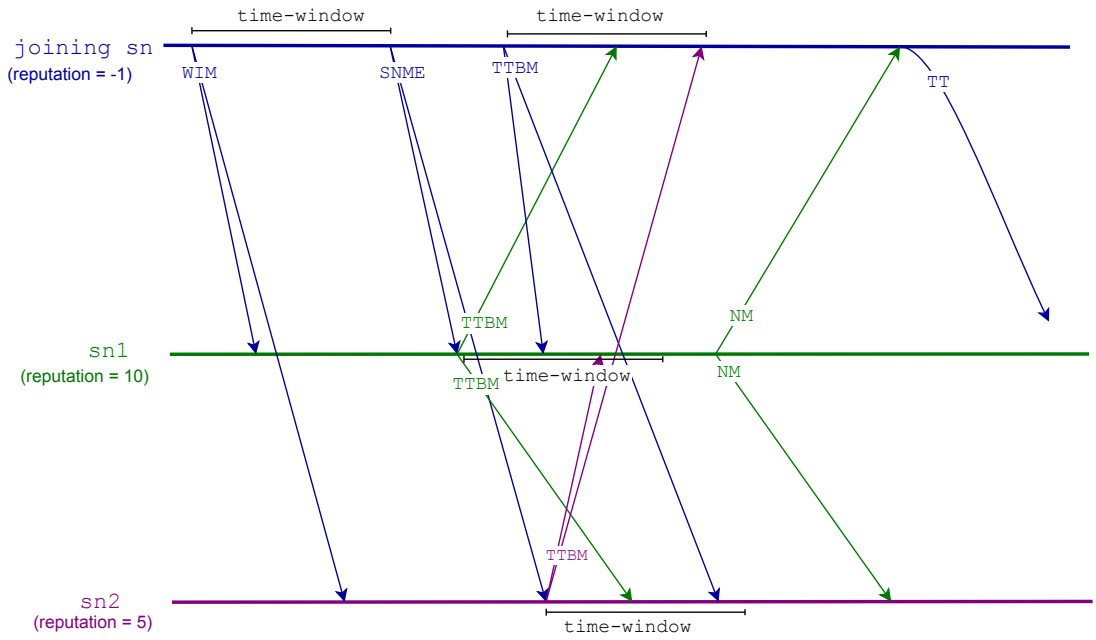


Figure 3.9: An illustration of master election protocol.

Server-node level: If the master server-node fails then the remainder nodes should eventually detect this issue and elect a new one, according to the Algorithm 3.1. The system detects the failure of the master-server when a node receives a PROGRESS message of a given task that it does not have on its local map yet then it asks the master for this task by sending a GET_TASK message (defined later in Section 3.6.2), and the master does not reply. Also, the system detects the master failure when a new node joins the system, broadcasts WHO_IS_MASTER message and no server replies. The system tolerates its failure by electing a new one.

Network level: An example of a problem that a network failure may cause is, suppose that the communication link breaks between the master and the remainder nodes. Then, the latter will assume that the master has failed and elect a new one. When the older master has the communication link with the system back, there will be two masters, i.e., the older one will behave like if it was the only one master when it is not. The aim is to have only one master in the system at any time but this failure may cause it to have more than one.

Although it has not been implemented, a possible way to solve this issue could be by forcing a master to broadcast its information periodically (e.g. a heartbeat message), which must contain a timestamp registering when it was elected. Each node when receives this information will update who is the current master regarding the timestamp, meaning that if the timestamp of when the message sender was elected in newer than

one from the master that it currently knows then it updates its knowledge about the master as being the sender. In case of the older master, when it receives the message from the newer one, it should update its local state as not being the master any more, save the information of the new master and stop broadcasting heartbeat messages claiming to be the master.

Also, the above solution could be employed to solve the conflict when some message loss has happened during the election, and due to this issue two servers may think that both of them won the election then they broadcast the NEW_MASTER message to all.

3.6.1.2 Properties

The master election algorithm has the following properties:

- Whenever a master is needed, or it exists at the moment or it is elected immediately;
- It ensures that if every server-node has received all proposals sent by other server-nodes, then a unique master will be elected, with basis on its tiebreaker conditions;
- In case of network partitions, it does not support conflict solving if two or more masters are elected in different partitions, when they reconnect. A possible way to deal with this issue can be by employing the solution previously described in Section 3.6.1.1.

3.6.2 Scheduling and Distributed Execution of Tasks

The following kinds of messages are exchanged among server-nodes in order to achieve the distributed scheduling:

ENQUEUE A server broadcasts a task to all its peers.

TRY_DEQUEUE A server notifies its peers that it is trying to remove a given task from the FIFO queue for the execution locally.

STATE Used by a server to notify its peers when some change happens on a task's state. These states can be:

Running For notifying that it has started running a task.

Terminated To notify that a task has successfully executed. The message will always contain the final result of a task, i.e., the identifiers of output datasets that were generated by the task execution.

Cancelled For informing that a task was cancelled.

PROGRESS A server reports to its peers the progress of a running task.

GET_TASK A server requests the master-server to deliver it a given task (t), identified by a UUID, when it receives the progress of t and it does not have t in its state.

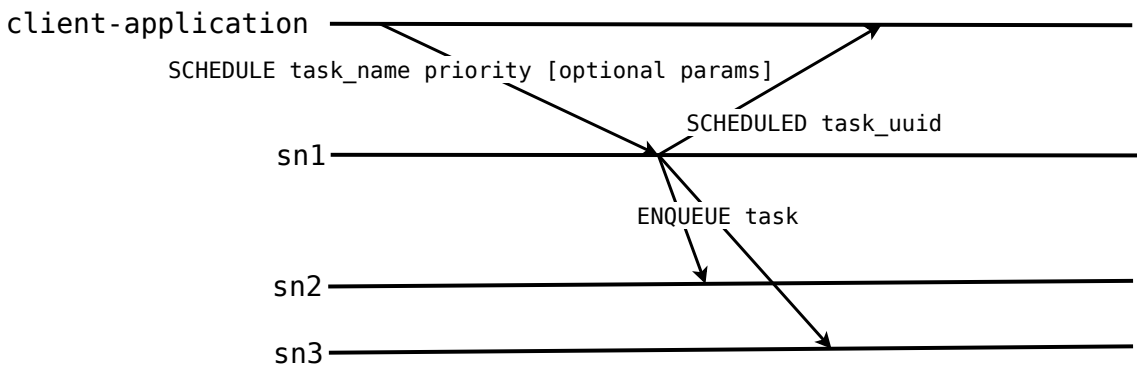


Figure 3.10: An illustration of the ENQUEUE protocol.

When a client-application requests a server-node to schedule the execution of a task then the server broadcasts an ENQUEUE message to all another servers, as illustrated in Figure 3.10. Upon the reception of an ENQUEUE message by a server, it places the corresponding task (t) on its local map and if the t's state equals to *Ready*, then t is also placed in the local ready-to-run task queue.

The algorithm for the distributed dequeuing of a ready-to-run task is presented in Algorithm 3.2 and it works as follows. Once a server enters in volunteer mode (it detects that its CPU has become idle) it broadcasts a TRY_DEQUEUE message to its peers, indicating that it wants to execute the next task in its ready-queue (line 3). This TRY_DEQUEUE operation is followed by a waiting time-window (line 9) of 15 seconds (as it was implemented), which has the purpose of assessing if no server-node has concurrently issued the same request. If no TRY_DEQUEUE message has arrived within this window then server can dequeue t. A TRY_DEQUEUE message that arrives a server out of the time-window is simply ignored. The possible concurrent execution of tasks will be dealt later in time. If one or more TRY_DEQUEUE are received for the same task, then a conflict arises and the server handles each one of them (line 11 to 15). A server loses the race for dequeuing t if it has received at least one proposal to execute t which is lower than its own, according to a pre-established total order relation (line 14). This order is given by the following properties: the server proposal's timestamp is older than the remainder proposals, or in case of a tie, then if its hostname is alphabetically lower than the other servers' hostnames. This total order relation is deterministic and is it computed locally in each server.

The server-node with the lower proposal, according to the total order relation, wins to the race to execute t. The remaining servers account (line 15) the rank of their proposals, to be used as a strategy for avoiding/minimizing the race conditions on the next time they want to try dequeue the next task. For instance, if a server has lost the race to dequeue t against two servers then on the next time it will try to dequeue the task that is in second position of the queue because its rank was 2. In this way, it will not compete

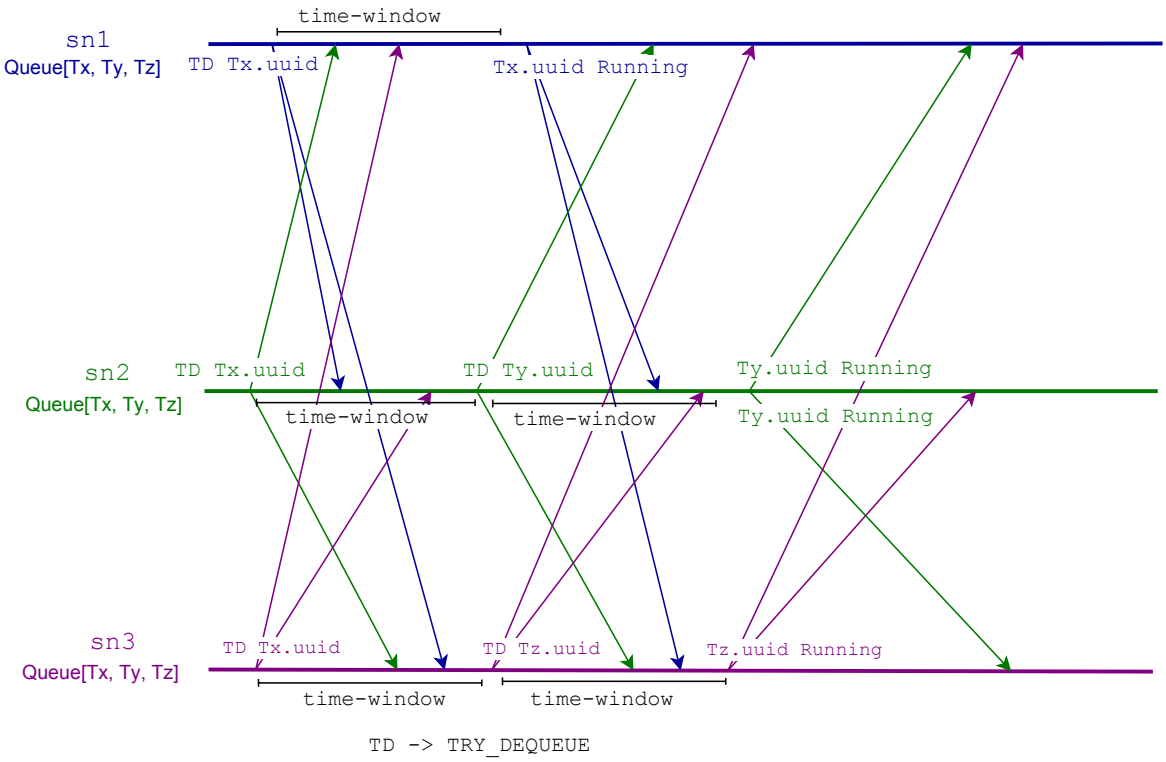


Figure 3.11: A system configuration on which can be minimized the race conditions.

with the server that has lost the race just once (rank 1) because that server will dequeue the task at first position of the queue. To illustrate this situation, consider the system configuration shown in Figure 3.11, where it has three server-nodes ($sn1$, $sn2$ and $sn3$) and each one of them has three ready-to-run tasks (T_x, T_y and T_z) in the local task queue. Then suppose that all three nodes are competing to dequeue the task T_x. One of them will win and remainder two will lose. Thus, the node which has lost the race for T_x just once will try to dequeue T_y and the node which has lost two times will try to dequeue T_z.

Whenever a server agrees that a given node will run t or when it is notified that the t's state became *Running*, then it removes t from its local ready-queue, but keeps t in the map of tasks until it receives the notification that the t has terminated its execution.

3.6.2.1 Fault-tolerance

As we have stated before in Section 3.6.1.1, we want the system to be able to support failure at server-node and network level.

Server-node level: Failures occurred at server-node level cause the task that eventually was executing at the node to fail. Thus, the remainder nodes should detect this failure and reschedule the failed task, so that it can be executed by one of the remaining server-nodes. The system notices that a node has failed/crashed during the execution of a task

Algorithm 3.2: Distributed dequeuing

```
Data: // Required variables.
1  int rank;// The server rank in last race to dequeue a task.
2  uuid try_dequeue_task_uuid;
3  time timestamp_of_my_last_try_dequeue;
4  string my_hostname;
5  priority_queue<task> local_queue;
6  priority_queue<TRY_DEQUEUE_Request> TRY_DEQUEUE_requests_queue;

Procedure on CPU idle()
7
1  trigger dispatch( );

Procedure on reception of TD(TRY_DEQUEUE task_uuid timestamp)
8
1  TRY_DEQUEUE_requests_queue.push(TRY_DEQUEUE_Request(timestamp, task_uuid,
   peer_hostname));

Procedure dispatch()
1  begin
2      if rank = 0 then
3          try_dequeue_task_uuid ← local_queue.top().task_uuid;
4      else
5          try_dequeue_task_uuid ← getTaskUUIDFromQueueAt(rank).task_uuid;
6          rank ← 0;
7      timestamp_of_my_last_try_dequeue ← time();
8      broadcast TRY_DEQUEUE try_dequeue_task_uuid timestamp_of_my_last_try_dequeue;
9      wait for a given time-window for messages of type TRY_DEQUEUE to arrive;
10     TRY_DEQUEUE_Request req ← null;
       // Process TRY_DEQUEUE messages received from other servers/peers.
11     while not TRY_DEQUEUE_requests_queue.empty() do
9
12         req ← TRY_DEQUEUE_requests_queue.pop();
13         if try_dequeue_task_uuid = req.task_uuid then // Conflict checking
14             if (timestamp_of_my_last_try_dequeue = req.timestamp and my_hostname > req.peer_hostname)
               || (timestamp_of_my_last_try_dequeue > req.timestamp) then
                   // Account my rank to determine which task to try dequeue on the
                   next call of "dispacth()".
15                 rank ← rank + 1;
16     if rank > 0 then // It is not the winner
           // The next calling of dispach() is when the CPU becomes idle again.
17     else
18         broadcast STATE try_dequeue_task_uuid Running timestamp;
           // Execute task.
```

if the latter has stopped reporting the progress of a running task. When a task is running, its progress is sent periodically to all nodes like a heartbeat message. In Section 4.5 of Chapter 4 we present how it was implemented the fault-tolerance supporting at server-node level.

Network level: The network partition, on which the nodes of one partition cannot communicate with other nodes located in any of the others, may cause two nodes, each one in different partitions, to start execute the same task.

To solve the above conflict scenario, when the partitions are reconnected, our implementation detects that two or more nodes are running the same task and cancels the executions on all nodes, and lets just one node to keep running the task, according to a pre-established total order function. Ideally, this function should take into consideration the current progress of each execution, in such a way that it would let the node which is almost completing the task execution to continue because in this way the total task completion time could be decreased.

If the partitions have a delay greater than the total execution time of tasks, given that database is located in one of partitions, then it will be the task that has run in that partition which commits its results with success to the database, while other tasks will get an error when they try to connect with the database.

Nevertheless, it is very unlikely that it may happen scenarios where more than one instance of the same task to terminate their executions and contact the database server with success. If such happens, the consequence is that the database will have more than one version of the same result. However, given this work context, it is very unlikely that such scenario occurs and an analysis of cost/benefit reveals that its treatment is not a priority.

In addition to the network partition, as our system follows a distributed approach, then it is exposed to more failures. For instance, if it happens some momentary network failure or some delay in message delivering/transmission, i.e., if a message has arrived out of the time-window (defined in line 9 of the Algorithm 3.2) then the nodes may start to execute the same task. This may happen because in such case, on each node the distributed dequeuing algorithm will behave like if the node is the only one in the system. The implementation solves this conflict scenario in the same way as described above, that is, by stopping the task execution at one of server-nodes and letting another to keep running. But, just to recall, the scope of this thesis is within a LAN, not the Internet where network level failures may occur frequently.

3.6.2.2 Properties and assumptions

The distributed scheduling algorithm takes into consideration the following assumptions:

- Tasks may be cancelled during their lifetimes in the system, either by an operator

or by the system itself;

- A given task may be running at the same time in two different hosts.

And it ensures the following properties:

- Since there is at least one server-node running in the system and if such a node has all tasks in its state and does not fail, then eventually all tasks will be executed;
- In case of two hosts executing the same task, if no network partition occurs, normally, just one instance of a task completes the execution, as explained previously in Section 3.6.2.1;
- The algorithm is resilient to network partitions, as explained in Section 3.6.2.1.

3.6.3 Server-node Joining/Leaving

Whenever a new server-node joins the system it has to obtain the system's state. To that end it begins by discovering the location of the master node by broadcasting the WHO_IS_MASTER message (defined in Section 3.6.1) to all. If no reply arrives, it assumes that no master is currently active and triggers the election process by broadcasting the START_NEW_MASTER_ELECTION message (also defined in Section 3.6.1) to other nodes for notifying that they must elect a new one (which was previously illustrated in Figure 3.9).

Otherwise, if a reply arrives, subsequently the node requests the master the system's state. The master sends all tasks to it, by iterating its local map of tasks and for every task it sends an ENQUEUE message directly to the node.

In addition to the WHO_IS_MASTER message, the following kind of message is added to the system, for allowing a joining server-node to get the current system's state:

TASKS_TRANSFER A new server requests the master-server to deliver it the current tasks in the system.

The protocol for allowing a joining node to get the system's state is illustrated in Figure 3.12.

Whenever a new server-node leaves the system, the remaining nodes consider that it has failed/crashed. If it was running a task before leaving the system, then the other nodes will rescheduled that task, as explained later in Section 4.5 of Chapter 4. If it was the master, then when the master is needed, the election algorithm is triggered (Algorithm 3.1).

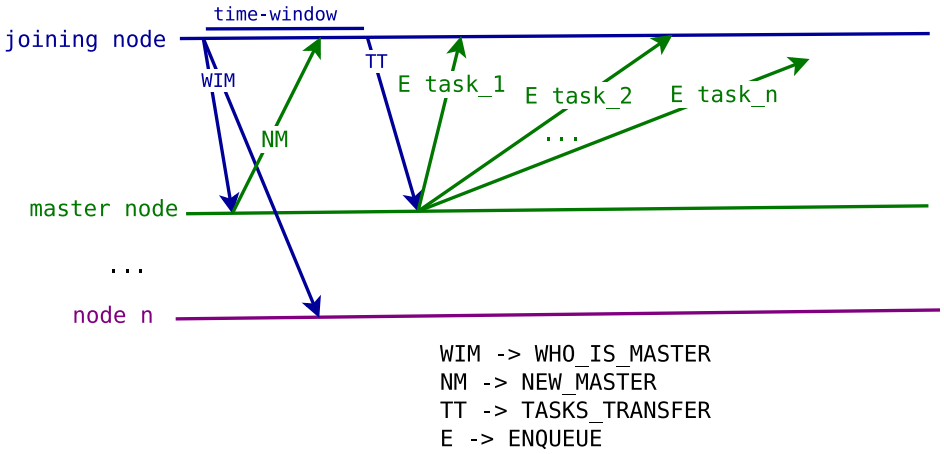


Figure 3.12: Example illustrating the interaction protocol for system's state downloading by a joining node.

4

Implementation

Throughout the previous chapter, we have presented what are the requirements that the system should meet, its distributed scheduling architecture and the communication protocols among its several entities, in order to achieve the distributed scheduling. We have also explained the distributed algorithms which implement those protocols and how the system supports failures at server-node and network level.

In this chapter we describe the implementation of the system prototype, which used some existing technologies, and we describe the architecture employed by every server-node and how the system execution log is saved persistently.

4.1 Introduction

The system was fully developed in C++11 [55] and with basis on two well-known Internet protocols, which are the Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Concretely, we use TCP for the communications between a client-application and a server-node, and UDP for communications among servers. In spite of being UDP not reliable and not offering flow control, it is fast for local area networks (LANs) [56] and we want each server to be stateless regarding the communication with other servers like the relation between a server and the clients in the Network File System (NFS) [57]. The developed system prototype is portable for both Unix-like and Windows operating systems. For Unix, we use The BSD UNIX Socket Library [58] and for Windows Sockets 2 API [59].

The remainder of this chapter is organized as follows. Section 4.2 briefly describes the task interface. Section 4.3 defines a possible way for the integration of new tasks in the system. In Section 4.4, we explain how the interdependencies among tasks were

solved and in Section 4.5 we present and describe the implementation all components of a server-node. Finally, Section 4.6 describes how a server-node's execution log is saved in a stable logging file.

4.2 Task Interface

As we have stated previously in Section 3.3, we use the Universality Unique Identifier (UUID) to uniquely identify a task in the system. To achieve this, our system uses the Boost C++ UUID library[1], which is an implementation of UUID, for the generation of tasks' identifiers.

To send a task t from one server-node to another, we implemented a *marshal()* function to convert a task's instance to its string data type representation and the bytes of this string which are sent to other server-nodes, are converted back to the task's original representation by using a *un-marshal()* function.

Regarding the system portability, the binary files (executables) of all tasks are placed in the same working directory as the executable of the server-node application. In this way, the server-node will use the relative path of a task instead of the absolute, when it launches the corresponding executable. For Unix environments, as an executable normally does not contain an extension associated and for Windows the *.exe* is the common extension, then our task scheduling protocol imposes the client-application to send the task executable name (the *task_exec_name* argument presented in Table 3.3) to the server-node. When the server-node has to start running a task in Unix, it just executes the program identified by the *task_exec_name*, and for Windows, it appends the *.exe* extension to the *task_exec_name*.

4.3 Integration of a New Task in the System

To integrate a new task in our system, the server-node was implemented in such a way that it does not have to know a task *a priori*, but the client-application should know and must strictly follow the protocols defined in Section 3.4.

If a new task has to be implemented, then it will be required to specify a configuration file which describes it (such as its type, its kinds of dependencies/inputs, etc.). The XML provided in Listing 4.1, can be a possible way to enable the specification of new task to be integrated in the system.

On the client's side a task can be simply integrated with the system, by adding its specification file to the client-application and on the server's side, a task can be added by putting its binary file (executable) in the same working directory as the server-node application.

[1] http://www.boost.org/doc/libs/1_55_0/libs/uuid/uuid.html

Listing 4.1: Example of task description file.

```
<?xml version="1.0" encoding="utf-8"?>
<task>
  <name>...</name>
  <type>...</type>
  <inputs>
    <input>
      <other_task_type>...</other_task_type>
      <other_nth_output>...</other_nth_output>
    </input>
    <input>
      <other_task_type>...</other_task_type>
      <other_nth_output>...</other_nth_output>
    </input>
  ...
  </inputs>
</task>
```

4.4 Inter-tasks Dependencies

To solve the interdependencies among tasks, presented in Section 1.1, we use the own tasks identifiers and ordinal numbers to represent that a task depends on results of another, e.g., if the first input of a task t_j depends on the first output of a task t_i, then we represent $t_j.input1 = t_i.task\_uuid/1^{st}$. The example in Table 4.1 illustrates this approach for those automatic tasks presented in Section 1.1, where *I*, *G*, *S* and *AD*, represent the *I*mport task, *G*eoreferencing, *S*egmentation and *A*nomaly-*D*etection, respectively.

This representation is built internally in a server-node with basis on the task's parameters passed from a client-application, when the latter requests it to the schedule a task (as described in Section 3.4). In this way, a server-node is able to pass the identifiers of output datasets from a terminated task to the tasks' inputs that depend on them.

Task UUID	Name	Inputs
$3aff3d90-2b79-11e3-8224-0800200c9a66$	I	Path to location with raw files
$679e9490-2b79-11e3-8224-0800200c9a66$	G	parameters.xml
		$input1 = 3aff3d90-2b79-11e3-8224-0800200c9a66/1^{st}$
		$input2 = 3aff3d90-2b79-11e3-8224-0800200c9a66/2^{nd}$
		$input3 = 3aff3d90-2b79-11e3-8224-0800200c9a66/3^{rd}$
$7f850cb0-2b79-11e3-8224-0800200c9a66$	S	parameters.xml
		$input1 = 3aff3d90-2b79-11e3-8224-0800200c9a66/1^{st}$
		$input2 = 679e9490-2b79-11e3-8224-0800200c9a66/1^{st}$
		$input3 = 679e9490-2b79-11e3-8224-0800200c9a66/2^{nd}$
$2daec57e-b129-4359-9986-21294643a0a3$	AD	parameters.xml
		$input1 = 7f850cb0-2b79-11e3-8224-0800200c9a66/1^{st}$

Table 4.1: Example of dependencies representation among ATs.

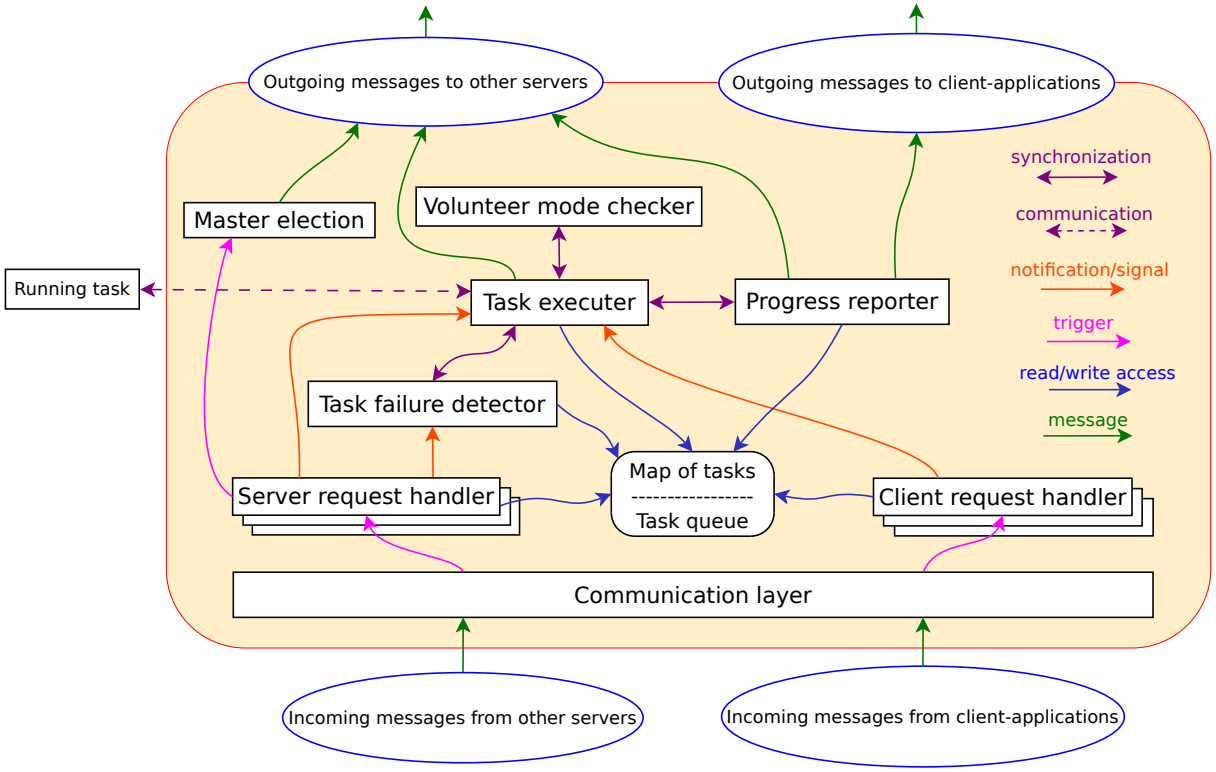


Figure 4.1: Overview of components of a server-node.

4.5 Server-node Module

In this section we present the main components of a server-node and describe the functionalities of each one of them. Figure 4.1 depicts all its components, where the synchronization between two components is represented by a bidirectional arrow, the communication by bidirectional dashed arrow, the operations of read and write over data structures by blue arrows, the notification/signal from a component to another by an orange arrow, the messages are represented by green arrows and the triggering of a new thread of execution by pink arrow. A rectangle represents a thread of execution or a running task, an ellipse represents an incoming/outgoing messages and a rectangle with rounded corners represents the data structures.

Map of tasks and Task queue: The **Map of tasks** is a map data structure, which contains all system's tasks that have not been executed yet. It stores key-value pairs, where the key is the task's UUID and the value is the task itself.

The **Task queue** represents a queue data structure with all ready-to-run tasks, which follows the priority-based First Come First Served (FCFS). It was used the *priority_queue*[2],

[2] http://en.cppreference.com/w/cpp/container/priority_queue

because its operations of push and pop have logarithmic complexity and also it provides a simple way to define a new sorting criterion.

As we have stated before, whenever a server-node receives an ENQUEUE message, it places the corresponding task (t) in the map and if the t's state is ready, or when eventually it becomes ready, then t is also placed in the task queue.

If a task t_a has priority *low* and a task t_b has priority *interactive*, then t_b is be placed in front of t_a in queue. If t_a and t_b have the same priority then it is applied the FCFS policy.

As illustrated in Figure 4.1 these two data structures may be accessed by multiple server-node's threads of execution simultaneously. To ensure mutual exclusion when they are accessed for read and write operations, the implementation uses the std::mutex[3] and std::lock_guard<std::mutex>[4] classes.

Communication layer: This component supports the incoming communications. It handles the requests coming either from other servers or from client-applications by using the *select()* system call and regarding the message sender, i.e., a client-application or a server, it creates a **Client request handler** or **Server request handler** to process the request, respectively. The communication layer may create/trigger multiple request handlers if it has received multiple request simultaneously, but a handler is deleted immediately when it has processed the assigned request.

A server-node has a TCP socket for communications with client-applications and three UDP Sockets for communications with other servers. When it starts up, the first thing it does, is the creation all needed socket file descriptors used to communicate with client-applications and other server-nodes. These sockets are:

1. A TCP socket for receiving new connections establishment with new clients;
2. A UDP socket which is used for receiving incoming messages (either broadcast or unicast) from other servers;
3. A UDP socket used for sending broadcast messages to other servers;
4. A UDP broadcast socket for task progress reporting.

Having the socket file descriptors created, the thread which runs the Communication layer will be always listening, by using the *select()*[5] system call to monitor all created socket file descriptors, to check if it has received messages in any of them.

Whenever a message is received on its TCP socket file descriptor then it is considered as being a new connection establishment request from a client-application and it accepts the connection using the *accept()*[6] system call, which generates a new file descriptor for this new client, which is also registered to be monitored with *select()* from that time.

[3] http://en.cppreference.com/w/cpp/thread/mutex

[4] http://en.cppreference.com/w/cpp/thread/lock_guard

[5] It allows a program to monitor multiple file descriptors, waiting until one or more of the file descriptors become "ready" for some class of I/O operation.

[6] It accepts a connection on a socket.

When it receives a message in one of registered file descriptors for client application then it creates a thread to handle that client request, which can be the scheduling or cancelling of task, or task subscription request.

When it receives a message in one of its UDP file descriptors from another server, which can be a broadcast or unicast message, then it creates a thread to handle that server's request. The kinds of messages which can arrive to its UDP file descriptors are, WHO_IS_MASTER, START_NEW_MASTER_ELECTION, ENQUEUE, TRY_DEQUEUE, STATE, GET_TASK, etc., that were previously described in Sections 3.6.1 and 3.6.2.

Task failure detector: This component is responsible for detecting the failures of tasks running remotely, i.e., the tasks running by the other servers. Every server-node has a dedicated thread, which runs this component, for detecting the task execution failure periodically (every 60 seconds) and when: there is at least one task running on a remote host. This is to avoid the thread from being always wasting the host computing resources when there is no task running on remote host to detect its failure. A task t running remotely is considered as failed if the server-node has not received its progress for a given time limit. In such case, this component reschedules t by adding it again to the **Task queue**.

If the **Task executer** is running a task t and it has to stop the t' execution because it detects that another node is also running t, then it may wake up the **Task failure detector** to start checking if t does not fail.

Volunteer mode checker: This component is responsible for checking, periodically, whether the host is idle or not. Our implementation considers that a host becomes idle if its CPU load keeps being less than or equals 10% since last verification time. This checking is done every 60 second intervals. It is run by a dedicated thread which only checks the CPU idleness if there is no task running locally. In other words, if a server-node is currently running a task then it cannot contribute with its computing resources to run another task. Taking this issue into account, it does not make sense to check if it is idle or not. To get the current CPU load percentage we use the Windows Performance Data Helper functions [7] for collecting host's performance data. Although being our implementation portable, this feature has not yet been implemented for Unix environments. Currently, we are considering that a server-node running on Unix can always try to dequeue a task even if the host is not idle.

Task executer: This component is run by a thread and it is responsible for cooperating with other servers in order to try dequeuing a ready task from **Task queue**. It runs the distributed dequeuing algorithm (presented in Algorithm 3.2), which has a for loop where in each step it tries to get a task from the **Task queue** to execute. In each iteration of its for loop, it blocks on a condition variable until the following conditions are true: the

[7] http://msdn.microsoft.com/en-us/library/aa939698(v=winembedded.5).aspx

Listing 4.2: Example of the server configuration file.

```
1 <?xml version="1.0" encoding="utf-8"?>
2 <server>
3   <reputation>10</reputation>
4   <first_startup>true</first_startup>
5 </server>
```

host CPU is idle, there is no other task running locally and the **Task queue** is not empty. The server-node's threads which may signal this condition variable are: the **Volunteer mode checker** component which decides whether the host CPU is idle or not, the **Client request handler** which may generate a new task if a client-application has requested a scheduling and the **Server request handler** which may receive an ENQUEUE message or some information that makes the state of a pending/dependent task to become *Ready*, for example when a server-node receives the results of dependable task that has terminated the execution.

When a server-node receives a scheduling request from a client-application then it checks the task's priority. If it is *interactive* then the task should be executed locally if there is no other running, even if the host is not idle. Otherwise, the system will eventually execute it and should save the execution results on the database server.

Up to now, we consider a batch task as being one with priority *low* and interactive task as being one with priority *interactive*, i.e., a task in which the user wants to get results as soon as possible.

Running task: It represents a task during the execution. The task execution is launched by the **Task executer** as a child process and they communicate through the standard input (stdin) and standard output (stdout). The messages exchanged between them, follow the communication protocol defined in Section 3.5.

Progress reporter: This component is responsible for reporting the progress of a running task, periodically (every 15 seconds), to other servers by broadcasting the PROGRESS message and to the client-applications which have subscribed interest in getting this task progress, by iterating the list of socket file descriptors of task's subscribers, and for each one it sends the PROGRESS message directly.

The component is run by a dedicated thread which waits on a condition variable until **Task executer** starts running a task.

Master election: This component represents the master election algorithm which is run by a thread locally in the node whenever the system needs to elect a new master. The thread is triggered/created to run the algorithm and deleted when the election terminates. As described in Section 3.6.1, the election algorithm has as input the node's reputation loaded from a configuration file (provided in Listing 4.2). By default, every sever-node starts with the same reputation, which is later decremented whenever a node stops

and restarts. The first time a node joins the system, its reputation is not decremented, but the content the element `first_startup` is set as `false`. In this way, the next time it restarts for some reason (e.g., it has crashed), then it will check the content of that element and decrement the value of `reputation`.

4.6 Execution Logging

Every server-node stores its execution log in a persistent logging file, for allowing the later retrieving of historical data of its behaviour and statistical data. The same execution log is also displayed on its console, in order to monitor its execution in real-time and analyse the reasons of unwanted behaviours.

To achieve this, our implementation uses the Boost Log library[8], which is simple to integrate with an existing application and also extensible. Each line that is saved in the log file has a severity associated, for better understanding about what happened. The format of the log messages are shown below, where [YYYY-MM-DD HH:MI:SS] corresponds to the date and time of day that the message was generated.

- [YYYY-MM-DD HH:MI:SS]: <normal> A normal severity message;
- [YYYY-MM-DD HH:MI:SS]: <error> An error severity message;
- [YYYY-MM-DD HH:MI:SS]: <debug> A debug severity message;
- [YYYY-MM-DD HH:MI:SS]: <info> An information severity message;
- [YYYY-MM-DD HH:MI:SS]: <warning> A warning severity message.

Listing 4.3 shows an excerpt of a server log file, where can be seen some information that is output by a server, namely its CPU load, TRY_DEQUEUE message, reception of task's states from other servers, etc.

In the next chapter we evaluate the system taking into consideration the results obtained from a simulation framework that we have developed.

[8] http://www.boost.org/doc/libs/1_55_0/libs/log/doc/html/index.html

Listing 4.3: Excerpt of a server log.

```
1  [2014-05-25 19:14:19]: <info> This server CPU became idle: 0.0840164%
2  [2014-05-25 19:14:19]: <debug> TRY_DEQUEUE UUID[7223e71f-cf39-4c8f-a2a5-2d02e5d2f5f2] was broadcast to all servers.
3  [2014-05-25 19:14:33]: <debug> Task UUID{fc89684f-99b5-4bb7-8803-426716c59721} State{Terminated} received from {gaviao
       } timestamp=[2014-05-25 19:14:35]
4  [2014-05-25 19:14:34]: <debug> TRY_DEQUEUE UUID[7223e71f-cf39-4c8f-a2a5-2d02e5d2f5f2] from Andorinha timestamp
       =[2014-05-25 19:14:34] processed.
5  [2014-05-25 19:14:34]: <debug> I won the race to dequeue task UUID{7223e71f-cf39-4c8f-a2a5-2d02e5d2f5f2} in this round
        of TRY_DEQUEUE.
6  [2014-05-25 19:14:34]: <info> Task(UUID{7223e71f-cf39-4c8f-a2a5-2d02e5d2f5f2} name{anomaly_detection} priority{
       interactive} state{Running} ScheduledBy{ROUXINOL} RunningOn{Acor})
7  [2014-05-25 19:14:34]: <info> Task executable anomaly_detection.exe started running.
8  [2014-05-25 19:14:34]: <debug> Server started communication with task executable.
9  [2014-05-25 19:15:03]: <debug> Task UUID{54e813af-003f-4e3d-a4c4-ab4ad94dbc37} State{Terminated} received from {Gralha
       } timestamp=[2014-05-25 19:15:04]
10 [2014-05-25 19:15:03]: <info> Task(UUID{40fda816-f118-4d70-8c0c-d82c35a870b9} name{segmentation} priority{interactive}
        state{Ready} ScheduledBy{ROUXINOL})
11 [2014-05-25 19:15:18]: <debug> Task UUID{40fda816-f118-4d70-8c0c-d82c35a870b9} State{Running} received from {Cotovia}
       timestamp=[2014-05-25 19:15:18]
12 [2014-05-25 19:16:03]: <debug> Task UUID{561f0c57-8533-40ae-8ca1-68e414d82936} State{Terminated} received from {
       ROUXINOL} timestamp=[2014-05-25 19:16:05]
13 [2014-05-25 19:16:34]: <info> Task(UUID{7223e71f-cf39-4c8f-a2a5-2d02e5d2f5f2} name{anomaly_detection} priority{
       interactive} state{Terminated} ScheduledBy{ROUXINOL} ExecutedBy{Acor} WaitingTimeOnQueue{16s} makespan{1109s})
14 [2014-05-25 19:17:18]: <debug> Task UUID{40fda816-f118-4d70-8c0c-d82c35a870b9} State{Terminated} received from {
       Cotovia} timestamp=[2014-05-25 19:17:19]
15 [2014-05-25 19:17:18]: <info> Task(UUID{9983e514-ece7-4a3c-9746-f5664488ae61} name{anomaly_detection} priority{
       interactive} state{Ready} ScheduledBy{ROUXINOL})
16 [2014-05-25 19:17:33]: <debug> Task UUID{9983e514-ece7-4a3c-9746-f5664488ae61} State{Running} received from {Andorinha
       } timestamp=[2014-05-25 19:17:34]
17 [2014-05-25 19:17:34]: <info> This server CPU became idle: 0.415445%
18 [2014-05-25 19:18:34]: <info> This server CPU became idle: 0.0385261%
19 [2014-05-25 19:19:15]: <info> Server::communication_layer(): New connection established with client 10.1.1.206:9965
```

5

Evaluation

This chapter presents and evaluates the results obtained from several executions of the developed prototype, considering different test configurations. Section 5.1 provides a brief presentation of functional requirements evaluation. In Section 5.2 we describe an implementation of a simulation framework that we have developed for automatic testing purposes and we evaluate the prototype taking into consideration the experimental results obtained from several tests. Finally, the Section 5.3 evaluates the satisfaction of non-functional requirements by our prototype.

5.1 Functional Evaluation

In Table 3.1 of Section 3.1, we have summarized the functional requirements that the system should meet. The majority of these requirements were fully satisfied, some of them were partially satisfied and just one was not, as shown in Table 5.1, where one check mark (✓) means partially satisfied, two check marks (✓✓) means fully and no check mark means not satisfied.

5.2 Experimental Evaluation

In this section we present and evaluate the developed prototype, using a simulation framework for automatic tests. We also present an evaluation of non-functional requirements that the system should meet, which were previously specified in Section 3.1.

ID	Satisfaction	Comments
FR1	✓	It was partially satisfied because the system is able to exploit idle computing time of workstations but currently it only executes simulated tasks of PLMI2 application, instead of real tasks, since these were not available.
FR2	✓✓	It was provided a way to represent dependencies among tasks, as defined in 4.4.
FR3	✓✓	The system is able to distinguish an interactive from batch task, as specified in Section 4.5.
FR4	✓✓	Client applications can request the scheduling, cancellation and subscription of a task, by following the protocols defined in Section 3.4.
FR5		This requirement was not satisfied because it was not possible to implement any User Interface for client applications due to time constraints. It was desirable to have but not crucial.

Table 5.1: Functional requirements satisfaction.

Hostname	CPU (model + speed)	RAM	Storage
acor	Intel(R) Core(TM) i5-2400S 2.56 GHz	4 GB	931 GB
andorinha	Intel(R) Core(TM) i5-3570T 2.30 GHz	4 GB	456 GB
corredor	Intel(R) Core(TM) i5-3570T 2.30 GHz	4 GB	465 GB
cotovia	Intel(R) Core(TM) i5-2400 3.10 GHz	4 GB	931 GB
gaviao	Intel(R) Core(TM) i5-3570T 2.30 GHz	4 GB	456 GB
gralha	Intel(R) Core(TM) i7-2600K 3.40 GHz	8 GB	175 GB
grifo	Intel(R) Core(TM) i5-3570T 2.3 GHz	4 GB	500 GB
pato	AMD Athlon(tm) II X3 440 Processor 3.00 GHz	4 GB	156 GB
rouxinol	Intel(R) Core(TM) i5-3570T 2.30 GHz	4 GB	465 GB

Table 5.2: List of workstations used to test the system.

5.2.1 Computing Resources

To measure the system scalability and the ability for supporting the fault-tolerance, we used nine workstations within the Albatroz's local network. Their characteristics are presented in Table 5.2 and all of them have the same operating system type, which is Windows 64-bit.

5.2.2 Simulation Framework

To test the system, we developed four simulated tasks' executables, as described below. The code for all tasks' executables is portable for both Unix-like and Windows operating system. Each one of them respects the communication protocol between a server-node and a running task that we have previously specified in Section 3.5.

import This task's executable simulates the inspection data importing to the database server.

georeferencing This task's executable simulates the geo-referencing of the imported data on database.

segmentation This executable simulates the classification of points of interest as ground, vegetation, road, building, etc.

anomaly_detection This task's executable simulates the classification of points of interest as an anomaly or not-an-anomaly, considering their distances to the power line.

The tasks' executables were implemented in such way that they can be executed as the following (command line-like):

$ $./task\_exec\_name\ [-p\ path\_to\_raw\_files]\ [-i\ input1]\ ...\ [-i\ inputn]\ [-x\ parameters.xml]\ >\ ouput1\ ...\ outputn$

task_exec_name The name of a task's executable.

[-p path_to_raw_files] This option means that a location in the file system (or a location within the LAN) containing the raw data files was passed. This option is only needed for the **import** task.

[-i input_nth] This option indicates that an integer number identifying an input dataset on database was passed. The number of input datasets to be passed to a task should be according to its need.

[-x parameters.xml] Indicates that an XML file with more task's parameters was passed.

ouput1 ... outputn are the identifiers of output datasets generated by the task's executable. These identifiers are supposed to be obtained when the task's executable generates datasets on database, but currently they are randomly generated by the simulated tasks.

We developed a dedicated tester application for automatic simulation of client-applications, where each client-application requests a server-node to schedule those four tasks described above. The priority of each task is chosen randomly according to a uniform distribution in interval $[1, 2]$, in which 1 means *low* and 2 means *interactive* priority, respectively.

Basically, the tester application creates between one and ten clients-applications by picking up a random number generated with a uniform distribution in interval $[1, 10]$. Also, this tester is easily expansible to support more server-nodes and client-applications.

We used nine workstations to work as the server-nodes (i.e., the server-node application was installed in each one) and a client-application chooses to which server-node to request the execution of its tasks randomly according to a uniform distribution in interval $[1, 9]$.

5.2.3 Test Configurations

The dedicated tester application that was implemented, may launch a specified number client-applications, where each client-application requests the scheduling of one workflow containing four tasks (illustrated in Figure 5.1) and the server-node to which a client-application requests the scheduling of its workflow is selected randomly, according to the number of servers used in each test configuration.

To show that the system is scalable with the increasing number of server-nodes we had to impose some restrictions on the test configuration, differently from that described in Section 5.2.2; i.e., in this case, some simulation parameters should not be chosen randomly, namely, the total task execution time and the number of client-applications. Indeed, we impose each task to take exactly 2 minutes to complete its execution, and for all tests, were scheduled 5, 10 and 15 workflows, which correspond to 20, 40 and 60 tasks, respectively. Regarding task's priority, we had to use the same seed for the uniform distribution, so that for every system execution tasks will have

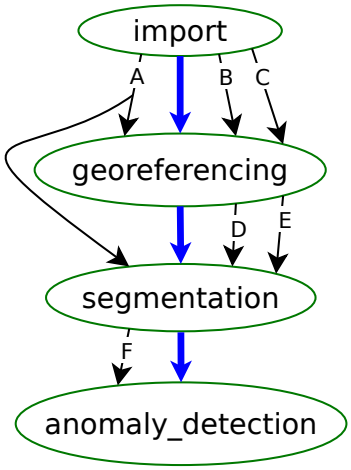


Figure 5.1: Workflow used for testing purposes.

Number of server-nodes	5 workflows	10 workflows	15 workflows
1	52,03	100,76	149,75
2	18,76	44,19	54,37
3	14,79	26,34	45,06
4	12,76	20,97	35,31
5	11,63	19,30	28,12
6	10,00	16,57	24,18
7	9,59	15,10	20,76
8	9,55	13,50	18,68
9	9,23	13,16	18,08

Table 5.3: Average makespan in minutes by a workflow for each number of server-nodes in the system.

the same priority as in the first execution. The only simulation parameter which changes from one test configuration to another is the number of server-nodes.

Although being the prototype developed in such a way that it only exploits the idle CPU cycles from workstations to execute tasks, we have to state that all tests were conducted with workstations in fully dedicated mode to execute tasks, i.e., the server-node was the only user application running on each workstation.

5.2.4 Experimental Results

In this section we present the results which show that our system is efficient/scalable and resilient to server-nodes' failures.

In Table 5.3 we present the results we have got with nine system executions, each one with a different number of server-nodes in the system and workflows. These results show that the average makespan of a workflow – the time since the submission to the system until its termination – decreases with the increasing number of the server-nodes. For instance, with 9 server-nodes and 10 workflows, in average a workflow took just 13,16 minutes to complete the execution, whilst with 1 server-node it took 1 hour and 40,76 minutes.

In Figure 5.2, we show the relationship between the number of server-nodes and the average completion time of a workflow, which uses the data previously presented in Table 5.3. This figure

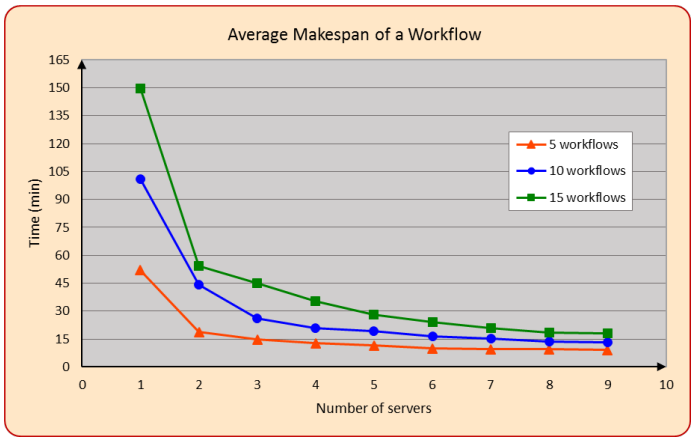


Figure 5.2: System scalability with the increasing number of server-nodes.

Number of server-nodes	20 tasks	40 tasks	60 tasks
1	11,01	23,19	35,44
2	2,79	9,05	11,71
3	1,80	4,57	9,27
4	1,29	3,23	6,83
5	1,01	2,81	5,04
6	0,63	2,13	4,05
7	0,54	1,77	3,20
8	0,53	1,39	2,68
9	0,44	1,31	2,53

Table 5.4: Average waiting time in minutes by a task for each number of server-nodes in the system.

shows, for instance, that the average completion time of a workflow significantly decreased from 1 to 3 server-nodes, either for 5, 10 or 15 workflows.

Table 5.4 presents the values of average waiting time of task in queue for each number of server-nodes and total number of tasks in the system.

To evaluate the average waiting time that a task of a workflow takes since its state gets ready until a server-node starts executing it, the line graphs in Figure 5.3 illustrate how the curves of waiting time changed with the increasing number of server-nodes and for different number of tasks in the system. As can be seen, with 9 server-nodes and 40 tasks in the system, a task waited in average 1,3 minutes to be started, whilst with just one server-node it waited 23,19 minutes. Taking into consideration that the waiting time of a task of a workflow depends on the time that its dependable tasks take to finish, and that each task takes 2 minutes to complete when it is started by a server-node and that each workflow has 4 tasks, then 1,3 minutes of waiting time by a task in a system configuration containing 9 servers is acceptable.

Ideally, a workflow used for testing purposes could be executed in 8 minutes by a server-node, since it has 4 tasks and each one takes exactly 2 minutes to complete. However, the implementation introduces some delay, that is, our distributed dequeuing algorithm establishes a waiting time-window when a server-node broadcasts a TRY_DEQUEUE message and also during the system execution some of computing resources may have periods that their CPUs are not idle.

In the same way as the makespan, the average waiting time by a task of a workflow – the

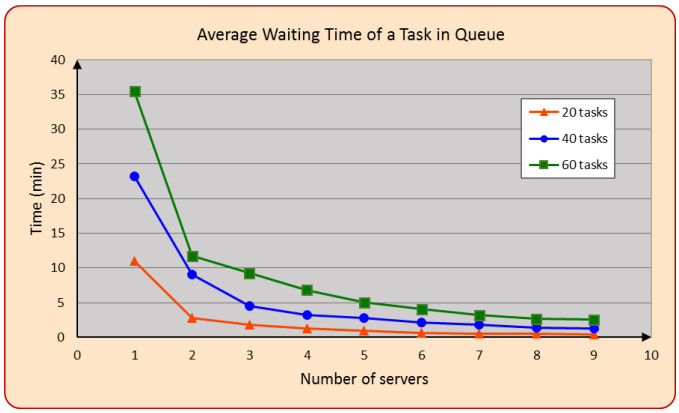


Figure 5.3: The average waiting time by a task in ready-to-run queue, according to the number of server-nodes in the system.

Number of server-nodes that failed	Avg. waiting time of a task	Avg. makespan of a workflow
8 out of 9	19,77	89,14
5 out of 9	3,35	22,81
2 out of 9	1,83	15,88
0 out of 9	1,31	13,16

Table 5.5: Average waiting time by a task and average makespan of a workflow, in minutes, for each number of failed servers.

time since a task becomes ready until its execution is started by a server-node – also decreases as illustrated by three curves in Figure 5.3.

Note that the line graphs presented in Figure 5.2 and 5.3 have similar slopes. This happens because the makespan of a workflow is related with the waiting time of its tasks, that is, the greater the waiting time higher is the makespan.

Fault Tolerance of Server-nodes

We have tested the fault-tolerance supporting of server-nodes when they were running tasks several times. For all tests the system was always able to detect their failures and reschedule the failed tasks. Moreover, to show that our system is resilient to the server-nodes failures, we have built 4 test configurations, in which client-applications requested the scheduling of 10 workflows (40 tasks) for a system with 9 server-nodes. Then, we intentionally caused 8, 5, 2 and 0 server-nodes to fail (i.e., cause them to leave the system) while they were running their first tasks, having the system started with 9 nodes. The remaining servers were able to detect the others' failures and rescheduled the failed tasks. Therefore, the remaining server-nodes executed all 40 tasks that were scheduled, with success. The results of average waiting time by a task and makespan of a workflow obtained from these system executions are shown in Table 5.5.

Fault Tolerance of Master Server

As we have presented previously, our system masks the master failure by electing a new one according the election algorithm defined in Algorithm 3.1. We have tested the master failure several times, where the joining server-node was always able to detect this issue and trigger new

ID	Satisfaction	Comments
NFR1	✓✓	The system supports fault-tolerance of task execution, employing the reschedule mechanism and the failure of a server does not imply incorrect behaviour of the remaining, regarding the specifications provided in Sections 3.6.1.1 and 3.6.2.1.
NFR2	✓	The heterogeneity was partially met because the system was developed in such a way that it works either for Unix-like and Windows operating systems, but for Unix it is missing to implement the Volunteer mode checker component presented in Section 4.5, and also it is missing some tests to ensure that communication Unix ↔ Windows works.
NFR3	✓	Experimental results provided in Section 5.2.4, have shown that the developed prototype presents an acceptable total task execution time, but unfortunately we cannot compare these results with those of existing system because our results were obtained with simulated tasks. The real tasks of PLMI2 were not available.
NFR4	✓✓	The performed tests have shown that a server-node has a low consumption of workstation resources, mainly the CPU usage.

Table 5.6: Non-functional requirements satisfaction.

election.

5.3 Non-Functional Requirements Evaluation

Table 5.6 presents whether a given non-functional requirement that was previously specified in Table 3.2 of Section 3.1, was met or not. The check marks have the same meaning as described in Section 5.1.

Summary

The results presented in this chapter show that the implemented system works as expected, in terms of fault-tolerance supporting and scalability.

We have also shown how quickly the implemented prototype dispatches workflows by increasing the number of server-nodes and that it is resilient to the failures of server-nodes, even if some of them fail, since the system still having at least one server-node running.

6

Conclusions and Future Works

This thesis has studied a problem that emerged as a real need of Albatroz Engineering, with the purpose of building a distributed task scheduling system able to schedule the execution of automatic tasks of a workflow of the company's PLMI2 application, to be executed by the available workstations within the Local Area Network (LAN) and tailored to the company's needs.

We have designed and implemented a new task scheduling system in the context of Volunteer Computing systems, which follows a distributed scheduling architecture, supports fault-tolerance of tasks execution by employing the rescheduling mechanism and takes into account the priority of a task. The task scheduling policy follows the priority-based First Come First Served (FCFS).

The implementation of the prototype has addressed some of challenging issues raised by distributed systems and Volunteer Computing, namely the dealing with hosts volatility and failures.

Furthermore, we have also defined three communication protocols between the system components:

- The protocol between a server-node and a task's executable, which can be used to easily add new tasks to the system;
- The protocol between a client-application and a server-node, to allow the supporting of new client-applications;
- The protocol among the distributed server-nodes within the LAN, in order to achieve the distributed task scheduling.

Our implementation relies mainly on two distributed algorithms, which respect a pre-established interaction protocol among server-nodes, in order to be achieved the agreement in distributed scheduling of tasks.

The evaluation results have shown that the system prototype is scalable with the increasing number of server-nodes and that it is resilient to the failures of server-nodes. Also, the results have shown that the system had in average an acceptable completion time of workflows dispatching

(i.e., according to the expected), and that the average waiting time for the execution of a task to be started by a server-node significantly decreases by adding more server-nodes to the system.

In order to extend the developed prototype, as a future work we recognize the need to:

- Improve our proposed distributed dequeuing algorithm to take into account the host CPU type, where a server-node is running, in order to assign a task to the host with better properties;
- Improve the system by adding a new scheduling policy to schedule tasks based on historical behaviour of computing resources, since this mechanism can significantly lower the global tasks execution time [9];
- Improve the server-node to consider a host as being idle, not only when the CPU load is low, as it is currently implemented, but also the mouse and keyboard activities, i.e., when the user moves away from the workstation for a given time;
- Design and implement Graphical User Interfaces for client-application's side, to inform the users about the current system state and to allow them to request the scheduling of tasks execution, cancelling the execution, etc.;
- Seamlessly integrate the developed prototype with PLMI2 platform.

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Appendix

A.1 List of Acronyms

AT	Automatic Task
CPU	Central Processing Unit
DAG	Directed Acyclic Graph
ECT	Estimated Completion Time
FCFS	First Come First Served
FIFO	First In First Out
GIMPS	Great Internet Mersenne Prime Search
GIS	Grid Information Service
GPIS	Grid Peer Information Service
GPS	Global Positioning System
GUI	Graphical User Interface
HEFT	Heterogeneous Earliest Finish Time
IMU	Inertial Measurement Unit
LAN	Local Area Network
LiDAR	Light Detection and Ranging
MT	Manual Task
P2P	Peer-to-Peer
PGS	Peer-to-peer Grid Scheduling
PPVC	A P2P Volunteer Computing System
PLMI	Power Line Maintenance Inspection
PoI	Point of Interest
SETI	Search for Extraterrestrial Intelligence
SJF	Shortest Job First
SCV	Sistema de Computação Voluntária
TA	Tarefa Automática
TBA	Task-Based Approach
TM	Tarefa Manual
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UUID	Universally Unique Identifier
VC	Volunteer Computing
VCS	Volunteer Computing System
WAN	Wide Area Network
WBA	Workflow-Based Approach
XML	eXtensible Markup Language