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FAKULTÄT FÜR WIRTSCHAFTSWISSENSCHAFTEN
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LEHRSTUHL FÜR PERVASIVE COMPUTING

Masterarbeit

ORIGNIAL FORMAT for the title of the work

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Zeitraum: 1.Januar 2010 - 1.Juni 2010

Contents

Abstract

The function of the abstract is to summarize, in one or two paragraphs, the major aspects of the entire bachelor or master thesis. It is usually written after writing most of the chapters.

It should include the following:

- Definition of the problem (the question(s) that you want to answer) and its purpose (Introduction).
- Methods used and experiments designed to solve it. Try to describe it basically, without covering too many details.
- Quantitative results or conclusions. Talk about the final results in a general way and how they can solve the problem (how they answer the question(s)).

Even if the Title can be a reference of the work's meaning, the Abstract should help the reader to understand in a quick view, the full meaning of the work. The abstract length should be around 300 words.

Abstracts are protected under copyright law just as any other form of written speech is protected. However, publishers of scientific articles invariably make abstracts publicly available, even when the article itself is protected by a toll barrier. For example, articles in the biomedical literature are available publicly from MEDLINE which is accessible through PubMed. It is a common misconception that the abstracts in MEDLINE provide sufficient information for medical practitioners, students, scholars and patients[citation needed]. The abstract can convey the main results and conclusions of a scientific article but the full text article must be consulted for details of the methodology, the full experimental results, and a critical discussion of the interpretations and conclusions. Consulting the abstract alone is inadequate for scholarship and may lead to inappropriate medical decisions[2].

An abstract[IGM97, **?**, MAdR02, Sal89] allows one to sift through copious amounts of papers for ones in which the researcher can have more confidence that they will be relevant to his research. Once papers are chosen based on the abstract, they must be read carefully to be evaluated for relevance. It is commonly surmised that one must not base reference citations on the abstract alone, but the entire merits of a paper.

Chapter 1

Introduction

[You should answer the question: What is the problem?]

This paragraph should establish the context of the reported work. To do that, authors discuss over related literature (with citations[1]) and summarize the knowledge of the author in the investigated problem.

ToDo: how to make citations

An introduction should answer (most of) the following questions:

- What is the problem that I want to solve?
- Why is it a relevant question?
- What is known before the study?
- How can the study improve the current solutions?

To write it, use if possible active voice:

- We are going to watch a film tonight (Active voice).
- A film is going to be watched by us tonight (Passive voice).

The use of the first person is accepted.

1.1 Motivation

A good introduction usually starts presenting a general view of the topic and continues focusing on the problem studied. Begin it clarifying the subject area of interest and establishing the context (remember to support it with related bibliography).

[1]To cite a work in latex

1.2 Problem definition

Additionally, focuses the text on the relevant points of your investigation and problems that you want to solve, relating them with the first part.

1.3 Thesis/Diplom/Bachelor/Master Structure

Present your work to the reader giving a brief overview of what is going to cover every chapter. Write only general concepts, no more than one or two sentences per chapter should be necessary.

Chapter 2

Materials and Methods

This section is to clarify the pre-existing tools, defining what was developed in this field until now, and why this tool was used instead of others.

The general structure is the following:

- Definition of the specific tool(s) studied (robots, sensor nodes, smart-phones). When relevant, pre-existing experiments.
- Definition of the context of use (indoor/outdoor, humans/animals/robots, with/without connection).
- Definition of used protocols (How the data are collected, when, etc.)

Chapter 3

Approach

In our system there are multiple robots that must handle various tasks. For example, visiting given rooms. To tackle this problem, a communication efficient task scheduling system is designed. This system allocate task according to system resources, including environment factors, robot status and task specifications. Once this information is attained, the task scheduling system assign robot a set of task.

- *Robot.* Each robot is responsible for moving in 2-dimensional physical space as well as colleting measurement result from sensors. It has a rechargeable battery, and its level drops as robot moves and rotates.
- *Tasks.* Each task requires one or more robots to traverse a path in the workspace and carry out certain actions[IGS17].
- *Environment.* In this project, all robots are considered moving in an office environment that contains a corridor along the central x-axis and 16 rooms located around the corridor. The environment model is shown in Figure 3.1. The environment factors, such as room locations and occupancy possibilities help task allocation.

3.1 Architecture Design

The architecture of the system consist of several parts: centralized pool, robot controller, navigation stack, charging station and system environment(Figure 3.2).

- *Centralized Pool.* A centralized pool consist of several modules: multi-robot task allocation module, map information, database, execution and monitoring. The database contains most of the environment information(Figure 4.2). The multi-robot task allocation module allocate tasks to robots once requested.
- *Robot Controller.* A robot controller contains several modules: local task queue, execution and robot action. The execution module receives commands from centralized pool and decides when and which task the robot should perform.

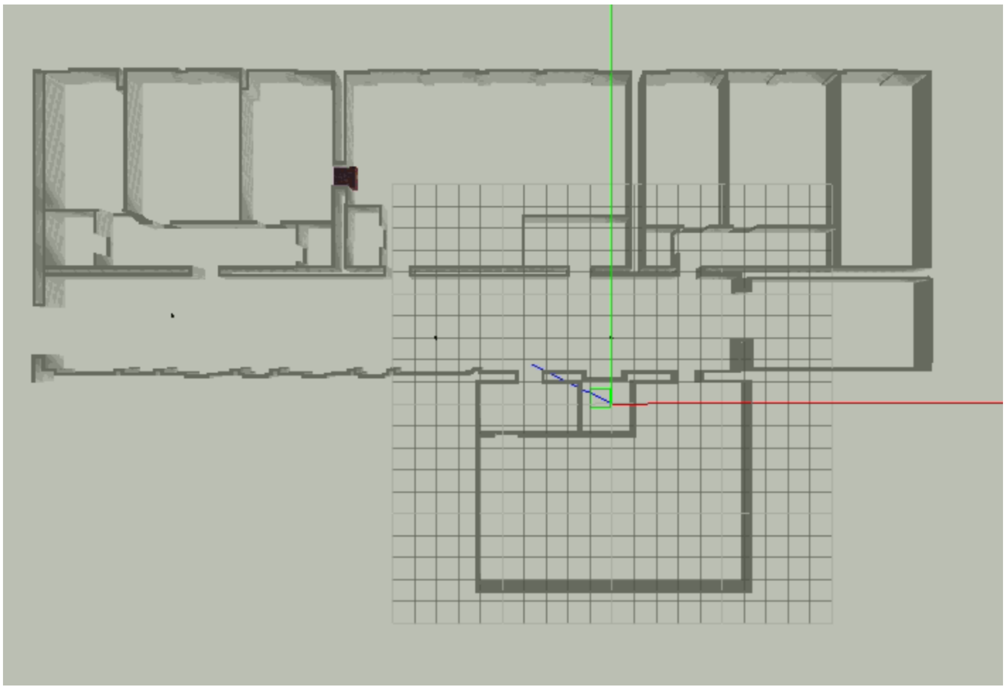

Figure 3.1: Gazebo Model

- *Navigation stack.* The move_base node provides a ROS interface for configuring, running, and interacting with the navigation stack on a robot. It makes robot move to desired positions using the navigation stack. Its advantages include optionally performing recovery behaviors when the robot perceives itself as stuck[mov].

3.2 System Environment

In this project, it is assumed that there are no dynamic obstacles. As is shown in Figure 3.3, the black lines are occupied area, which is the wall in 3D-Model(Figure 3.1). The gray area is unknown area. The white area is unoccupied. In unoccupied area there are following important areas and coordinates:

- *Rooms.* The rectangle areas (Figure 3.4) are used to represent Rooms. Each rectangle has its upper and lower limit in x and y coordinates, in order to identify which rooms the robots or targets belong to.

- *Doors.* The positions of doors (Figure 3.5) are stored in database. There are used by a ROS door simulator node, which broadcasts positions and door status periodically. The broadcast messages are received and filtered by robots.

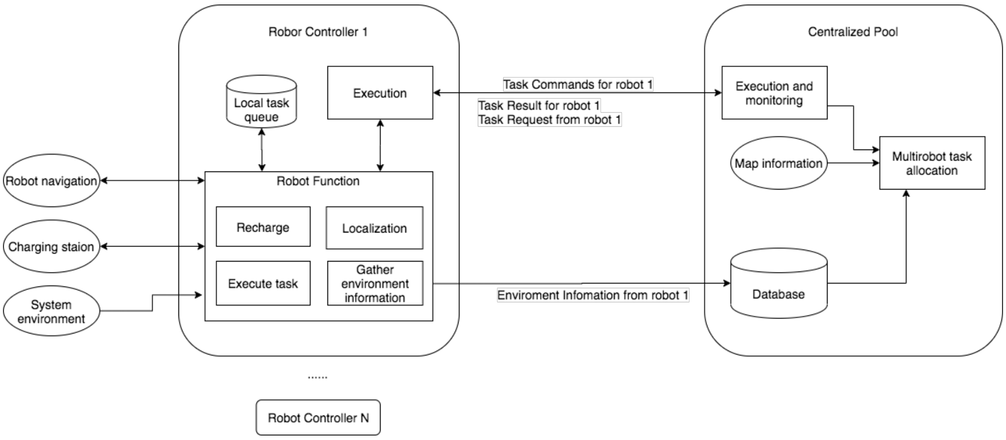

Figure 3.2: System Architecture

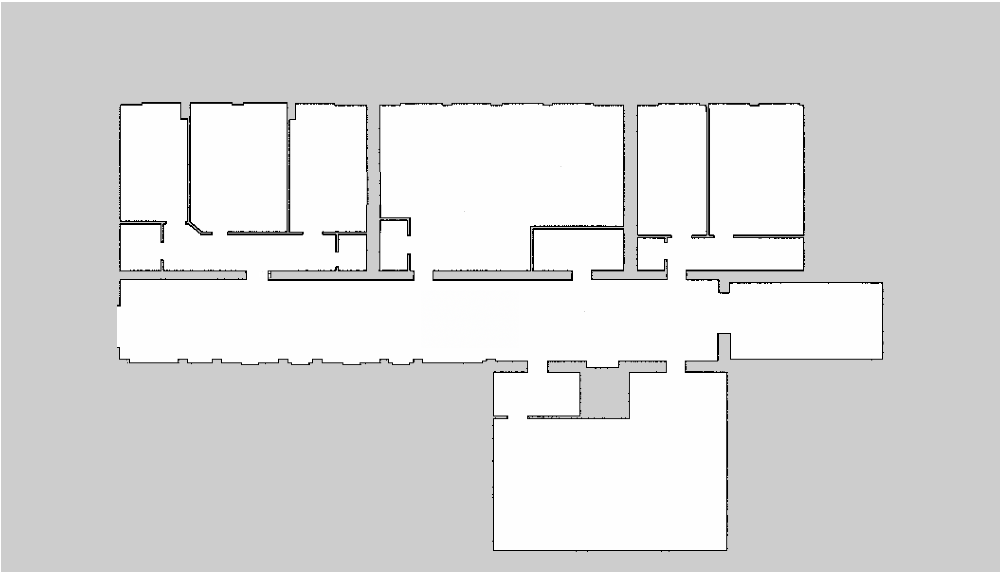

Figure 3.3: Environment Occupancy Grid

- *Charging Stations.* The positions of charging stations are used by ROS charging station nodes. For details please refer to Section 4.3.3.

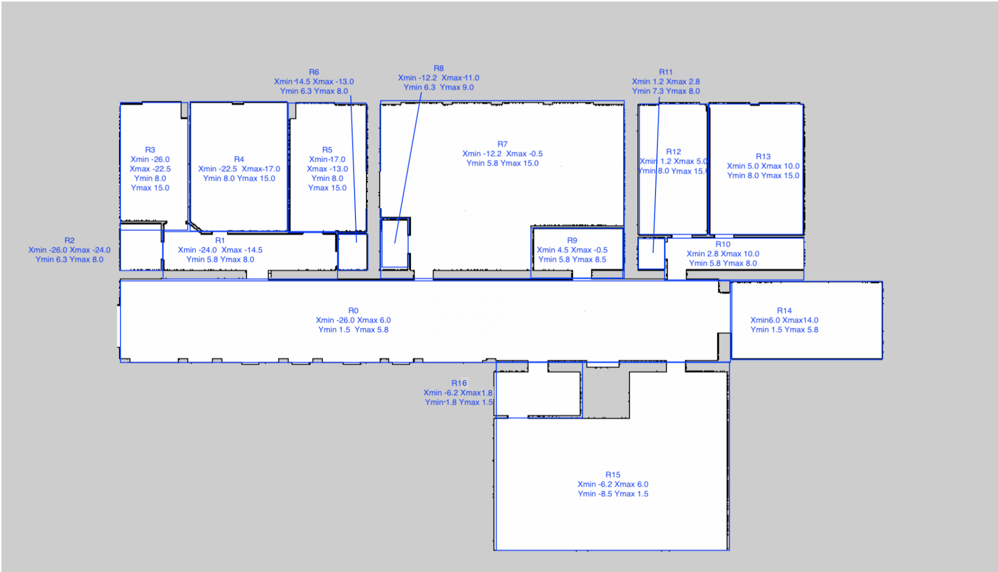

Figure 3.4: Room division

3.3 Task Allocation

3.3.1 Task Specifications

In order to improve overall execution efficiency, one single robot can carry either small task, which make robot move to one position, or large task, which consist of multiple small task. On one hand, recharging is necessary for robots to work long hours. On the other hand, a robot should gather environment information as much as possible, which centralized pool would learn from and make better decision. Therefore, three types of task are defined. The task specifications are various for different task types (Table 3.1 and Table 3.2).

Task Specifications / Task type	Target	Dependency	Priority	Generator
GatherEnvironmentInfo Task	Door	No	1	Centralized Pool
Execute task	Any point	Dependent on Execute-task	2,3,4	User
Charging Task	Charging station	No	5	Centralized Pool

Table 3.1: Task Specifications Part 1

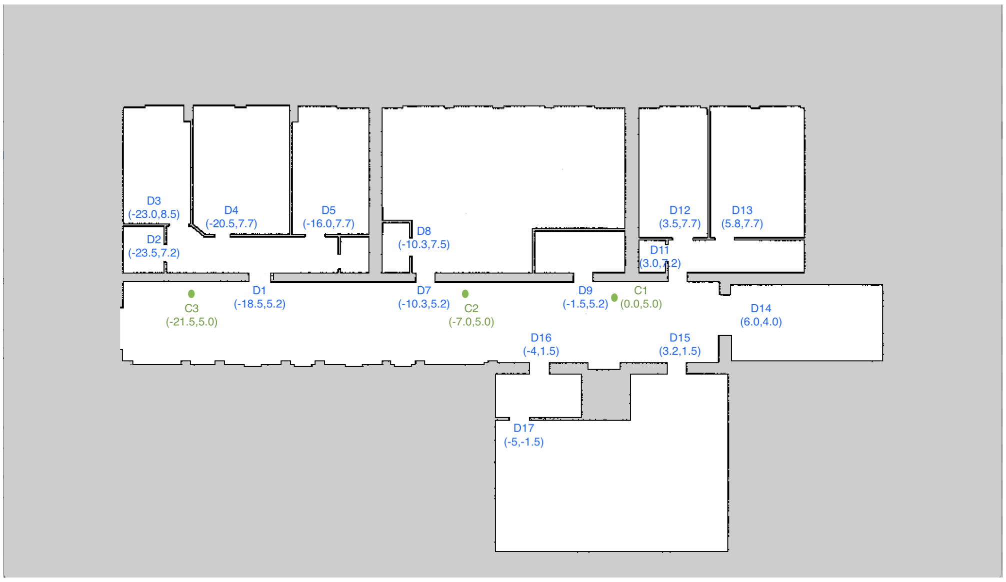

Figure 3.5: Doors and Charging Stations

Task Specifications	Start Time	Finish Time
Explanation	The time when robot start moving	The time when robot finished interacting with the target

Table 3.2: Task Specifications Part 2

- *Task Size.* The task in database (Table 3.3) is referred to small task. The example of small task includes ”charging task” and ”gather environment information task”. Those small tasks form a dependency chain, also referred to a large task. Execute task can be a large task which ask a robot to move continuously to several positions.

- *Target.* Targets include doors, points and charging stations. When a robot run a ”gather environment information task”, it moves to the front of a door and interact with a sensor in the door position without entering the door. When robot run an ”execute task”, the robot moves to a given point ether in corridor or in the room. When robot run a ”charging task”, the robot moves to a charging station and interact with this charging station.

Task Id	Task Type	Start Time	Target Id	Robot Id	Priority	Status	dependency	Finish Time	Description
1	2	10:00:00	10:59:59	0.80	2	RanToCompletion	0	2020-06-01 9:00:00	Succeeded

Table 3.3: Task Table in Database

3.3.2 Execute Task Allocation

With robot status such as positions and available battery provided by robot, the multi-robot task allocation module in the architecture should perform multi-robot task allocation. To select an "execute task", the following decision variables are considered.

Door Id	Door Status	Date Time
1	1	2020-06-01 09:00:01

Table 3.4: Measurement Result

Door id	Day Of Week	Start Time	End Time	Init Open Possibility	Open Possibility Statistic
1	2	10:00:00	10:59:59	0.80	0.80

Table 3.5: Door Open Possibility

Decision variables

- *Task Priority.* Task Priority. Task priority is an important factor that describes task emergency level. The "charging task" has the highest priority of 5. The "gather environment information" task has the lowest priority of 1. The "execute task" is determined by users but must be in the range of [2,4].

- *Product of Door Open Possibility.* Because of the limitation of simulation, the door open possibilities are used to represent room occupancies. A door open possibility is based on the statistic of door measurement results in a specific time period of a working day. The doors that the robot may pass through can be obtained from the map information module. An example of "measurement result" table is shown in Table 3.4, an example of "open possibility" table is shown in Table 3.5.

- *Waiting Time.* The waiting time is the difference between the current simulation time and start time of the first task to be executed. $T_{waiting} = T_{first\_task} - T_{now}$

- *Battery Consumption.* The Battery Consumption is related to robot trajectory. For a Large "execute task" that contains n small task, Equation 3.1 can be used to calculate battery consumption. The centralized pool will send the task with the lowest cost to this robot.

$$
\begin{aligned}
&B : Battery\_Consumption W : Weight \\
B_{large\_task} &= \sum_{task_0}^{task_n} B_{trajectory} \\
&= \sum_{task_0}^{task_n} \sum_{waypoint_0}^{waypont_M} [W_{position} \times position\_variation + W_{angle} \times angle\_variation] \\
&= \sum_{t=task_0}^{task_n} \sum_{p=waypoint_0}^{waypoint_M} [W_{position} \times \sqrt{(x_p - x_{p-1})^2 + (y_p - y_{p-1})^2} \\
&+ W_{angle} \times 2 \times \arccos(w_p)]
\end{aligned} \tag{3.1}
$$

In conclusion, equation 3.2 can be used to calculate the cost of a large "execute task".

$$
\begin{aligned}
Cost_{Large\_execute\_task} = \frac{W_{battery} \times Battery\_consum}{n} + W_{waiting} \times Waiting\_time \\
+ W_{possibility} \times \prod_{i=1}^{n} Door\_open\_possibility + W_{priority} \times Priority
\end{aligned} \tag{3.2}
$$

3.3.3 Environment Task Allocation

Once robot request a task, The task allocation module select only tasks with cost below the threshold. Once either no task in database or all costs above the threshold, the task allocation module should create a "gather environment information task", in order to collect more measurement result and further more improve the accuracy of "open possibilities" table. To create a "gather environment information task", which door should the requesting robot visit must be considered. The following decision factors help task allocation module to select the door.

Decision variables

- *Door Last Update Time.* The latest timestamp when the door is measured.
- *Battery Consumption.* Similar to "execute task" allocation, the battery consumption is related to the trajectory from robot to the door. Equation 3.1 can be used to calculate battery consumption.
- *Whether door is used.* If another robot is going to this door, the value is 0, otherwise the value is 1.

$$Cost_{door} = \frac{W_{battery} \times Battery\_consum}{n} + W_{time} \times (T_{last\_update} - T_{now}) + W_{possibility} \times \prod_{i=1}^{n} Door\_open\_possibility + W_{is\_used} \times Is\_used \tag{3.3}$$

3.3.4 Charging Task Allocation

Once a robot sends task request to the centralized pool, the centralized pool figures out whether this robot need charging, if yes it should create a "charging task" for requsting robot (Figure 4.3). Since there are multiple charging station in the system environment (Figure 3.5), the centralized pool selects a charging station for this robot using the following decision variables.

Decision variables

- *Remain Time.* It describes how long will a charging station be free.
- *Battery Consumption.* Similar to "execute task" allocation, the battery consumption is related to the trajectory from robot to the charging staion. Equation 3.1 can be used to calculate battery consumption.

In conclusion, equation 3.4 can be used to calculate the cost of a charging station. The centralized pool will generate a "charging task" for requesting robot to charging station with the lowest cost.

$$Cost_{charging\_station} = \frac{W_{battery} \times Battery\_consum}{n} + W_{time} \times T_{remain} \tag{3.4}$$

Chapter 4

Implementation

4.1 Communication Protocols

Centralized pool, robots, charging staions and sensors need to share information with each other. To improve the communication efficiency, communication protocols are designed.

4.1.1 Message about Measurement

When a robot passes by a door, it will receive messages from a sensor. In order to save resources, instead of a system enviroment in real life, a door simulator ROS node is used to publish all measurement result for all doors. The message formart is shown in Table 4.1 The measurement results(opened and closed) are created according to the ”open possible” column in the ”open possibilities” table (Figure 4.2).

Door ID	Position	Timestamp	Measurement Result
1	(-18.5,5.2)	2020-06-01 9:00:02	Door opened

Table 4.1: Measurement Message Format and Example

4.1.2 Message about Task

There are some basic requirements for communication between robot and centralized pool: firstly, robot should initiate the communication once it has finished all task in task queue and get free. Secondly, robot should forward sensor data to centralized pool while processing a task. These Communication protocols save unnecessary communication cost by avoiding keep tracking the current position, availability and states of all robots (Figure 4.1). Four types of message are defined: (1)Task request message(Table4.2); (2) Task goal messages(Table 4.3); (3) Task feedback message (Table 4.4); (4) Task result message (Table 4.5).

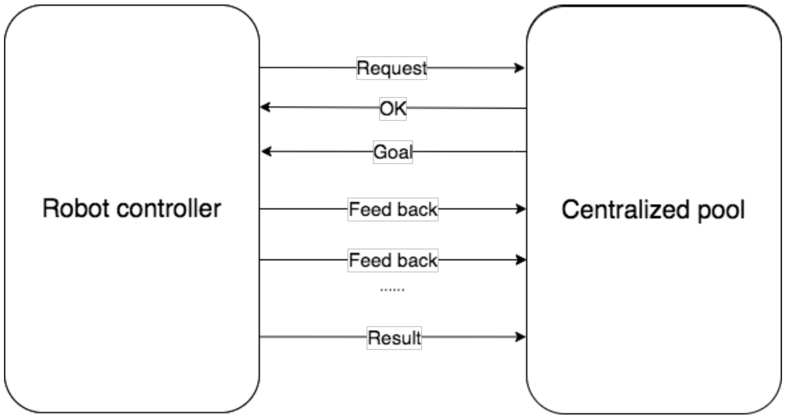

Figure 4.1: Communication between Robot and Centralized Pool

Battery	Pose	Robot ID
93	(2,4)	1

Table 4.2: Request Message Format and Example

4.1.3 Message about Charging

When a robot arrives charging station's position, it sends a message to Charging station(Figure 4.6). The details of charging station is discussed in Section 4.3.3.

4.2 Database

The centralized pool keep enviroment information in database to make decisions. The structure of database is shown in Figure 4.2. Following are explanations of some tables.

- *Table doors.* Table "doors" stores enviroment information. In table "doors", the "is used" column will be updated when the centralized pool gives a robot a task to the corresponding door. The "last update" colum will be updated when the centralized pool receives a new measurement result of the corresponding door.

Task ID-[]	Task type	Target ID	Goal[]
1	Gather Environment Info	9	(-1.5,5.2) 2020-06-01 9:00:00
[3,4]	Execute task	21, 22	(-24.0,12.0), 2020-06-01 9:02:00 (-21.0,12.0) 2020-06-01 9:02:00
5	Charging	17	(0.0,5.0), 2020-06-01 9:04:00

Table 4.3: Action Goal Message Format and Example

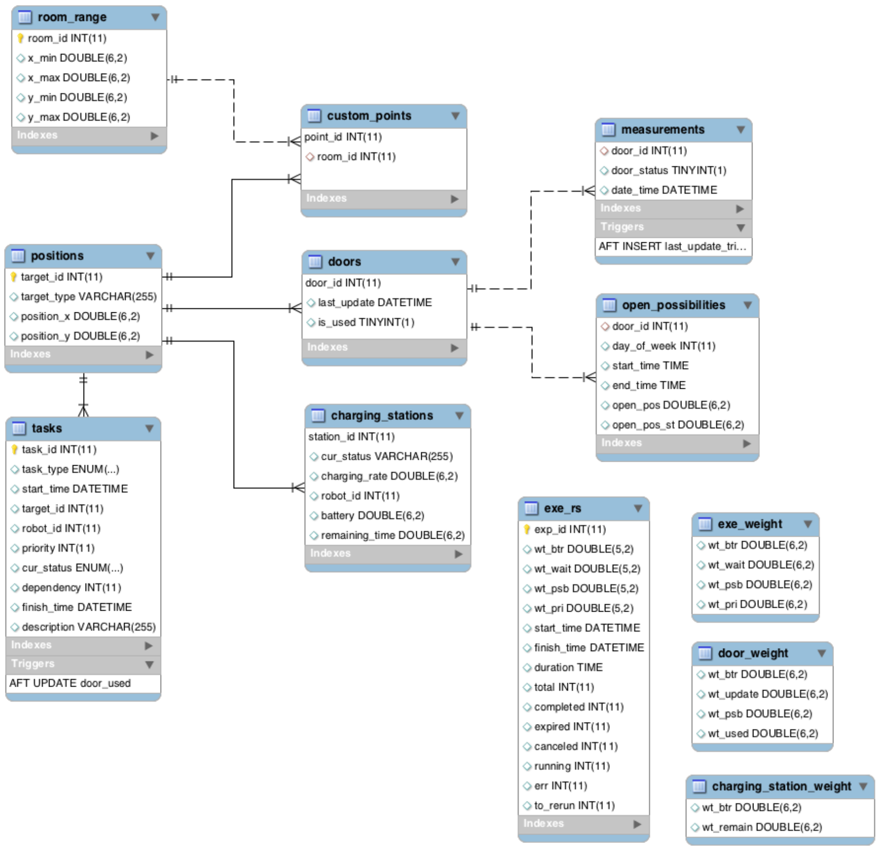

Figure 4.2: Database Entity Relationship Diagram

Robot ID	Door ID	Measurement time	Measurement result
1	3	2020-06-01 9:00:03	Door open

Table 4.4: Action Feedback Message Format and Example

Task ID	Task type	Result
1	Gather Enviroment Info	Success

Table 4.5: Action Result Message Format and Example

- *Table open_ossibilities.* Table "open ossibilities" is based on the statistic of measurement result in "measurement" table in a specific time period of each working day. These two table will be updated when centralized pool receive a new measurement result.
- *Table exe_rs.* Table "exe rs" stores experiment result while table "exe weight", table "door weight" and table "charging station weight" store weight values for experiment. Chapter 5 introduces the details of experiment.
- *Table costum_points.* When a task is created, the target point of this task will be stored in "position" table, and a "target ID" will be generated. This "target ID" will be stored in "custum points" table. Additionally, with the information in "room range" table, the system will recognize which room does the point belong to and write "room ID" column in "costom points" table.

4.3 Procedure

As stated in the Chapter 3, the goal of task scheduling is finishing all tasks as soon as possible while keep the cost as low as possible. The task assignment and execution happends at two level. [IGS17] the task and the path planner solves a planning problem. It takes and occupancy grid, a specific robot and a set of task specifications, and generates trajectorys for each task. According to those trajectorys and task specifications, the task with the lowest cost is assigned to robot. At the dynamic level, after each robot receive a task, it runs a navigation stack to execute this task stepwise. Each robot computes

Robot ID	Battery Level
1	93

Table 4.6: Message to Charging Station

a local trajectory but takes into account dynamic obstacles. The process of the robot task allocation system is as follows.

4.3.1 Centralized Pool

Task Allocation When the centralized pool receives a task request (Table 4.2) from robot, it performs task allocation. The task allocation algorithm is discussed in Section 3.3.2. The process of task allocation is shown in Figure 4.3.

1. When the battery of robot belows 10%, the centralized pool will create a charging task to the charging staion with the lowest cost.
2. When the battery of robot aboves 10%, the centralized pool will load all "execute tasks" in database and combine small tasks with dependencies into large tasks(Section 3.3.1), finally calculate task costs and select one large task with the lowest cost.
3. If there are no suitable tasks, a "gather enviroment task" to the door with the lowest cost is generated.
4. The output of the task allocation includes: task ID, goal coodinates, timestamp and selected robot ID. The task is sent to the selected robot, and the robot performs the tasks.

Handle Task Feedback. When the centralized pool receives a task feedback (Table 4.4) that contains a new measurement result from robot, it will add a record in measurement table and update "open possibilities" table in database.

Handle Task Result. When the centralized pool receives a task result (Table 4.5), it updates "tasks" table. The failed "execute tasks" will be reused whileothers will be marked as "Cancel" or "Error"(Figure 4.4).

4.3.2 Robot

Robot Process Tasks When the task queue(Figure 3.2) in a robot is empty, the robot requests a new task. If the robot gets a "charging task", it will move to the position of charging staion(Figure 3.5) and interact with charging station node (Section 4.3.3). When a robot gets an "execute task" which is a large task, it will move to all goals in order. When a robot gets a "gather enviroment information" task, it will move to the door's position. During task processing, the timer checks periodically the status of navigation stack. If any errors occurs, the robot send a "failed" result with description

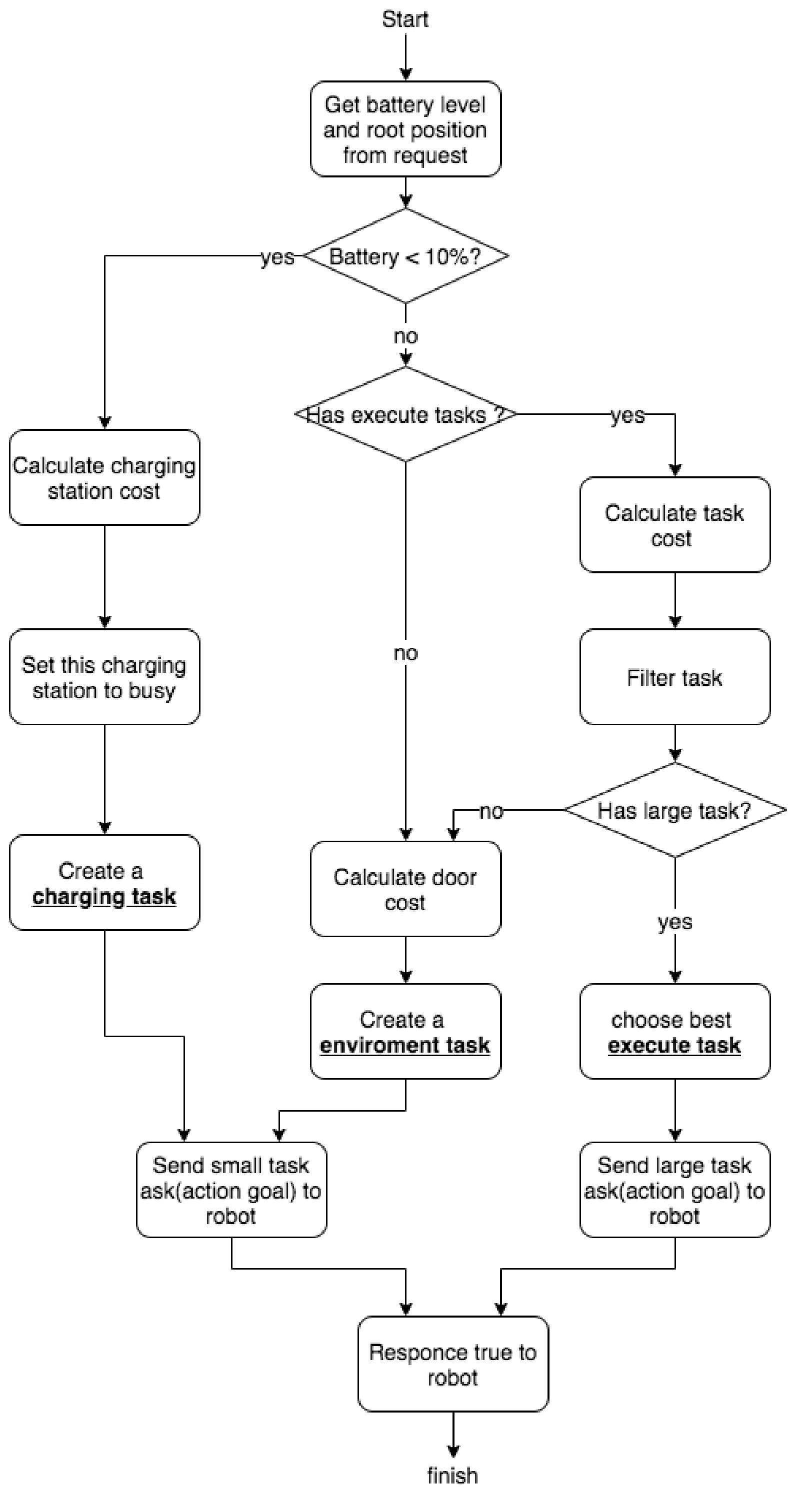

Figure 4.3: Centralized Pool Task Allocation

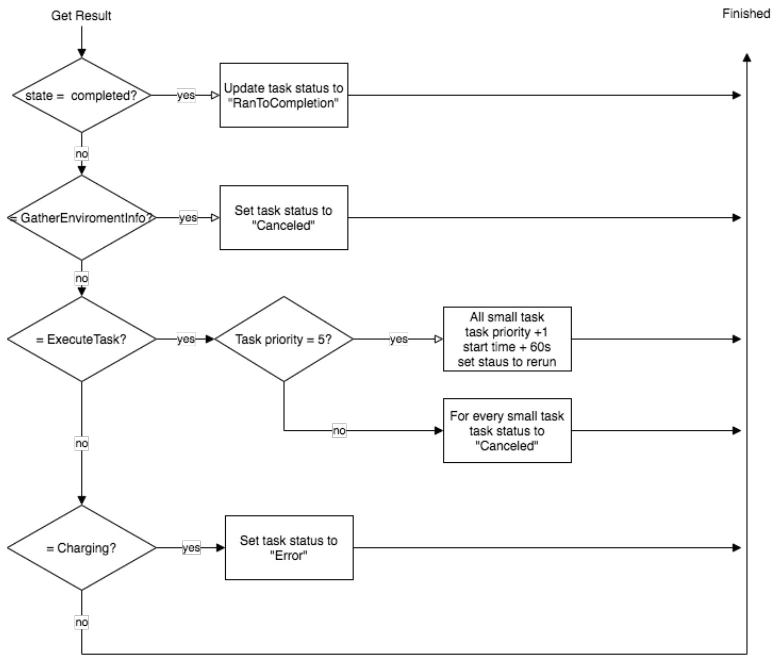

Figure 4.4: Centralized Pool Handle Task Result

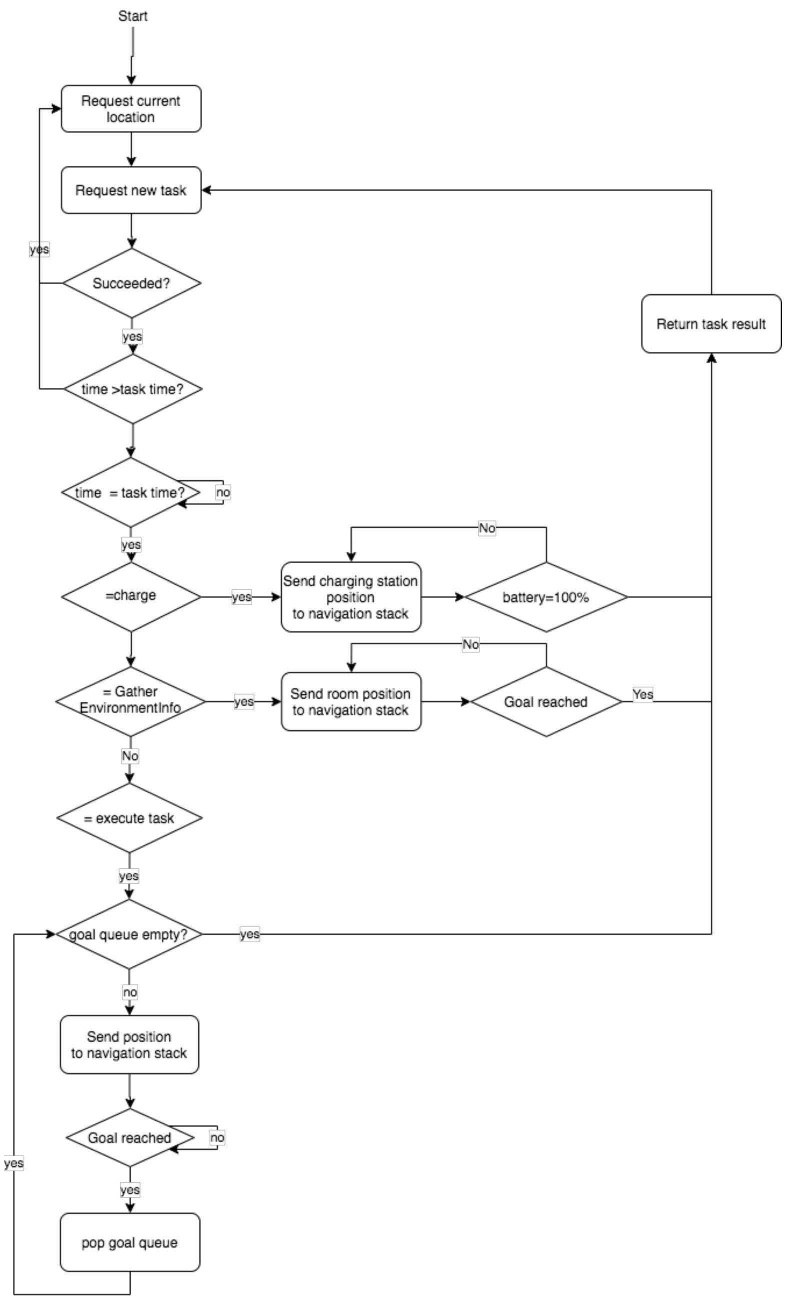

Figure 4.5: Robot Process Task

to the centralized pool. When all tasks are complted without error, the robot will send "Succedded" result to the centralized pool.

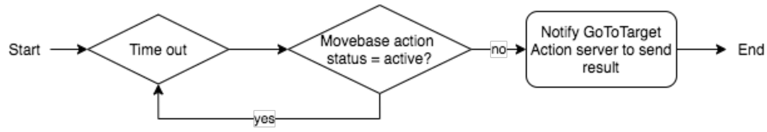

Figure 4.6: Robot Timer

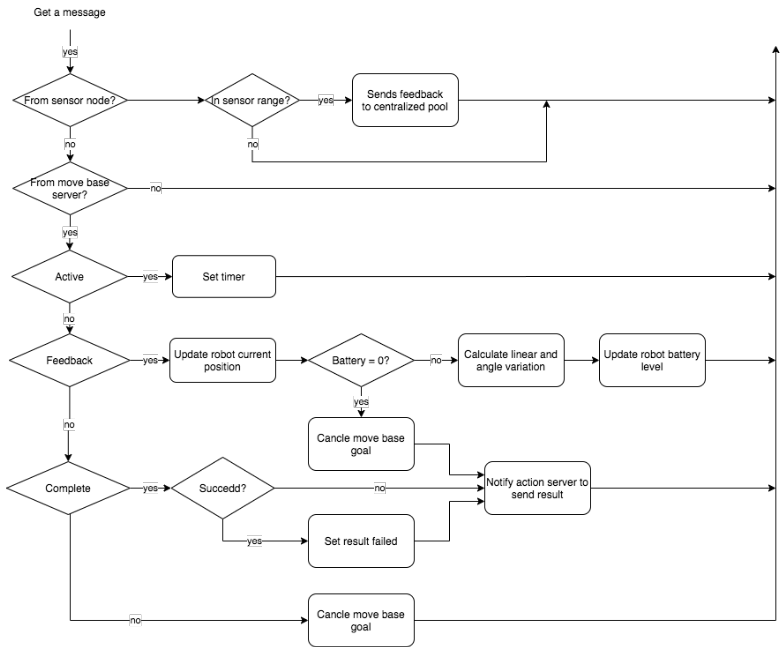

Figure 4.7: Robot Hanlde Message

Robot Handle Messages While a robot is processing a task, it listens to door sensors and forwards measurement result to the centralized pool. Besides messages from sensor, it also receives messages from "move_base" node. The details of robot message handling is shown in Figure 4.7.

4.3.3 Charging Station

The charging station consists of a charging station node and "charging station" table in database (Table 4.2). When a robot arrives the position of charging staion, it will start interacting with charging station node. Once the charging station receives robot information(Figure 4.10), its state will be changed to "charging"(Figure 4.8) and its "battery level" will be increased and its "remaining time" will be decreased(Figure 4.9). Once finishing charging, its status will be set "charging finish". Once robot leaves charging station, its status will be set to "free".

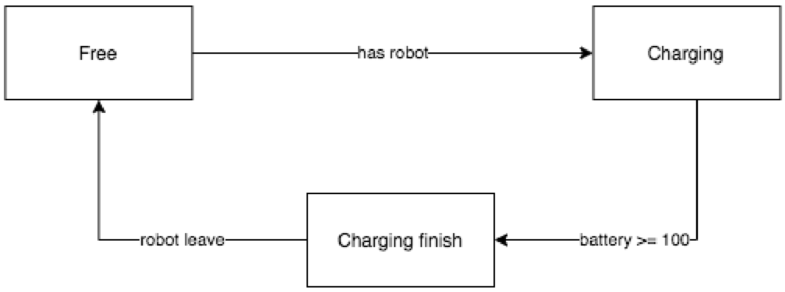

Figure 4.8: Charging Station State Machine

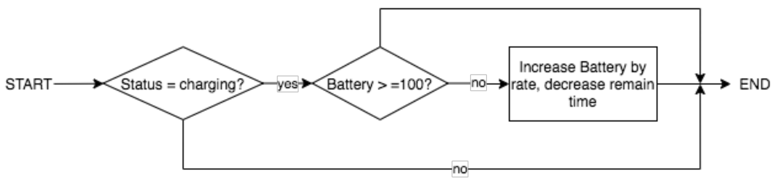

Figure 4.9: Charging Station Scheduled Charging Event

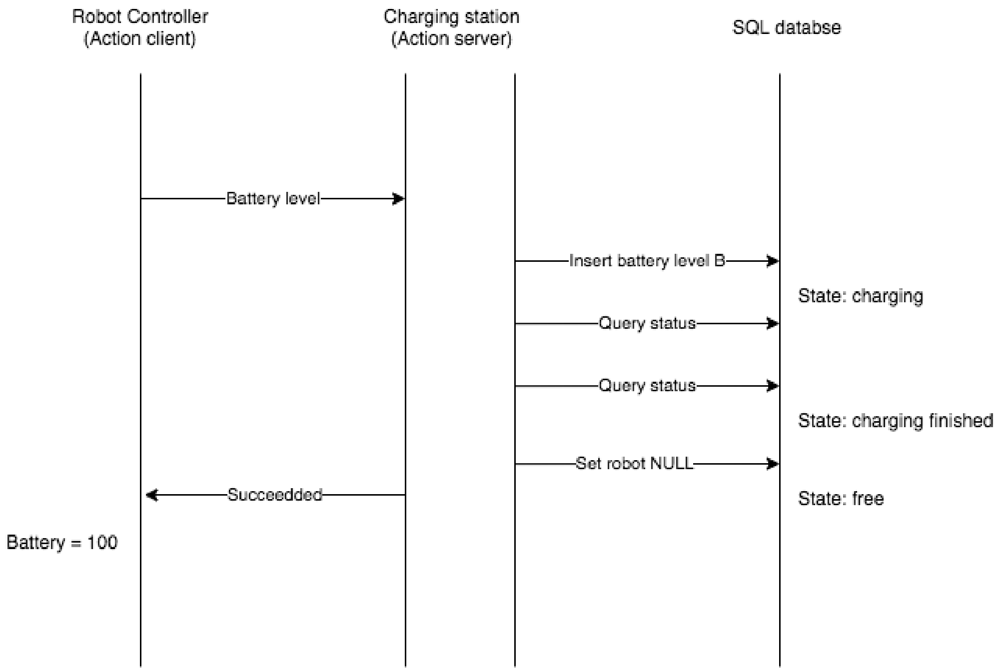

Figure 4.10: Charging Station Message

Chapter 5

Evaluation

In this chapter you should describe the previous (if possible) and final experiments performed on the implementation.

Every single experiment should be explained individually, providing to the reader information about the meaning of the experiment, the expected (theoretical) results, the final results, the comparison between them and others (if possible) and the conclusions.

Each experiment should include a description, covering (when possible) the following information:

- Significant physical features (obstacles present on the environment, human presence, temperature, humidity, possible noise sources, computational speed of the machine, etc.)
- The precise location of the experiment (latitude and longitude, room number or citation to a description of the used laboratory).
- Sampling design (variable(s) measured, transformation performed to the data, samples collected, replication, comparative with a Ground Truth system, collecting data protocol).
- Analysis design (how the data are processed, statistical procedures used, statistical level to determine significance).

The provided information should be sufficient to allow other scientists to repeat your experiment in the same conditions. Thus, the use of standard and well-known equipment could only be represented by a simple sentence, but the non-standard equipment should be described in detail, citing the source (vendor) and most important characteristics.

To write it, try to use the third person when describing the experiments and results. Avoid to use first person. Past tense should be the dominant conjugation (the work is done and was performed in the past).

Note: Graphics represent really well data, use them! (Matlab or Octave could be useful for that).

Chapter 6

Discussion

The meaning of this paragraph is to interpret the results of the performed work. It will always connect the introduction, the postulated hypothesis and the results of the thesis/bachelor/master.

It should answer the following questions:

- Could your results answer your initial questions?
- Did your results agree with your initial hypothesis?
- Did you close your problem, or there are still things to be solved? If yes, what will you do to solve them?

Chapter 7

Acknowledgements

(This part is optional, and it could be completely excluded by deleting
\include {content/chapters/chapter7}
from the Firstname_Lastname_Diplom_Master_arbeit.tex file)

This paragraph could mention people or institutions that supported you to some extent with your work or friends and relatives that supported you during your study period.

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Versicherung an Eides Statt

German

Hiermit versichere ich, dass ich die vorliegende Bachelor(Master)arbeit selbständig - mit Ausnahme der Anleitung durch die Betreuer - verfasst, keine anderen als die angegebenen Quellen und Hilfsmittel benutzt, sowie Zitate kenntlich gemacht habe. Ich versichere dass ich alle entsprechenden Angaben nach bestem Wissen und Gewissen vorgenommen habe, dass sie der Wahrheit entspechen und dass ich nichts verschwiegen habe. Mir ist bekannt, dass eine falsche Versicherung an Eides Statt nach §156 und nach §163 Abs. 1 des Strafgesetzbuches mit Freiheitsstrafe oder Geldstrafe bestraft wird.

English

I hereby declare that I have written this Bachelor (Master) thesis - except for the guidance of the supervisor - independently, using no other than the specified sources and resources, and that all quotations have been indicated. I declare that I have reported to the best of my knowledge all the relevant information, that it is true and that I concealed nothing. I am aware that a false declaration will be punished according to §156 and §163 par. 1 of the criminal code with a prison sentence or a monetary penalty.

Essen, September 25, 2020
(Ort, Datum)

First Name Second Name