

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN
Knowledge-Based Systems Group
Prof. G. Lakemeyer, Ph.D.

Simulation of the RoboCup Logistic League with Fawkes and Gazebo for Multi-Robot Coordination Evaluation

BACHELOR-THESIS
by

Frederik Zwilling
Matrikelnummer: 304314
frederik.zwilling@rwth-aachen.de

November 23, 2013

First Supervisor: Prof. Gerhard Lakemeyer, Ph.D.

Second Supervisor: Prof. Dr. Matthias Jarke

Advisor: Dipl. Inform. Tim Niemueller

Hiermit versichere ich, dass ich die Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet sowie Zitate kenntlich gemacht habe.

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Acknowledgements

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Chapter 1

Introduction



Multi-robot systems are combinations of multiple robots that work together on specific tasks. Currently, they are mostly used in assembly lines, where many robot-arms simultaneously do repetitive tasks on the same objects. More autonomous examples of multi-robot systems can be found in the warehousing domain. Here, many robots bring demanded goods from the storage and store new ones [15]. The major advantages of multi-robot systems are high flexibility and the possibility to run different tasks in parallel. The amount of possible applications is large. Beside assembly and warehousing, they can also be used in rescue scenarios [20], soccer [19], planetary exploration [10], logistics and more. Developing a robotic system is challenging. Robots have to detect objects, localize themselves, reason about their surrounding and manipulate it. Developing a multi-robot system is even harder because the robots have to do all these tasks in coordination with other robots. Furthermore, the systems have to be robust against the failure of single robots and should be as efficient as possible. Because of these challenges, testing is an essential part of the development process. It is necessary to identify mistakes in the source code and to evaluate how the system performs in a complex environment. Often, tests reveal problems the developer did not expect. However, testing can be difficult and time consuming for several reasons. The robot and the environment have to be available and set up. A component to be tested can depend on other components that are still being developed. Some tests require cautious execution because the robot could harm itself or the environment and full system tests have to run a longer time. Testing a multi-robot system is even harder. On the one hand the testing effort scales with the number of robots. On the other hand the system is more complex and therefore requires more test runs for evaluation.

In this thesis, we tackle these problems by developing a **multi-robot simulation environment**. This environment has to be physically and visually realistic. The robot software runs in the real world and gets simulated sensor data instead of real sensor data. When the robot software uses actuators, the actions are executed in the simulation. This brings many advantages and can speed up the testing process. With a simulation environment, the majority of tests needs neither available robots nor the environment, the setup can be automated and unfinished components, that other components depend on, can be

simulated as well. Furthermore, we want to evaluate the whole multi-robot system by measuring its performance in multiple runs. This enables us to easily compare different configurations and strategies in the simulation.

Such a simulation is useful in most robot developments. In this thesis we concentrate on **the** logistics domain and the mobile robot platform *Robotino*. We participate in the *Logistic League sponsored by Festo (LLSF)* with the *Carologistics* team. The Carologistics is a joint team consisting of the Knowledge-based Systems Group at RWTH Aachen University, the IMA/ZLW & IFU Institute Cluster at RWTH Aachen University and the Department for Electrical Engineering and Information Technology, Robotics Group at FH Aachen. LLSF is an industrially motivated competition within the **RoboCup** initiative. Three robots have to manage the material flow in a production area. The goal is to produce as many ordered products by feeding different machines in **the** production area with resources and intermediate products. To achieve a good performance, robust robot behavior and an efficient scheduling is necessary. Because of this, we have a special need for a multi-robot simulator, which can test the performance of single robots as well as the efficiency of the whole multi-robot system.



We use the *Fawkes* robot software framework to control the robots and we choose *Gazebo* as robot simulator. Important tasks of this thesis are the connection between Fawkes and Gazebo, the simulation of sensor data and the modeling of the LLSF environment and the actions of the robot in this environment. Because we want to use the multi-robot simulation to evaluate and improve our own LLSF system, we will also develop some concrete improvements and compare the performances of this system with different configurations. The majority of these improvements relate to the high level agent, which is responsible for the decisions of the robot and the coordination between the agents.

In chapter 2, we show the background of this thesis. This includes descriptions of the Robotino, the RoboCup and LLSF, Fawkes, Gazebo and other used tools. In chapter 3, we present related work about other simulations and agent strategies. Furthermore, we describe the current LLSF solution of the Carologistics team. The approach of this thesis is described in chapter 4. In chapter 5, we present the implementation. This includes a description of the developed simulation modules and the improvements on our LLSF system. The evaluation results of the changes of the agent and the simulation itself are shown in chapter 6. In chapter 7, we suggest future work and conclude.

Chapter 2

Background

This chapter presents the background of the thesis. On the one hand, we describe the RoboCup and LLSF in section 2.1 and the Robotino in section 2.2. On the other hand, we present the most important software for this thesis. In section 2.3 we present the two robot software frameworks ROS and Fawkes. Section 2.4 describes the robot simulator Gazebo, followed by additional software in section 2.5 which includes the data exchange format Protocol Buffers, the CLIPS Rules Engine and the document database MongoDB.

2.1 RoboCup

The *RoboCup*¹ is an international robotics competition founded in 1997 [21]. It provides standard problems as a platform for artificial intelligence and robotics research. Research teams from all over the world compete in different leagues to benchmark their robotic system. The RoboCup fosters important research results because the participating teams realize **theoretic approaches** and make them robust against the challenges of the real world complexity. Furthermore, the competition leads to comparison and evaluation of different approaches. Every year, the competition takes place at the RoboCup world championship, which is hosted by changing nations. There are also offshoots, such as the RoboCup GermanOpen in Magdeburg.

Initially, RoboCup started as a robot soccer world cup. The goal “By mid-21st century, a team of fully autonomous humanoid robot soccer players shall win the soccer game, comply with the official rule of the FIFA, against the winner of the most recent World Cup.” [37] shows how far the RoboCup **is going** to push the development of artificial intelligence and robotics. Since then, RoboCup has grown and now features a variety of different leagues in different domains. In the following we give an overview of the RoboCup leagues in 2013:

Soccer Leagues: The majority of the RoboCup leagues are soccer leagues with different robot sizes and platforms. There is a *Standard Platform League (SPL)* where the teams have to use about 60 cm high humanoid NAO robots without any hardware modifications. This enables the teams to focus on vision, behavior and motion tasks. There is also a

¹<http://www.robocup.org>

league for other humanoid robots. This league is divided into three sub-leagues with kid, teen and adult size robots. The *Middle Size League (MSL)* features up to five robots per team on a 18 m x 12 m field with each robot having a footprint smaller than 52cm x 52cm. In the *Small Size League (SSL)*, there are six robots, each with a diameter up to 18 cm, per team. There are also two simulation leagues which focus on artificial intelligence and team strategy instead of developing robot hardware. There are a 2D simulation league and a 3D simulation league. In the 3D simulation league, teams consisting of eleven virtual NAO robots compete against each other in a realistic soccer environment. In the chapter 3 about related work, we show both simulations in detail.

RoboCup @Home: The RoboCup @Home league is a competition about service robots. The robots have to assist humans in a domestic environment. There are a variety of tasks, such as following a human, serving drinks and handling emergency situations. Especially important in this league are the technical and open challenge. Here, the teams can present their own ideas and how the robot implements them.

Rescue League: The rescue league is a test-bed for urban search and rescue robots. The robots have to find victims in a setup course that simulates an urban area after an earthquake. This league also has a simulation offshoot we show in the chapter about related work.

RoboCup @Work: The RoboCup @Work league targets working tasks with the YouBot. The YouBot is a mobile robot with an advanced manipulator. The goal is to perform work-related tasks, such as identifying and handling different objects, placing them in bins and transportation.

Logistic League: We describe this league in detail in the following subsection.



2.1.1 Logistic League sponsored by Festo

The Logistic League Sponsored by Festo (LLSF) is a competition within the RoboCup. LLSF aims to foster scientific work on autonomous solutions for logistics and to provide a test-bed for existing approaches [31]. The participants should find new approaches and improve already existing ones to optimize material and information flow in logistics. LLSF takes place in a simplified production hall [34]. Figure 2.1 shows a part of the 5.6m x 5.6m hall with two Carologistics robots, three machines and some material-pucks. The main task of LLSF is to produce and deliver ordered products as efficiently as possible by feeding machines with resources and semi-finished products. The participants can use up to three Robotino robots by Festo [17]. We present the Robotino in the next section in detail. Orange pucks represent resources and products. They are equipped with an RFID-chip² which is needed to store the different product states of the pucks. The machines are represented by the RFID-readers with lamps on top. The lamps indicate the current status of a machine, such as “ready”, “producing” and “out-of-order”. The machines

²Radio-frequency identification allows the wireless identification of objects with small chips.



Figure 2.1: Part of the LLSF field

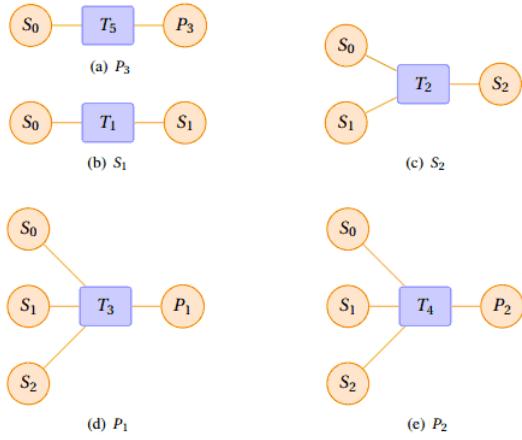


Figure 2.2: LLSF Production Chain [34]

need resources and semi-finished products as input and turn the last input puck into a further precessed puck. All other input pucks are turned into consumed pucks which can be recycled to produce new resource pucks. There are different types of machines. The type defines the needed input and the produced output of a machine. Figure 2.2 shows the production chain. There are the raw-material pucks S_0 , intermediate product pucks S_1 and S_2 and product pucks P_1 , P_2 and P_3 . The machine types are labeled with T_1 to T_5 . Beside these regular machines, there are also recycling machines, which turn consumed pucks into raw-material pucks, and delivery machines which are used for delivering finished product pucks. Teams are awarded with points for delivering finished products, producing complex pucks and recycling. The game is divided into two phases. In the first phase, the *exploration phase*, the robots have three minutes to explore the production area to identify which machine is of which type. Teams also receive points for each correctly reported machine-type. The second phase is the actual *production phase* and lasts 15 minutes. The league also features an automated referee box (Refbox). It controls machines and communicates with participating robots during the game. The Refbox gives orders which products are to be produced, informs the robots about the game state and rewards points for achieved goals.

2.2 Robotino

The *Robotino* [17] is a mobile robot developed by Festo Didactic³. It is used for research and education. The shape of the Robotino is a cylinder with 37cm diameter and 21cm height. It holds omni-directional wheels to be able to drive in any direction and turn at the same time. It is equipped with nine infrared distance measuring sensors ordered around the robot, a bumper to detect collisions and a webcam. A micro-controller and an embedded PC with 800 MHz and 128 MB RAM are used to control the robot. The PC runs with a Linux Operating System. The Robotino is designed to be extendable to be

³<http://www.festo-didactic.com>

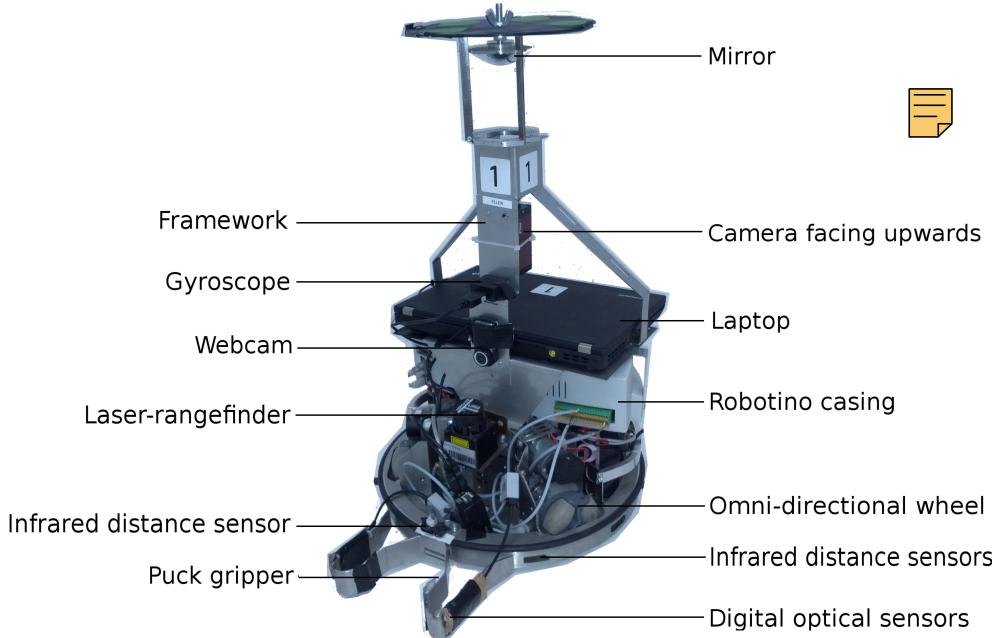


Figure 2.3: A Robotino extended by Carologistics

used in different applications. Therefore additional sensors and actuators can be attached. At the front of the Robotino, there is a loading bay with some space for extensions. Some common extensions are a forklift, a static gripper to move pucks on the ground and a laser range finder. Figure 2.3 shows a Robotino extended by us. In addition to the default sensors shipped with the Robotino, we added a laser-rangefinder for localization and obstacle detection, a gyroscope and a framework which holds an omni-directional camera. The omni-directional camera consists of a camera facing upwards and a hyperbolic mirror above. The camera can see the whole area around the Robotino through the mirror. We adapted the omni-vision camera from former MSL-robots and now use it to detect LLSF pucks. The framework also holds a laptop connected to the Robotino, because we need more computational power than the Robotino provides. explain why? We also attached a simple gripper to the front to move pucks. This gripper is equipped with an infrared distance sensor to recognize if there is a puck in the gripper and a digital optical sensor on each side of the gripper. These are used to align the robot in front of LLSF machines. To observe the lamps on the machines, we use a webcam.

2.3 Robot Software Frameworks

2.3.1 Robot Operating System

The *Robot Operating System (ROS)*⁴ is an Open Source framework designed to operate on many robot platforms and to provide a standardized integration framework [36]. It

⁴<http://www.ros.org>

provides a collection of useful Open Source libraries and tools for the development process of robot-software. Currently, it is widely used and has a large community. Each component integrated in ROS runs an own process and is called *node*. ROS features peer-to-peer communication between nodes. Nodes can register a publisher or subscriber to a specified *topic*. If a publisher of a topic sends a message, every subscriber of same topic receives the message. We will describe the message protocol Google Protobuf used by ROS later. The communication is managed by a process called *Roscore*. Roscore acts as a **server**. All nodes have to connect to the server in order to operate.

We use ROS in LLSF for two reasons. First, we use ROS for motion planning. The ROS package **Movebase** provides a global path planning and local motion planning with collision avoidance. We provide a ~~global navigation graph~~ for the LLSF field, the position and orientation of the robot, laser data for obstacle detection and motion goals by publishing messages to specified topics. With this data, Movebase computes a motor command. We subscribe to the motor command topic and execute received commands. Second, we use the *Rviz* package for visualization. On the one hand we visualize incoming laser data and the localization of the robot in the LLSF field with all position hypotheses of our Adaptive Monte Carlo Localization (amcl).  plain?. On the other hand we visualize the global and local motion plan. Moreover, we use Rviz to send localization hints to amcl.

2.3.2 Fawkes

*Fawkes*⁵ is an Open Source robot software framework developed primarily at the Knowledge-based Systems Group⁶ (KBSG) at RWTH Aachen University. It is designed to run on multiple platforms and domains. It is written for Unix systems and follows a component-based software design [32]. It provides an infrastructure to load and unload binary components (implemented as *plugins*) at run-time. Fawkes features a *blackboard* as communication structure between plugins. The blackboard lists structured entries called *interfaces*. Plugins can read and write interfaces with a specified id. There can be many readers but only one writer for an interface. Furthermore, Fawkes organizes plugin activity in threads to make use of multi-core architectures. Because of this design, Fawkes is flexible and dynamic. The interchangeability of the plugins, which is caused by well defined interfaces, makes hardware abstraction and reuse easy. This is also an important advantage for the development of the simulation because the simulation can easily exchange lower-level robot control and sense plugins. The robot control plugins on higher levels **can operate as usual** because the interface is the same. The features of Fawkes are provided as *aspects*. These aspects are based on aspect-oriented programming [18] and give access to a particular feature. Threads that want to use a feature can inherit from the corresponding aspect. For example there are aspects for accessing the blackboard, logging and timing [30]. In this thesis, we provide communication with the simulation by **using** such an aspect. Two other important features for this thesis are the centralized clock and the configuration.

⁵<http://www.fawkesrobotics.org>

⁶<http://www.kbsg.rwth-aachen.de/>



The centralized clock provides the time for all plugins. Especially important for this thesis is the possibility to give Fawkes an alternative time-source. So, it is easy to exchange the system time with the simulation time for all plugins without having to modify them. Also important for this thesis is the way Fawkes provides configurations. The configuration-files for all plugins are described in the same format. A super-ordinate configuration file chooses which configuration files have to be loaded. There is the possibility to start Fawkes with a specified configuration by setting a super-ordinate configuration file. Furthermore, there is the possibility to override configuration values.

In comparison to ROS, the advantage of Fawkes is the tighter integration of the used components. The main loop of Fawkes controls the execution order of all component threads. This makes it possible to match certain time criteria for the components and to provide a *sense-think-act* cycle.

We use Fawkes as our main robot software framework. Nearly all software components for our robot are integrated as plugins into Fawkes. Therefore, in this thesis, we have to provide the sensor data from the simulation and get commands for the actuators in Fawkes. **bbsync?** **behavior engine?**



2.4 Gazebo

Gazebo⁷ is an Open Source robot simulator [24]. It provides a platform to simulate all kinds of robots with sensors and actuators and their environment in a three dimensional world. It runs on UNIX and is written in C++. Originally, Gazebo was designed for large outdoor environments, but it is well suited for indoor environments, too. The development was started as part of the Player/Stage project [13] and was an alternative to the two dimensional simulator stage. Gazebo became independent later. Now, it has **S** strong relation to ROS and is even available as a package in ROS. Gazebo is a frequently used simulator. It is, for example, the simulator chosen for the recently held Virtual Robotics Challenge founded by DARPA. We present the use of Gazebo in this challenge in the related work.

Gazebo uses proven Open Source engines for graphical presentation and physics. *Ogre*⁸ is the graphic engine used in Gazebo. It allows rendering graphically realistic environments with reflections, shadows and detailed textures. This is important for the simulation of camera sensors because often reflections of light sources and inconstant lighting can cause problems. Gazebo uses the *Open Dynamics Engine (ODE)*⁹ and *Bullet*¹⁰ to simulate physical interactions between objects. It features an abstraction layer for physics and can therefore use both physic engines interchangeably. Bullet features lower computation cost and more complex shapes than ODE, whereas ODE has a larger documentation and background in robot simulators. Furthermore, the abstraction layer for the physics engine

⁷<http://gazebosim.org>

⁸<http://www.ogre3d.org>

⁹<http://www.ode.org>

¹⁰<http://bulletphysics.org>

allows the access to detailed parameters of the engines.

A simulation in Gazebo consists of different elements: *Models* describe physical objects in the simulation, such as a table or a robot. The model is built out of *joints* and *links* which consist of a number of geometries. These geometries can either be visible objects or collision objects used for physics. Joints connect two links and define the possible motion of the links in relation to each other. For example, joints are used to define axes of wheels. Furthermore, a model can contain sensors which are represented by a set of properties to define the sensor. A *world* describes the whole simulation environment in Gazebo. It consists of models and light sources. It also has a range of properties for the physics simulation, rendering and the general simulation. Models and Worlds can be defined in an XML-like format called *Simulation Description Format (SDF)* which is based on the *Unified Robot Description Format (URDF)* of ROS but is optimized for the use in a simulation. Beside the physical description of objects in the simulation there are also *plugins* in Gazebo to modify the simulation at run-time. These plugins belong to a model, a sensor or a world. **They inherit from the Gazebo API** and use it to model the behavior of different objects. For example, there are plugins for robot models, which apply motion to the corresponding model if the robot receives a movement order, and plugins for the world, which can spawn new models.

Out of the box, Gazebo includes a variety of generalized sensors and models of common robots and other objects such as tables, cups and even buildings. For example, there are robot-models for the PR2 by Willow Garage, Atlas by Boston Dynamics and the Kuka YouBot. In the Gazebo framework, there is basic support for a set of general sensors. This includes cameras, contact-sensors, GPS, inertia measurement units, laser sensors and sonar sensors. The support of all these common sensors and models allows easy development of a specific simulation environment. Not included models, sensors and plugins can be added and fit well in the existing context.

The reason why Gazebo was chosen as the most suitable simulator for this thesis is shown in the related work.

2.5 Additional Software

2.5.1 Protocol Buffers

*Protocol Buffers (Protobuf)*¹¹ is a data interchange format developed by Google. Protobuf serializes data in a pre-defined structure for efficient data transportation and storage. It is flexible and language-independent. The user can define a data structure. Protobuf then uses this data structure to generate code in a specified programming language. The code is able to efficiently serialize and deserialize data. The generation of code in the different languages makes it easy to include Protobuf in an implementation. The data structures are kept simple and can be built hierarchically. In the following, we use the term type

¹¹<https://developers.google.com/protocol-buffers/>

to refer to the data structure behind a Protobuf message. Because of its efficiency and simplicity, Protobuf is widely used. Especially ROS, Gazebo, the LLSF Refbox and our agent use Protobuf to transport messages. However, Protobuf also has the downside that a received sequence can only be deserialized if the type of the message is known. Because Protobuf has the additional feature that the data structures are down-compatible **against** extension, this downside can be compensated by manually adding the message type as a field to the message. In this thesis, we use Protobuf for the communication between Fawkes and Gazebo.



2.5.2 CLIPS Rules Engine



The *CLIPS* rules engine¹² is an expert system developed by NASA¹³ with rule-based, object-oriented and procedural programming paradigms [11, 43]. It basically consists of a *fact base*, a *knowledge base* and an *inference engine*. The fact base acts as a kind of working memory [33]. *Facts* in the fact base represent pieces of information. The values of a fact can be **in an array or structured defined before**. The knowledge base consists of *rules* and *functions*. Rules represent heuristic knowledge and are the basic part of the expert system. They are composed of an *antecedent* and a *consequent*. The antecedent contains an ordered set of conditions. If all conditions of the antecedent can be matched by facts in the fact base, the rule is applicable. The consequent contains a set of actions which are executed if a rule is applied. For example, these actions can assert new facts to the fact base or delete existing ones. Functions represent procedural knowledge. The inference engine realizes a forward-chaining mechanism. It matches the fact base to the antecedent of the rules to determine which rules are applicable. Then, it decides which applicable rule to execute by a priority defined in the rules. After executing the rule and probable changes to the fact base, the whole method is repeated until no more rules are applicable.



The special feature of CLIPS is its integration into programming languages, such as C and Java. On the one hand, it is possible to run CLIPS and to dynamically assert facts from a program. On the other hand, functions in CLIPS can call functions of the language CLIPS is embedded in. This integration makes CLIPS a good choice for the control of an embedded system. We use CLIPS for our high level control agent. Here, we encode the world belief and which actions to take in which situations.



2.5.3 MongoDB

*MongoDB*¹⁴ is an Open Source, document-oriented database [9, 23]. The basic elements in MongoDB are documents. Documents are grouped in so called collections which are contained in a database. Documents **contain** a set of key-value pairs, can be nested and

¹²<http://clipsrules.sourceforge.net>

¹³National Aeronautics and Space Administration (NASA) of the USA

¹⁴<http://www.mongodb.org/>

are schema-free. This means that there are no constraints to the keys in a document. This provides a flexible and simple use. MongoDB uses indexing to increase querying speed.
cut off MongoDB section or better description?

In this thesis, we use MongoDB to store statistics about simulated LLSF games. MongoDB also gives us the possibility to log sensor data and the belief and decisions of the agents [23].

Chapter 3

Related Work

In this chapter, we present related work of this thesis. In section 3.1, we describe alternatives to Gazebo and why we choose Gazebo. In section 3.2, we give an overview of other popular simulations, especially a simulation that also uses Gazebo and other multi-robot simulations. Section 3.3 describes our current multi-robot strategy as well as other attractive strategies our simulation should be able to evaluate. In the following, we will use the terms *multi-robot* and *multi-agent* interchangeably because the common term in literature is **multi-agent** and we want to use **multi-robot**. A multi-agent system can consist of fully abstract agents, but we are dealing with multi-robot system and therefore robots which interact physically with their environment.

3.1 Other Simulators

3.1.1 Stage



*Stage*¹ is an Open Source multi-robot simulator for a two dimensional environment. It is a part of the *Player/Stage* project [13]. **Player** is a robot control server, which provides a simple connection between a robot control program, sensors and actuators of a robot. Stage uses this connection and replaces the sensors and actuators by simulated ones. Stage was a popular simulator in the last years and is able to simulate a large amount of robots. For the simulation, Stage uses simple and computationally **cheap** models, that provide **still** enough fidelity for **most** applications. Furthermore, the computational effort is linear in the number of robots. Because of that, Stage can simulate a large amount of robots [40]. This makes Stage attractive for the simulation of swarms and multi-robot systems with many robots.



¹<http://playerstage.sourceforge.net/index.php?src=stage>



3.1.2 Webots

*Webots*² is a commercial 3D simulator [28]. It is platform independent and features a whole development environment for robot software including an editor and an API [explain term?](#) for inter-robot communication. Webots supports many programming languages and several standard robots and sensors out of the box. It is also able to simulate multiple robots and provides a ROS and Matlab [introduce Matlab?](#) interface. Webots was used in a RoboCup Soccer simulation league [29].

3.1.3 USARSim

*USARSim*³ is a 3D simulator developed for urban search and rescue scenarios [7]. It [was](#) evolved to be able to simulate other domains too. Therefore, the abbreviation USARSim now stands for “Unified System for Automation and Robotics Simulation” instead of the previous “Urban Search and Rescue Simulation” [6]. It is platform independent and free of charge for research and education. The advantages of USARSim are the graphical realism of the Unreal engine⁴ and the physical realism by the PhysX engine⁵. USARSim also provides an interface to ROS [25] and is able to simulate multiple robots.

USARSim is used as a basis for the RoboCup Rescue Simulation League we also present in section 3.2.2.

3.1.4 SimSpark

*SimSpark*⁶ is an Open Source 3D simulator [5]. It was developed by the RoboCup community for the RoboCup 3D Soccer Simulation and has been used there since 2004. Therefore SimSpark is able to simulate multiple robots and specialized on the NAO as soccer robot. There are several improvements and new features of SimSpark [39,45], such as visualization of agent intentions, realistic servo motors for the NAO and better support of heterogeneous robot teams.

3.1.5 Robotino Sim Professional



*Robotino Sim Professional*⁷ is a 3D simulator for the Robotino developed by its manufacturer Festo. It is a commercial software and only usable on Microsoft Windows. Furthermore, it is limited to the Robotino and the default sensors the Robotino is shipped with.

²<http://www.cyberbotics.com>

³<http://sourceforge.net/projects/usarsim>

⁴<http://www.unrealengine.com/udk>

⁵<https://developer.nvidia.com/physx>

⁶<http://simspark.sourceforge.net>

⁷<http://www.festo-didactic.com/int-en/learning-systems/software-e-learning/robotino-sim-view/robotino-sim-professional.htm>

3.1.6 Choice for Gazebo

We already presented Gazebo and some of its advantages in section 2.4. Here, we explain why we have chosen Gazebo instead of an alternative simulator we described above.

The stage simulator is well suited for multi-robot systems and comparatively fast and easy to use. However, the restriction to two dimensions is a problem. We want to simulate vision components to be able to test our system as a whole and under more realistic conditions. We also want to be extendable for future changes of LLSF or the use of the simulator in **an other** domain, such as the RoboCup @Home league.

Webots is a proven simulator with many features, but has **the same problems** as Robotino Sim Professional. ~~On the one hand~~, both simulators are commercial and on the other hand, both are no Open Source software. Therefore, it can be difficult to expand the simulation how we need it.

SimSpark is not so well suited as Gazebo because it and the community behind are mostly specialized on the RoboCup Soccer Simulation. Gazebo is used in large variety of domains and has a bigger community. Gazebo is well **founded** by the Open Source Robotics Foundation⁸ and Willow Garage⁹ and there also are many plans to develop Gazebo further¹⁰. Therefore, Gazebo is likely to become even more important in the future.

An other important argument for Gazebo is that it was used at KBSG before. It was used as a simulator for MSL [4] and for scene reconstruction for fault analysis [23]. We will present both applications later in this chapter.

There are only few disadvantages of Gazebo. A disadvantage is that Gazebo **can not** handle a large amount of robots. The complexity of the simulations limits the simulation speed when using multiple robots. The number of robots to simulate at a reasonable speed is in the order of ten [24]. This can become a problem if the simulation runs on a slow computer or there are more robots to simulate at the same time. However, these disadvantages have a small impact on this thesis because we use only three robots in **LLSF**.

3.2 Simulations



3.2.1 Virtual Robotics Challenge

The *Virtual Robotics Challenge (VRC)* is a competition by DARPA¹¹. The goal of the competition is to solve challenging tasks with a humanoid robot in a simulation. VRC is the first part of the *DARPA Robotics Challenge (DRC)*¹². DRC aims to spur the development of robots that can operate in a disaster scenario if the situation is too dangerous for humans. An example for such a scenario is the disaster in the Fukushima nuclear power plant after the tsunami in March 2011 [41]. The developed robots should be able to operate

⁸<http://osrfoundation.org>

⁹<http://www.willowgarage.com>

¹⁰<http://gazebosim.org/wiki/Roadmap>

¹¹DARPA is the Defense Advanced Research Projects Agency of the USA.

¹²<http://www.theroboticschallenge.org>

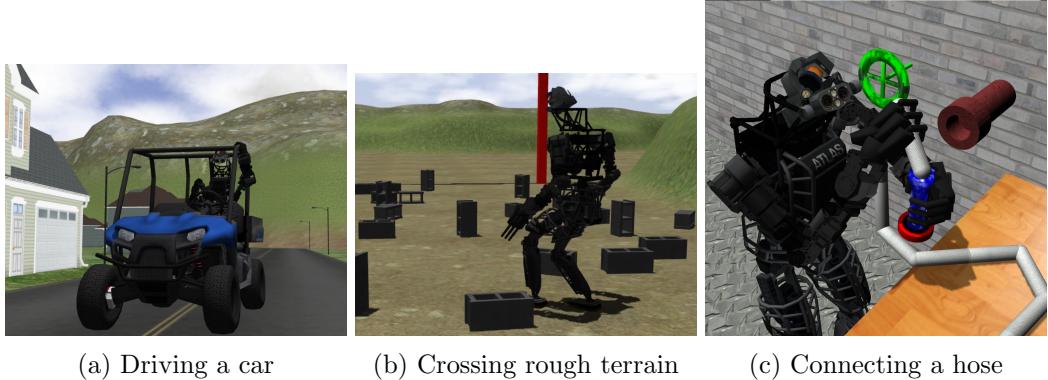


Figure 3.1: Tasks of the Virtual Robotics Challenge [2]

in environments made for humans, even if the environment is damaged, and to use tools made for humans, such as screwdrivers and cars. During the competition, the robots act **partly autonomously** and are supervised by human instructors. For the challenge, DARPA provides six humanoid robots. The Robots are called *ATLAS* and are developed by Boston Dynamics. The six best teams of VRC receive a ATLAS robot for free. Therefore, ATLAS is the only robot simulated in VRC. However, the participating teams can also build their own robots. VRC consists of three different tasks [12] showed in Figure 3.1. In the first task, the robot has to walk to a car, enter it and drive along a street. The chassis of the car consists of a framework to simplify the entry. On the road, there are obstacles the robot has to avoid. The second tasks tests the walking capabilities of the robot. The robot has to cross slippery and irregular terrain to test balancing and a terrain with obstacles to test perception and footstep planning. The last task is about manipulation. The robot has to connect a hose to a pipe by **plugin** it in and screwing it down. Afterwards, it has to open a valve. All tasks have randomized parameters, such as the position of obstacles and goals.

VRC is related to this thesis because it also uses the Gazebo simulator [1]. Therefore, it shows what Gazebo is **capable of and how important a simulation** is for the development and research of cutting-edge technology. Although the technology fostered by DRC is important and useful without doubt, it seems questionable what DARPA as a military agency will use this technology for.

3.2.2 RoboCup Simulation Leagues

In the RoboCup competition, there are different simulation leagues. On the one hand, there are the 2D and 3D soccer simulation leagues and on the other hand there are two rescue simulation leagues. In all of those leagues, multi-robot coordination is an important field. This is not surprising because it is much simpler to benchmark multi-robot strategies in a simulation. There is no need to operate real hardware and difficult low level control **and sense** problems, that are not in the focus of the competition, can be simplified or left out.

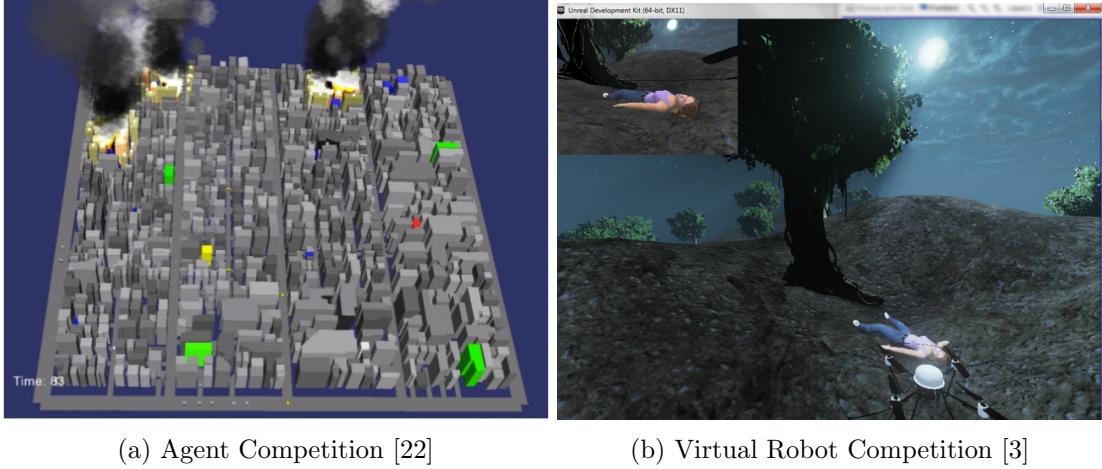


Figure 3.2: Rescue Simulation Leagues

The *Rescue Simulation League (RSL)* aims to benchmark intelligent software agents and robots in a disaster scenario [3]. RSL is separated into two leagues with focus on different scales. Figure 3.2 shows snapshots of both simulation. The *Agent Competition* is about a large scale disaster in a city with multiple robot teams. The *Virtual Robot Competition* is about finding victims in a burning house or limited outdoor area with a team of eight robots and one human operator. The operator can give high level commands, such as the area where to look for victims, and is needed to verify the observations of the robots. So, the robots should find and approach victims autonomously and the operator has to confirm the find. The task of the agents include victim-detection, autonomous generation of maps, navigation and multi-agent coordination. In the Agent Competition, there is no realistic robot control and perception necessary. The focus is on the coordination of many **heterogeneous** agents and taking high level decisions. There are teams of fire brigade, police and ambulance, each with up to 30 simulated agents. Each agent acts autonomously and can communicate with other agents. The tasks of the agents include exploration, scheduling and planning in cooperation with other agents and building of agent teams (e.g. to fight fires more effectively).

The soccer simulations of the RoboCup are similarly split in two leagues. In the *2D Soccer Simulation League*, 22 agents in two teams play soccer in a two dimensional environment. A single server called Soccer Server simulates and controls the game with its physics, the actions of the agents and the perception of the agents. Each agent is an autonomous program and communicates with the soccer server to receive noisy sensor data and send action commands to influence the simulation [38]. The main challenges of the 2D Soccer Simulation League are planning the actions of each agent when playing in offense and reacting on the opponent and predicting his movement when playing in defense. The *3D Soccer Simulation League* features a more realistic simulation. This league fully simulates nine NAO robots per team. Therefore, the low level control and perception are an important part of the challenge [26]. This is an important opportunity for the teams

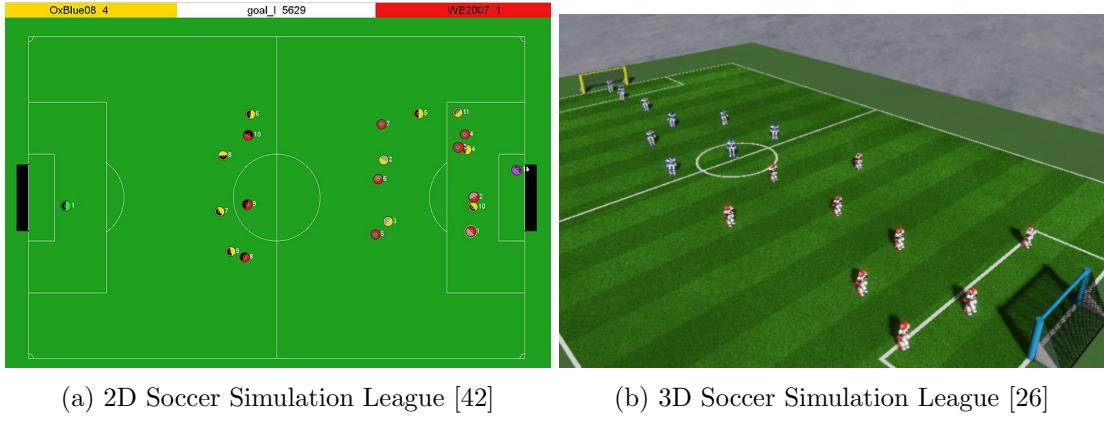


Figure 3.3: RoboCup Soccer Simulation Leagues

participating in **SPL** to test their approaches first in the simulation because **SPL** also uses the NAO as robot platform. The communication between agents and the Soccer Server in this league is similar to the 2D league. The rules of the league are inspired by the FIFA football rules but have some reasonable extensions [35]. For example a goal directly **from** the kick off is not allowed and if too many robots are in a small area around the ball, the position of some robots is reset.

All simulations we have looked at in this section are similar to the simulation we developed for LLSF. The simulations are important for benchmarking multi-agent systems because the system can be tested with low effort in comparison with real multi-robot systems and some details, such as low level control and perception, can be left out. Furthermore, the simulations have in common that the evaluation of the whole system can be done by looking at the results and progress of the simulated games. Especially by 2D Soccer Simulation teams, this is used to do reinforcement learning [16, 27]. Similar as it is possible to improve a real multi-robot system in SPL by improving the performance of the multi-robot system in the 3D Soccer Simulation League [44], we also want to improve our real system by using a simulation.

3.2.3 Scene Reconstruction for Fault Analysis

Some work was already done with Gazebo and Fawkes. Bastian Klingen developed a scene reconstruction for fault analysis in his diploma thesis [23]. The scene reconstruction was primarily made for a mobile robot with a **Microsoft?** Kinect and a laser range sensors for perception and a gripper arm for manipulation. The task of the robot was to **grep** a colored cup on a table. The scenario and the reconstruction are shown in Figure 3.4. Because this gripping task involves many components and often fails if a single component fails, a tool was needed to analyze unsuccessful attempts afterwards. This tool reconstructs the scene with the position of the robot, its sensor data and world belief. Therefore the movements, sensor data and belief of the robot have to be logged while performing a grep. The logging was also done with MongoDB because of the **needed speed**. Gazebo was

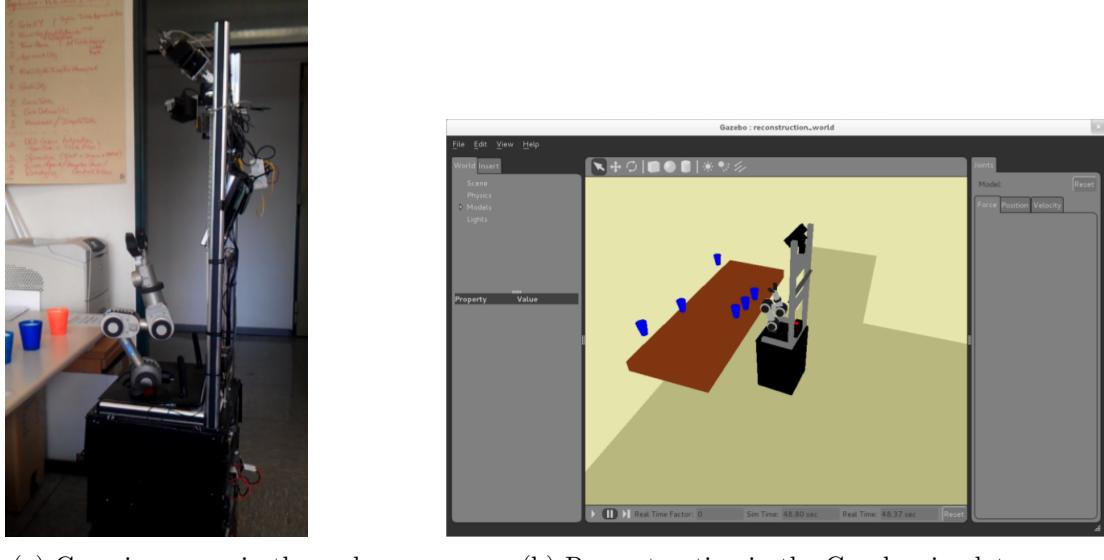


Figure 3.4: Scene Reconstruction for Fault Analysis [23]

used to visualize the perception and belief of the robot to reconstruct the scene. Fawkes was used to control the robot, to log the needed data and to control Gazebo and read the log while reconstructing the scene. Together with the scene reconstruction, Klingen provided a tool to analyze faults to find components that causes the faults. Therefore, he constructed a dependency tree of the components and ordered it in a data-information-knowledge hierarchy.

To establish the communication between Fawkes and Gazebo, Klingen developed a Fawkes plugin that provides the communication objects of the Gazebo API as an aspect. In this thesis, we use this plugin and expand it according to our needs. **Similar** but not so sophisticated as in the thesis by Klingen, we want to provide a possibility to reconstruct faults to find the causes. We do not record the perception of the robots in the simulation, but we record the movement of all simulated objects and the high level decisions of the agents which can be used to derive the belief of the robot. The motion of the objects in the simulation can be recorded by Gazebo and the agent decisions by logging the results of our rule-based production system CLIPS.



3.2.4 Simulation Environment for the Middle Size League

An other work with Gazebo and Fawkes developed a simulation environment for **MSL** [4]. This simulation environment became necessary because the field size and the amount of robots per team was increased in MSL. Therefore, testing became more difficult. The work used an early version of Gazebo and Player as interface between Fawkes and Gazebo. On the one hand, it showed that Gazebo is capable of simulating complex robot components that cause problems in other simulators. This was shown for omni-directional wheels and an omni-directional camera. Both devices are non-trivial to simulate and often used

in MSL. On the other hand, the work proposed the idea of *multi-level abstraction*. If a robot software contains separate components for steps that are based on each other, it is useful to simulate not only the hardware level, the lowest abstraction level, but also higher abstraction levels. For example if the robot software includes a component that reads an image from a webcam and a component that computes the state of a traffic light from this image, the simulation can provide the simulated image as well as the information about the traffic light. A simulation with multi-level abstraction is able to switch between different abstraction levels. This can be useful to test components on a higher level independent of low level components which can introduce an error or are not finished. Multi-level abstraction has the additional advantage that the components of a higher abstraction level often can be simulated with less computational effort. This makes it easier to run the simulation on a slow computer. However it is not always reasonable to introduce multiple abstraction layers, because some components, such as a collision avoidance, can not be simulated easily. In this thesis, we also use multi-layer abstraction to be able to test high level components more individually.

3.3 Multi-Agent Strategies

In this section, we present our current high level agent approach, which we want to evaluate and improve during the thesis. We also present some advanced and attractive multi-agent strategies. On the one hand, our simulation should be able to simulate and evaluate these approaches as well and we might want to use one of these approaches in the future because our current one has some limitations.

3.3.1 Incremental Task-level Reasoning

Our current implementation of the high-level agent uses the CLIPS rules engine. Our implementation is based on the idea of incremental task-level reasoning [33]. This means that the agent takes the next best possible action whenever the robot is idle. Simplified, every action is represented by a CLIPS rule. The action is possible if the antecedent of the rule can be matched by the fact base. The consequent of the rule includes the execution of the action itself and changes to the fact base to remember the current situation. If new perception data is available for the agent or the execution of an action finished or failed, this is asserted as a fact and can therefore cause in the application of some rules to update the belief of the agent in the fact base or to execute the next best action. If more than one action is possible, the action with the highest priority is executed. simplify sentence? The incremental reasoning approach with CLIPS has several advantages. Actions and handling perception can easily be represented by rules which work with the current belief of the agent. The approach is computationally inexpensive, because no costly planning is needed, and it is easy to cope with incomplete knowledge because the agent just takes the next best action and updates the belief if new information is available. 2012 necessary? In

the LLSF competition of 2012, incomplete knowledge was a part of the problem because the robots had to find out the types of the machines by trying how they react on different input pucks. The refbox, which was introduced in 2013, now provides the information about the machine types. However, dealing with incomplete knowledge is still important, especially if the agent recognizes that it made a mistake and the world belief is partially wrong.

Until the RoboCup 2013 we have been using only two robots. For coordination of these two robots, we use a **role based** approach with additional resource locking. Every agent has a specific role, which determines for which tasks the agent is responsible for and which machines it may use. We have one role for an agent which only produces P3 pucks and delivers them. This agent continuously provides easy points because P3 is the simplest product, which needs only one resource puck (see Figure 2.2). In the following, we call this role the *P3-role*. A second role is responsible for producing more complex products, the P1 and P2 pucks. This role can provide a large amount of points, but is more risky because of the higher amount of intermediate steps. We call this role the *P1P2-role*. Whether the P1P2-role produces P1 or P2 pucks is determined by the distance between the needed machines to the machine for P3 products. This spacing is necessary because the different robots drive independently and crossing paths can cost much time. Most of the objects in LLSF, such as machines and the delivery zone, can only be used by one robot at a time. Therefore, we implemented a master-slave resource locking mechanism for the agents. If an agent decided to drive to a position, he requests the lock of this position and waits till he receives the lock. Then, he drives there and frees the lock when he leaves the position. The roles are also used for multi-robot coordination in the exploration phase. The roles determine which machine an agent investigates first. After the first machine, the agents continue the investigation of the other machines in the same cycle till all machine types are identified. The agents can pass each other on the cycle.

It is easy to see that the current approach has limitations which **of** **uct** a significantly better performance. The static roles do not allow a tight cooperation between the agents. For example, a tighter cooperation would allow us to produce P1 and P2 pucks faster because the agents could split the work. An other problem of the static role approach is that the agent behavior often can not take the situation into account. For example if there is not enough time to produce an other P1 or P2 puck or there are no more P1 or P2 pucks ordered, the P1P2 role would still start another production.

There already is a less sophisticated **simulation**, which is able to test if the high-level agent basically works. This simulation is implemented within the CLIPS-agent and provides information about the execution of actions and perception results in a trivial way. A few seconds after every action is called from the agent, the action is reported as successful. The perception results match exactly the ground truth published by the refbox. This is useful to test the behavior of the agent in the best-case scenario. Though, this simulation is only useful to test agent decisions and can therefore not indicate many important real world problems. Furthermore the simulated situation is not graphically visualized and

therefore difficult to evaluate. Testing and evaluate multi-robot coordination is also not possible in this simulation because every agent uses an own simulation and the different time-spans for different actions can not be taken into account.

3.3.2 Marked Based Strategies

more task allocation strategies with e.g. dynamic role assignment?

The simulation should be able to test and compare complex multi-robot coordination strategies. An example of such a strategy, which is attractive for our needs and used for orientation in the design process of the thesis, is *Murdoch* [14]. Murdoch is an auction-based task allocation strategy. It solves a special instance of the *Optimal Assignment Problem*. The Optimal Assignment Problem is to assign n weighted jobs to m workers with non-negative skill ratings $h_{i,j}$ for each worker-job combination. Each worker is capable of doing one job at a time and each job can only be done by one worker. The task is to find the assignment which optimizes the performance, taking into account the weights of the jobs and the skill ratings of the workers to the jobs. The Murdoch method was especially developed for multi-robot scenarios. Therefore, it was designed to be able to handle robot failure and communication message loss. If a robot discovers a new task, it becomes an auctioneer and publishes a broadcast message to inform other robots about the task. All robots that are capable of doing the task calculate a metric of how well they probably will perform on the task. The metric is sent as a bid to the auctioneer. Finally, the auctioneer decides after a predefined time interval which robot gets the task and informs this robot. After the allocation, the auctioneer observes the progress of the task and starts a new auction if the robot assigned in the first place fails. This method is to some degree decentralized because the different auctions and metric calculation are not executed by a single robot. However, this approach is not optimal for a set of tasks because every auction only considers a single task. [14] showed that the method performs well in different multi-agent tasks, such as cooperative manipulation.

Murdoch allows a dynamic and situation dependent task allocation and is especially well suited for heterogeneous robots with different abilities. It is also a useful method to allow reallocation of tasks. An agent which is executing a tasks and has already completed a part could change his task if a new task is more important. The agent could simply include the penalty, that it has to cancel a task, and the advantage, that it has from completing the previous task, in his bid for the new task. An example in our domain is a robot which is carrying an intermediate product S1 for the production of a new P1. If a S1 is needed at an other machine with higher importance, the robot can change the task. The cancel of the old task is no problem because the agent can just start a new auction for the old task. Disadvantages of Murdoch are the high demand of communication and the difficulty to detect failures.



Chapter 4

Approach

In this chapter, we describe the approach of this thesis by presenting the main ideas to reach our goals for the simulation in section 4.1. In section 4.2, we present the architectural approach.

4.1 Goals and Approaches

Realistic simulation: The **realism** of the simulation is an important goal of the thesis. A more realistic simulation allows better testing because the simulation is more similar to the reality. Therefore, more problems of reality can be simulated. The **reality** of the simulation has many different aspects. The first group of aspects are about the realism of the sensor data. There are some sensors that are easy to simulate, such as distance sensors, bumpers and gyroscopes. Others, especially cameras, are more difficult to simulate realistically. The choice of Gazebo with ODE and Ogre for the visual appearance already allows us to simulate a wide range of sensors realistically. An other aspect of the simulation-realism is noise in the sensor data. For all metric sensors, we simulate this as Gaussian noise with the calculated value as mean and a configurable variance. The second group of aspects are about the realism of the physical environment. Objects have to behave in the simulation and the reality in a similar way. This is especially important for robot movement and manipulation tasks. Here, Gazebo with ODE also provides high realism out of the box. Nevertheless, it is important to find good physical parameters for the simulated objects. Examples of those parameters are the mass and coefficients of friction. An other important aspect of simulation-realism is that the simulation should not introduce new problems which do not occur in reality. Such a problem, which occurred in the development of the thesis, is that the simulation ran slower than the system time although the robot software used the system time.

Different levels of simulation: **Beside a simulation, which is so realistic as possible, it is also useful to test with a more abstract simulation.** This allows testing the optimal case without sensor noise or without using low level components, such as localization, if those produce new errors or are not finished **yet**. To be able to simulate on different levels, we

use the multi-level abstraction approach [4] presented in the chapter 3. We use multi-level abstraction for sensing and for **actuating**. How we use multiple abstraction levels is shown in the next section about the architecture.

Compatibility with original robot software: We want to achieve that the robot software runs in the simulation in the same way as in reality. This is important because otherwise it would result in additional effort to keep the robot software running in the simulation and this effort can cause more difference between simulation and reality. In the thesis, the simulation should use the same **interfaces** as the real components that are simulated. In Fawkes, this is easy to achieve because the interfaces between components are well defined and components using an interface do not recognize whether the interface is provided by the simulation or a real component.

Efficient testing: We want to make the use of the simulation as efficient as possible. To achieve this, we provide scripts which automatically start the full simulation with all needed programs. Without **this** scripts, it would take much time. For a full simulation of an LLSF game, it is necessary to start Gazebo, the Refbox, a controlling Fawkes instance and, for the Robotinos, three times Fawkes, **Roscore and Movebase**. Each program-instance has to be started with correct parameters. An other approach we use to increase the efficiency is the feature to load different configurations and setups. For example, the scripts are able to load the simulation with different numbers of Robotinos, abstraction levels and simulation environments. Loading different configurations for the robot software is a feature of Fawkes and useful for us. We also integrated this in the scripts. We also provide the possibility to draw objects into the simulation. This makes it possible to visualize belief and intention of a robot to identify mistakes or ways to improve the system [39].

Multi-robot system evaluation: An important part of this thesis is the evaluation of multi-robot systems. Here, the features we already mentioned in the previous paragraph are especially useful because the testing effort (e.g. to setup the simulation or analyzing the coordination between robots) often scales with the number of robots. To evaluate the performance of the multi-robot system faster without having to observe the simulation all the time, we provide the possibility to run multiple simulation runs, in our case runs of LLSF games, automatically. With this feature, the simulation can run, for example, 20 times over night. To analyze executed simulation runs, we keep statistics of each run. For our LLSF domain, we keep the amount of achieved points with a detailed list of all actions that provided points with the time. These statistics can easily be extended by the amount of collisions between robots, waiting time for resource locks or other useful measurements. Sometimes, it can happen that single simulation runs have a very different result. To find the reason for this result, we keep log files of each run and also record the simulation itself. With this record, the simulation run can be reconstructed. The record contains the position and movements of all objects in the simulation. Here, it is also useful to draw additional information, such as the localization of the robots, in the simulation to be able to analyze faults without having to look in the log files. Automated simulation runs also allow the comparison of different configurations of the multi-robot system. The

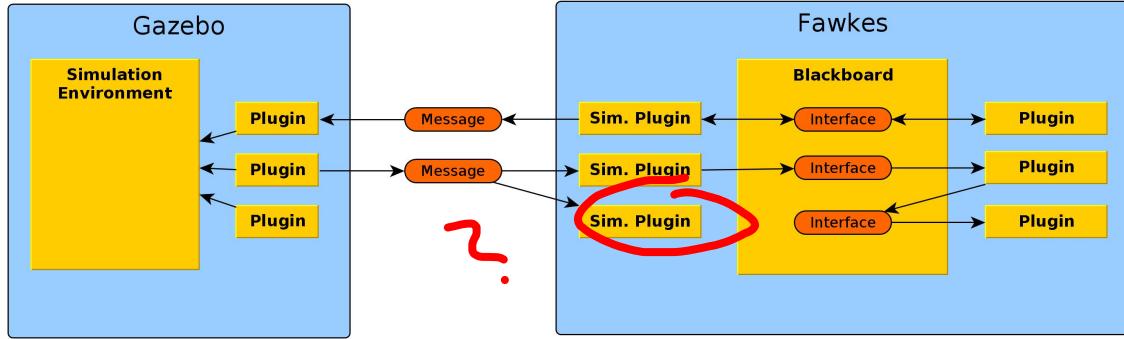


Figure 4.1: Architecture of the simulation

automation script can be started with a number of configurations to test. This can be useful for finding the best performing role combination or parameters such as thresholds.

Expendability and flexibility: An essential criterion of a good simulation is the expendability to adapt to future changes. On the one hand, there will be changes to the Carologistics Robotino and to LLSE. These changes have to be easy to implement in the simulation, otherwise the simulation would not remain useful. On the other hand, it is attractive to use the simulation also in other domains, such as RoboCup @Home. To achieve the expendability of the simulation, we provide a framework for simulated devices in Gazebo and Fawkes. Furthermore, we focus on developing small modules that are exchangeable and reusable. In Gazebo, new modules can easily be added to robot and world plugins. In Fawkes, it is easy to implement a new plugin which provides the wanted features because the plugin can use the provided Gazebo aspect. In addition, a detailed documentation and example plugins allows other developers to easily extend the simulation. **TODO: wiki plugin dev!**. The simulation should also be flexible to adapt to small changes. Therefore, we provide several configuration files for the simulation environment, for the simulated objects and robots and for plugins in Gazebo and Fawkes. **Gazebo config**

4.2 Architecture

4.2.1 Simulation

The basic structure of the simulation is shown in Figure 4.1. On the **one** side, there is the Fawkes robot software framework we want to run in the simulation. On the other side, there is the simulator Gazebo. Roughly, the simulation is composed of a simulation environment, which handles the physical and visual simulation of the environment with all included objects, and plugins associated to the world and all models with some kind of behavior. There are **plugins** instances for the sensors and actuators of each robot as well as plugins that control the world to, **for example**, set machine lights. At this point, Fawkes can be seen as a composition of plugins, which are used on the real robot system, simulation plugins, which communicate with the simulation and exchange original sensor and actuator plugins, and the blackboard. The blackboard manages several interfaces which are used

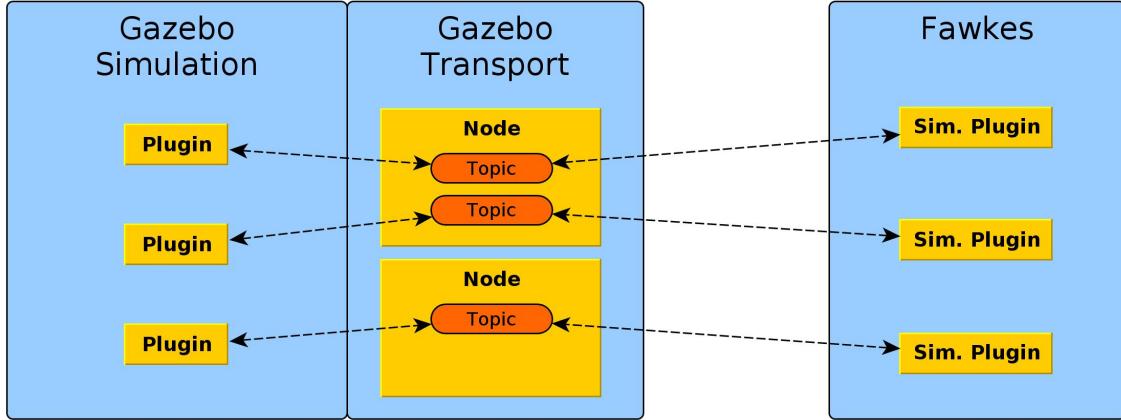


Figure 4.2: Communication between Fawkes and Gazebo

for communication between Fawkes plugins. The Fawkes simulation-plugins send actuator messages to the corresponding Gazebo plugins and receive messages from sensor-plugins in Gazebo. This architecture has the advantage to be flexible and extendable. To add a new sensor or actuator to the simulation, it is sufficient to create or modify a Gazebo plugin and a Fawkes simulation-plugin to provide the corresponding interface. Furthermore, the architecture is flexible enough to allow multi-level abstraction as we see later in this section. It is also easy to change plugins on either side. It is even possible to use the Gazebo simulation with an other robot operating system than Fawkes. The other system just has to send and receive the same messages as our simulation-plugins.

4.2.2 Communication Fawkes-Gazebo

The communication between Fawkes and the Gazebo simulation has a specific structure to organize the distinction between multiple robots and different sensors and actuators. Figure 4.2 shows this structure. Fawkes simulation-plugins and Gazebo plugins communicate over a message-transport system. In our case, this system is embedded in the Gazebo Transport API. In the message-transport system, there are different nodes which act as communication channels. There is one node for each simulated robot and for the simulated world. **The topics in a node represent what the messages that are send on this topic are about.** Each plugin can listen to or send on the topics in a node. For example, there are topics about laser data and motor commands. This architecture is extendable because it is easy to add new nodes or topics. It is flexible, because the communication through a topic in a node is a many-to-many relationship, and it is comfortable because instances of plugins in different Fawkes instances can listen to the same topic and get data from different simulated robots because the plugins listen do different channels.

4.2.3 Multi-level Abstraction

Figure 4.3 shows how multi-level abstraction fits in our simulation architecture. We choose a simple example about the localization with laser data. In Figure 4.3a, there is the system

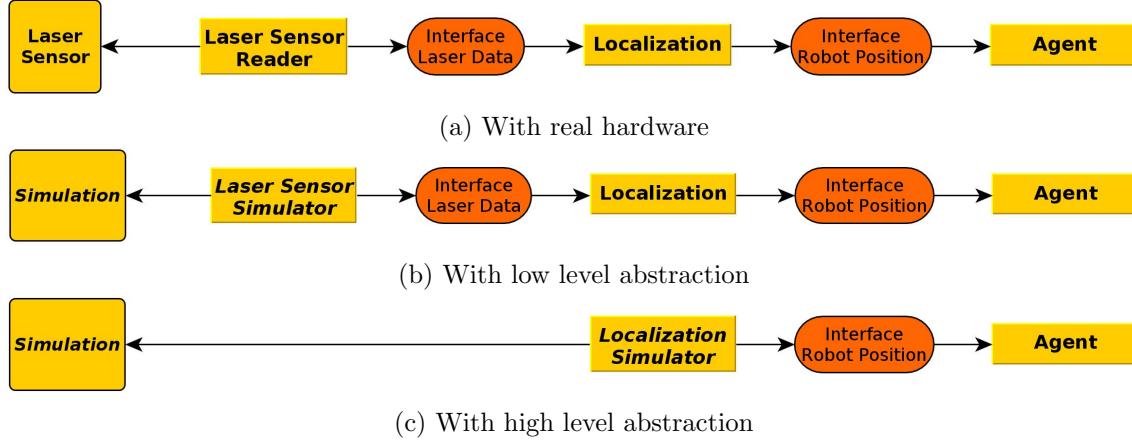


Figure 4.3: Example for multi-level abstraction



as it is used in the real application. There is the laser sensor hardware, a plugin which reads out the sensor and publishes the laser data in an interface, a localization plugin which uses the laser data interface to determine a robot position and to provide the position in an other interface. Then, the robot agent uses the position information from the interface. Figure 4.3b shows the system in the simulation with low level abstraction. The hardware is replaced by the simulation and the laser sensor reader by a simulation-plugin which gets the laser data from the simulation. This simulation-plugin provides the same interface as the original plugin. An other possibility with high level abstraction is shown in Figure 4.3c. Here, the localization plugin is replaced by a simulation-plugin which simply looks up the position of the robot in the simulation and writes it in the interface. The agent can now be simulated with ground-truth position data and without using of the original localization plugin. An example for multi-level abstraction for actuators could be the movement of a robot. It is possible to simulate the motors with motor commands from an interface or the motion of the robot by applying the motion command in an interface directly to the simulated robot.

Chapter 5

Implementation

In this chapter, we describe how we implemented the simulation. Section 5.1 presents the various components we developed by describing what their task is, what we noticed during the implementation and why we implemented it this way. **module dependencies extra?** In section 5.2, we describe the dependencies and interaction between the modules we developed and in section 5.3, we present the improvements of the multi-agent system we implemented during the thesis.

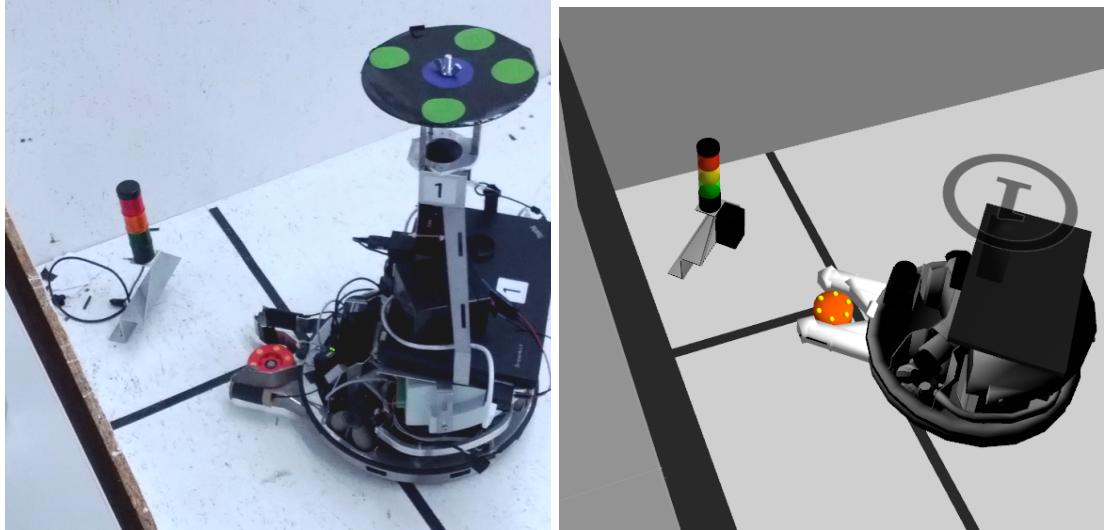
5.1 Components

5.1.1 Gazebo Models

In order to simulate the LLSF environment, we need to model all objects appearing in this domain. The models developed in this thesis are available at <https://github.com/zwilling/llsf-models.git>. Here, we present our simulation models and why we modeled them this way. Figure 5.1 shows a comparison between a real LLSF scene and the same scene in the simulation. In this comparison, the most important objects of the simulation can be seen. In the following, we describe each model in detail:

LLSF Field: The model of the LLSF field has a rather simple structure. It consists of a ground plane and four side walls. For the visual appearance and possible future changes, the field has a visual representation with lines and colored areas just as the real field. The machines are not realized as a component of the field and are attached to the field in the description of the simulation world.

Machine: The model of the machines matches their real counterpart structurally. Though, it is challenging to represent the lamps consisting of colored Plexiglas and a LED **abbreviation?** inside. We decided to use simple colored cylinders in the simulation. If the lamp is turned off, we use a dark and slightly transparent color and, if the light is turned on, we use a bright color. This looks reasonable in the simulation and the images from the simulation are sufficient for our vision plugin which determines light states of the machines. The vision plugin measures the brightness at the position where it expects the machine-lamp to be and it even was not necessary to change brightness thresholds. In Figure 5.1a,



(a) A Robotino delivers a puck to a recycling machine.
(b) The same situation in the Gazebo simulation

Figure 5.1: Comparison of the real scene and the simulated scene in Gazebo

the black RFID box at the front of the machine is missing because we currently do not have the RFID readers.

Puck: The visual appearance of the puck model can be seen in Figure 5.1b. Physically, they are represented by a single cylinder. The difficult part was to find good friction parameters for the surface of the cylinder. On the one hand, it should be easy to slide the puck across the floor. On the other hand, the puck should stay inside the gripper of the Robotino when the Robotino turns. If the friction parameters are too small, the pucks move outside the gripper during turning because of the centrifugal force. [mention other solution?](#)

Robotino: The model of the Robotino is the most complex model because it holds different sensors, the casing and the puck gripper. It is also the most important one because it represents the robot we want to simulate. The major visual difference between real world and simulation is caused by the missing framework on top of the Robotino and the visual appearance of the puck gripper. Both is not important because we do not detect other Robotinos with a camera. We detect them with the laser sensor. Therefore and because of the manipulation with the gripper, the physical representation is more important. [collisions picture?](#) The physical model of the Robotino is composed of the gripper and two cylinders, one on the ground to represent the basic circle of the Robotino and one on laser and machine height. The cylinder on laser height is smaller and shifted back so that it does not block the laser sensor and it fits better to the real shape. The gripper has in the simulation a similar shape as the real one. We needed to assign higher friction parameters to the inside of the gripper than to the outside because in reality the puck slides into the gripper if the front side of the gripper and stays in the gripper while turning. Because we were not able to simulate this with a single set of friction parameters, we modeled an

additional geometry for the inside of the gripper with higher friction parameters. Originally, we intended to add wheels to the physical design for the final version. However, the omni-directional wheels caused an abnormal physical behavior in the simulation. The wheels irregularly bounced on the ground because of gravity and collision. Because we could not solve this problem in an arguable time and there is no important advantage, we decided to stay at the simple model without wheels. We only lose the possibility to physically simulate odometry with a realistic error. Therefore we introduced an artificially odometry error in the Gazebo plugin for the Robotino. **Simulation World:** The world file simply combines the developed models to an LLSF environment. Our world consists of the LLSF field, 16 machines with configurable orientation, 20 pucks and three Robotinos.

5.1.2 Gazebo Plugins

In order to control the simulation environment and models created before, we need Gazebo plugins. Each plugin belongs to an object in the simulation, such as a robot, a sensor or the simulation world. We developed two main plugins, one for a Robotino and one for the simulation world. Both plugins are composed of smaller reusable modules, which can easily and dynamically be turned on and off. [refactoring?](#)

World Plugin Our Gazebo plugin for the simulation world is called *llsf_world*. It manages the LLSF field, collects simulation data which is needed by several plugin instances and sends general simulation information to Fawkes. An important component of the *llsf_world* plugin is the simulation data table. It contains general data about the simulation and can be used by all plugins. In our case, the table contains machine locations, machine light states and puck locations. This simple data table allows decoupling information gathering modules, storage and modules which use this information. This is useful to make the simulation flexible and expendable for future changes. [race conditions to real problem?](#) We implemented a module which receives messages about puck states and light states of the machines and writes it into the data table. An other module uses this data in the data table to apply the light state to the visuals of the lamps in the simulation. Furthermore, there is one plugin, which writes the position of the pucks into the data table. The RFID readers are simulated by an other module which uses the puck and machine positions. The results are stored in the data table and then sent to the Refbox. We also implemented a module to remove delivered pucks from the field. In reality, the referee does this task. There is also a module which sends the simulation time to Fawkes.

Robotino Plugin The plugin for the Robotino robot mainly consists of sensor and actuator modules. We have implemented two actuator modules. One simulates the motor. It receives motor commands from Fawkes and applies the motion to the Robotino model. Because setting the velocity in Gazebo only means to apply an corresponding impulse to the model, friction of the model with the ground leads to a resulting velocity which is smaller than the original intended velocity. Therefore we increase the velocity set to

the model so that the resulting velocity is similar to the intended one. The other actuator module operates on a higher abstraction level. It keeps pucks inside of the gripper if the Robotino is turning. This module is optional but useful because of the difficulty to simulate the puck in the gripper physically correct. The modules we implemented for the sensors also can be separated into low-level and high-level abstraction. On the low abstraction level, we developed modules for a gyroscope, a laser range finder, a webcam, a infrared distance sensor to detect pucks in the gripper and digital optical sensors on the sides of the gripper. Most of these modules use sensors defined in the Robotino model. On the high abstraction level, we developed modules for ground truth localization, machine light signal detection and puck detection. The ground truth localization can be used in Fawkes in exchange of the amcl plugin and as a basis to simulate motor odometry. The machine light detection and puck detection both use the simulation data table so that the multiple Robotino plugin instances do not have gather the information separately.

Native Plugins [caption ok?](#) visuals etc spawnen

5.1.3 Fawkes Plugins

The Fawkes plugins developed in this thesis provide access to the simulation in Fawkes. In order to identify plugins for the Gazebo simulation quickly, we named them with the prefix *Gazsim*. We divided the plugins into two groups. The first group of plugins generally cover the access to the Gazebo simulation, sensors and the Robotino robot without limitation to a specific domain or task. All these plugins can be found in the simulation branch of the Fawkes repository¹. The second group of plugins are needed for the simulation of the LLSF environment. They can be found in our LLSF repository² which includes the general Fawkes repository. The access to the LLSF repository currently is limited because it contains new code we want to take advantage of in the LLSF competition.

Common Gazebo and Robotino Plugins

Gazebo: The plugin called *Gazebo* provides general access to the Gazebo Transport API which is needed to communicate with the simulator. Therefore, it provides a Fawkes aspect also called *Gazebo*. After connection to the Gazebo simulator, the aspect gives access to two communication nodes. One node is responsible for the communication with the simulated robot Fawkes should control and has to be initialized with the name of the robot in the simulation. The other node is responsible for the communication with the simulation world and therefore used for robot independent information environment information. It is also possible to spawn new models and visuals through this node. This is useful for controlling of the simulation and visualizing tasks to show, for example, the robot intention. [bei klingen noch nicht multi-roboter faehig?](#)

Gazsim-Robotino: The *Gazsim-Robotino* plugin exchanges the Robotino plugin which

¹<http://git.fawkesrobotics.org/fawkes.git>

²<http://git.fawkesrobotics.org/fawkes-robotino.git>

connects Fawkes with the hardware of the Robotino robot. Therefore our plugin provides the same interfaces as the original plugin. The original plugin provides motor and sensor features, each with an own interface. Because both are combined in the original plugin, we also combine these two features in the simulation plugin. However, we developed separate modules for these two features to improve re-usability. The module responsible for the motor sends the wished motor movement to Gazebo and receives the position of the robot in the simulation to compute the odometry. Because sending many Protobuf messages has been found to be computationally costly, we only send messages if the wished movement has changed. Here we also introduced an error to the odometry which occurs more strongly when the speed changes quickly. As in reality, the odometry also changes if the robot drives against an obstacle and does not change its position. **important because driving against machine?** The module responsible for the sensors of the Robotino receives information from the simulated gyroscope and distance sensors of the Robotino.

Gazsim-Laser: The *Gazsim-Laser* plugin exchanges the laser plugin and provides data from a simulated laser range sensor. The plugin converts received data into the in Fawkes used format and writes it into the laser-interface. **difference 5m-Nan?**

Gazsim-Localization: The plugin called *Gazsim-Localization* receives the position of the robot in the simulation and publishes this information in the corresponding interface. Normally, this information is provided by plugins, such as amcl (Adaptive Monte Carlo Localization). Therefore this plugin operates on a higher level of abstraction. It uses ground truth information to allow testing high level components without error in the localization.

Gazsim-Webcam: The *Gazsim-Webcam* plugin receives a camera image from the gazebo simulation. It converts the received image from RGB**explain abrv?**, which is used in Gazebo, into YUV**explain abrv?**, which is used in Fawkes, and writes the image to a shared memory buffer. Unlike in other simulation plugins, there is no interface because vision plugins can directly load a camera through Fawkes tools. However, it is possible to load a shared memory image in the same way as a real camera. The vision plugin just has to be configured to use an other camera-identification string. We identify the shared memory images with the robot name as prefix because multiple Fawkes instances use the same set of shared memory images. Otherwise, there would be one shared memory image which alternately shows camera images from different robots.

Gazsim-Timesource: The *Gazsim-Timesource* plugin provides the simulation time in Fawkes. This is important to avoid timing problems that occur if the computer is not able to run the simulation at real-time. Furthermore it allows to run the simulation faster than real time to speed up the testing process. The plugin replaces the default time-source in Fawkes. To provide a precise time avoid bad performance because of many synchronization messages, we decided to estimate the simulation time between two received time messages from Gazebo by using the current simulation speed and the real time passed since the last time synchronization message. To guarantee a monotonous time, we do not set the time in Fawkes back if the simulation has slowed down between two time synchronization

messages. The error can create a error in time and is more acceptable than a worse performance with many messages and a frozen time between two messages. **measurement for created time error**

Gazsim-Comm: The *Gazsim-Comm* plugin simulates the communication between multiple Fawkes instances without using Gazebo. It runs on a separate Fawkes instance which does not control a simulated robot and acts similar to a hub. It uses a set of peer-to-peer connections to the different Fawkes instances and forwards broadcast messages from one peer to all other peers. This solves the problem that usually the different Fawkes instances communicate on the same ports which is not directly possible if the instances run on the same computer. We preferred this approach over others because also want to simulate communication over a bad wireless network. This is an important problem we want to simulate because during the RoboCup competition the wireless network usually is overcrowded. The package loss is simulated by the plugin by setting the likelihood for messages to be dropped before forwarding.

Gazsim-Vis-Localization: The *Gazsim-Vis-Localization* plugin visualizes the localization of a robot in the simulation. It spawns a label which identifies the robot with an arrow which indicates the orientation of the robot above the position where the robot believes to be. The visualization is only visible from above so that the robot can not see the label in the simulation. This visualization is very useful during testing because a wrong localization is one of the most common reasons for misbehaving of the robot. Without this visualization in the simulation, it would be time-consuming to check the localization of multiple robots because it would be necessary to look into a separate Rviz for each robot. Furthermore, the visualization can be used to indicate the localization of the robots in a reconstruction of an automated simulation run.

LLSF specific Plugins

Gazsim-Light-Front: The plugin *Gazsim-Light-Front* exchanges the vision plugin *Light-Front* which determines the light state of machines by using a webcam. Light-Front uses the laser-cluster detection to know where to look for the machine light in the camera picture. Gazsim-Light-Front also uses laser-cluster results and the positions of the machines to determine on which machine the Robotino is looking at. If there is a machine near the position returned by the laser-cluster the plugin determines the light state by using the last message received from Gazebo. The plugin also writes the visibility history, which indicates how long the vision result is stable, and the ready flag, which indicates if the plugin believes it has correctly determined the light state. This plugin also simulates on a higher level of abstraction and provides ground truth information about the machine light states. This is useful for testing the agent because a wrongly detected light can have a crucial impact on the performance of the system.

Gazsim-Puck-Detection: The plugin *Gazsim-Puck-Detection* replaces the plugin *Omnivision-*

Pucks which finds pucks by using the omni-directional camera. Gazsim-Puck-Detection receives the positions of the robot and the pucks from Gazebo and writes the position of the pucks relative to the robot into the corresponding interface. A puck is only recognized if it is in a certain area around the robot. The maximal distance is similar to the real range in which Omnivision-Pucks can detect pucks. Here we also have a plugin with high level abstraction. Omnivision-Pucks sometimes has problems with two pucks lying next to each other because it can interpret them as one puck with the center between both pucks. This can cause problems when trying to grab a puck and therefore providing ground truth data about the puck positions can be useful for testing.

Gazsim-LLSFrbcomm: The plugin *Gazebo-LLSFrbcomm* connects the LLSF Refbox with the Gazebo simulation. It connects to the Refbox as a client because only clients receive information about the machine light status. On the one hand it sends received information about the machine light status to Gazebo via Protobuf messages. On the other hand it receives messages from Gazebo about pucks placed or removed under RFID readers of machines and sends this information as a client to the Refbox. We did not implement the connection to the Refbox directly in the simulation because Fawkes already provides a simple way for the connection and we do not want to duplicate the code used there. This plugin also sends the simulation time to the Refbox. [important bla?](#) In this context we modified the Refbox to use the simulation time messages similar as the Gazsim-Timesource plugin. Similar as Gazsim-Comm, the plugin can run in a robot independent Fawkes instance.

Gazsim-LLSF-Control: The plugin *Gazsim-LLSF-Control* works in combination with the automation scripts. It waits until the Refbox announces that the game is over and then stops the simulation run. The automation script recognizes that the simulation stopped and can start a new run. This plugin also can be started in a robot independent Fawkes instance.

Gazsim-LLSF-Statistics: The plugin *Gazsim-LLSF-Statistics* keeps statistics about the result of automated simulation runs. For example it keeps track of the amount of points scored in the several phases, the types of pucks being produced and the used configuration. When the game is over, the plugin writes these statistics to MongoDB. The statistics collected in a simulation run are inserted as a single document in the collection which includes all simulation runs of the schedule initiated with the automation script.

5.1.4 Automation Scripts

There are two major reasons why we decided to develop scripts to automate starting the simulation. On the one hand, a full LLSF simulation with three simulated robots requires a large amount of running programs. It is necessary to start Gazebo, the Refbox, a Fawkes instance for robot independent plugins and for each robot a separate Roscore, Movebase and Fawkes instance. Starting all programs with the required parameters is time consuming and can be automated. On the other hand, we need an automated start-up if

we want to run multiple simulation runs. This is useful to get an overview of the average system performance and to compare different strategies and configurations. Therefore it should be possible to let the simulation run 20 times with different configurations over night.

We implemented the automation scripts as simple bash scripts because they are powerful and easy to use and extend. There are two main automation scripts called *gazsim.bash* and *gazsim-schedule.bash*. The script *gazsim.bash* can start or stop a simulation and has several options. It is possible to start the simulation with a specific configuration and amount of robots. The simulation can also be started in a headless mode³. It is also possible to determine if the simulation starts with ROS, recording, statistics and which level of abstraction should be used. With the script *gazsim-schedule.bash*, multiple simulation runs can be scheduled. It is possible to define a set of configurations, which should be compared, the amount of simulation runs for each configuration and the level of abstraction.

5.2 Module Dependencies

5.3 Agent Improvements

The main task we want to use our simulator for is the improvement of our multi-robot system. Therefore improving our agent in this thesis is doubly important because we need it anyway and it is necessary to evaluate how useful our simulator is for the development of a multi-robot system. In the following we present the three major improvements we made during this thesis. These improvements are not independent from each other because we combine them to improve the system even further. In addition, we also made several minor improvements. We mention these during this section and the evaluation chapter, when we present some of the problems found with the simulation.

5.3.1 Using Three Agents

Before the thesis, we used only two of three usable robots in the competition. Because we want to maximize our performance in LLSF, we have to use all three robots. In this thesis, we extend our current role based approach to work with three robots. On the one hand, we introduce new roles which can be easily allocated to the three robots. On the other hand, we try how the current roles work with three robots and where the limitations are. A part of this is covered in the evaluation chapter.

First we introduced two new roles by splitting the old P1P2-role which produces P1 or P2 depending on what lets the P3 agent more space. Now we have a P1-role and a P2-role, which produce only P1 or respectively P2. Both roles use a disjoint set of machines to avoid conflicts while producing intermediate products. To coordinate the use of resources

³In the headless mode, Gazebo runs without a graphical user interface. This can save computation time. Although there is no visualization for the user, all visual sensors are still simulated.

shared by multiple robots, such as the delivery machines, we use the already existing locking mechanism which scales well with an additional robot. Therefore, we can also assign multiple robots to the P3-role because there is no context information needed to produce a P3. Every time a robot receives a lock of the T5 machine, which produces P3, the robot can bring a new resource puck to produce a P3. Actually, assigning multiple robots to the P3-role seems to be a good idea because P3 is often highly demanded and producing P3 provides simple and quick points. There also are adjustment we have to make to use three robots in the exploration phase. The three agents have to manage which robot explores which machine. Our current approach defines a circular path passing all machines. Each agents start at a specified machine and explores all unknown machines along this path and can pass already explored machines and machines that are blocked by other agents. To use this approach with three agents, we separated the start machine from the role in the production phase and introduced a new set of starting machines.

5.3.2 Recycling

An other opportunity we were not able to use before the thesis is recycling. Recycling of consumed pucks can provide quick points because each recycled puck gives five points and takes only around two seconds to produce on a recycling machine. When using three robots it is also useful to reduce over-crowding of the insertion area where robots usually get new resource pucks from. The implementation of the recycling took two basic steps. First, we implemented necessary skills of the robot to grep a consumed puck lying next to a machine and to use a recycling machine. We have to use a modified method to use recycling machines because our usual one for normal machines does not work in the corner of the field. Here, the simulation already revealed a problem we did not know about before. The two digital optical sensors which we use to check if the robot stands directly before the machine does not work in the corner of the field. The sensor triggers if there is an obstacle in a certain range in front of the sensor and if the robot stands near a recycling machine, the sensor already triggers because the wall of the field is in this range. Because we can decrease this range in the simulation, it is possible to test and continue the rest of the development necessary for recycling. This is not so easily possible in reality. The second part of the implementation was including recycling in the agent. Therefore the agent has to keep in mind where consumed pucks are and to know how and where to recycle them. We also implemented the possibility to configure when to do the recycling. Currently, the agent can recycle whenever it is possible and it needs a new S0 or when the production of a P1 or P2 is finished and there is no risk on loosing the points for the product caused by a failure during recycling. We decided to introduce no recycling role because it would be less effective than doing recycling as an alternative way to get a new S0. The reason is that an agent with a recycling-only role would drop the new resource puck which could be used for a production step.

5.3.3 Dynamic Role Change

Our current static role based approach has the downside that the role allocation can not be adapted to the current situation. In some situations, there are roles which are significantly less useful than other roles. For example, assigning a P1-role to a robot makes no sense if there are no more P1 pucks ordered. Therefore, the robot should better produce P2 or P3 pucks. To be able to adapt the role allocation to the current situation, we introduced a dynamic role change. This dynamic role change is based on a set of rules which define under which circumstances a role is changed into another role. This is similar to the approach of [8] where the dynamic role change is formalized by an automaton with the roles as states and the changing rules as transitions. The most important role changes we implemented is from the P1P2-role, P1-role and P2-role to the P3-role and depends on the time left for the production phase. The production of a complex product takes a long time with our current approach. In five test runs we made with a single robot with the P1P2-role, the production without the delivery took in average about 10:30 minutes. Therefore it is not reasonable to start a second production after the first one or, in general, if there is not enough time left. Producing P3 with multiple robots is more useful because the capacity of the T5 machine is better used. **failed production P3**

Chapter 6

Evaluation

In this chapter, we evaluate the results of the thesis. The evaluation is separated into two parts. In the first part, we evaluate our simulation. This includes the how good the simulation is in terms of realism and problems it can simulate, the computational effort with the resulting simulation speed, the use and advantages of the simulation and the limitations we encountered. The second part shows the evaluation of the multi-robot system and our improvements with the simulation. Here we present the performance of different configurations with different agent improvements.

6.1 Simulation

6.1.1 Realism

In this section, we show how realistic our simulation is, which problems we can simulate and which problems we can not simulate. Because there is no general measurement method to determine the realism of a robot simulator, we divide the problem and investigate all building block of the simulation. Afterwards, we also give a qualitative review how the simulation as a whole differs from reality.

Visually, our simulation can represent the basic structure of the LLSF environment. This already allows us to perform our vision tasks, which include brightness detection and color finding, in the simulation. However, it is difficult so simulate some problems that appear in reality. Especially reflections and ambient light can cause false positive vision detections we can not simulate. Physically, Gazebo is able to simulate a realistic interaction between objects, but it is difficult to find appropriate friction parameters for objects, what can result in weird physical behavior. Furthermore, we have to compose the physical representation of an object by simple geometries because complex geometries are computationally costly to simulate. This also can cause a difference between simulation and reality. We are able to simulate movement of the Robotino, collisions with objects and other robots and pushing pucks well. However, we simulate the movement of the Robotino and carrying pucks in a gripper on a higher abstraction level because of already mentioned problems with omni-directional wheels and pucks moving out of the gripper during turning. The

distance sensors of the simulation produce realistic data because the data is easy to compute and we add Gaussian noise to the data. The only problem with the added noise in the current version is that the variance of the error added to a computed distance is constant whereas in reality the error depends on the distance. Therefore, in the simulation, the noise in the measured distance is higher as in reality for near objects. This seems to be no problem. We have not recognized a difference between the localization with amcl in the simulation and in reality. The gyroscope sensor also is easy to simulate and we have not recognized a difference to real sensor data. The communication between robots and the Refbox can also cause problems in reality. We simulate package loss which is the major cause for the problem. We do not simulate communication delay because this problem is not so important in the LLSF environment. In the simulation, the impact of communication problems on the multi-robot system is similar to what we have observed during the RoboCup 2013.

The simulation speed also can have an impact on the realism of the simulation. We minimized this impact by synchronizing the time of Fawkes and the Refbox with the simulation time. Because of the estimation method we use there to decrease the amount of sent Protobuf messages, a small time difference remains. We measured this difference 5 times. [append measurements?](#) Every time, the difference was less than 25 seconds for an 18 minutes game. Therefore, the impact on the performance is small. Slower update rates of sensors and movement commands are useful to increase the speed of the simulation but can also cause differences between simulation and reality. We use update rates which are compromises between realism and computational speed. The update rate of the laser range finder is 5Hz , what is the half frequency of the real sensor, and there is no impact on the localization recognizable. The update rate of the webcam is 2Hz and therefore much slower than in reality. This increases the delay of vision results and has no important impact on the performance of a robot because the plugin light_front detects light states with a delay of about one second.

We compare the performance of our system at the RoboCup 2013 with the performance of the system with the same configuration in the simulation in section 6.2. The raw amount of points achieved in simulation and reality can not be used to evaluate the realism of the simulator because of different conditions. In the real competition, teams can take misbehaving robots out of the game and can restart a single robot once. We do not use this possibility in automated simulation runs. Furthermore, less vision failures which can have a large impact on the performance occur in the simulation. However, LLSF games in reality and our simulation look very similar because the robots perform the same actions and the problems that cause the robots to loose time or behave wrongly are the same or similar. For example the Movebase movement, which looks nervous and does much recovery behavior when facing obstacles, is the same in the simulation and the problem of interpreting a green light as a finished production, although the robot did not correctly place a puck under the machine, happens in the same way. [pictures?](#)

6.1.2 Computational Performance

The computational performance is important for a good simulation. If the simulation is computationally costly and runs on a slow computer, the simulation speed drops significantly. The *simulation speed* is the time interval that can be simulated per second. For example, if a simulation needs 10 seconds to simulate what a robot does in 5 seconds, the simulation speed would be 0.5. In the following, the simulation speed also is called *real-time factor*. The simulation speed is important for testing because testing with a low simulation speed requires more time. This is especially important for manual testing. There are possibilities to increase the simulation speed and to reduce the computational cost of the simulation. This can also be used to run the simulation with a speed greater than one and can therefore speed up the testing process even more. Gazebo provides three parameters for adjusting the simulation speed and detail. [link Gazebo SDF description?](#)

First, it is possible to determine a *target real-time factor* which limits how fast the simulation may run. It is only an upper limit and may not be reached if the computer is too slow. The default target real time-factor is 1. Second, there is the *maximal step-size* which determines the maximal time interval between two times a component of the simulation can do updates. Increasing the maximal step-size allows the simulation to run faster because the simulation simulates a larger time with one step. However, this can cause the simulation to be less accurate because simulation components have a higher response time. The default value of the maximal step-size is 0.001. Third, there is the possibility to adjust the *real-time update-rate* which determines the update calls of the physical simulation per real-time second. By decreasing this parameter, the simulation becomes computationally less costly and the physical simulation of objects in the simulation becomes less detailed. This has an especially high impact on the simulation of collisions because collisions are detected later. The default value of the real-time update-rate is 1000.

We could increase the simulation speed significantly by tuning these three parameters. However, we experienced an impact on the quality of the simulation. With a real-time update-rate below 600, we recognized unrealistic simulation of collisions between pucks and between robots. With a maximal step-size above 0.002 and a resulting real time-factor above 1.5, we recognized that the Robotino more often drives against obstacles. We think this is due to the higher distance the Robotino can travel between two update iterations of the Movebase. We think a maximal step size of 0.0015, a real-time-factor of 1 and a real-time update-rate of 750 are a reasonable compromise between quality and speed of the simulation. [Include Figure simulation speed and CPU usage over time at different parameters](#)

There also is another important bottleneck. Often the computational power needed for the programs which control the robots in the simulation is so large that there is less CPU usage available for Gazebo. This is caused by the fact, that we operate multiple robot control programs on the same machine. The impact on the simulation speed is especially high if there are obstacles on the path of a robot and Movebase costly re-plans the path

repeatedly. Therefore, the simulation highly depends on the number of simulated robots. **Figures composition of CPU usages with full simulation and only one simulated robot.** We reduced this problem by distributing the simulation and the robot control programs over multiple computers. This is especially easy to do with Movebase and helps us to avoid the major simulation speed drops when robots face obstacles. The memory usage of the simulation is no real problems because most current computers can handle the memory requirements. **Figure Memory usage full simulation**

6.1.3 Use for Multi-Robot System Development

In this section, we argue how useful our simulation is for the development of a multi-robot system. Because we already mentioned many advantages and disadvantages of design and implementation decisions in detail, we focus here mainly on the practical experience of improving our multi-robot system with the simulator. The probably most important practical advantage of the simulator is the possibility to test changes of the robot software without the real robot and environment. This allows testing although we currently do not have a working LLSF field. Therefore the quality of the resulting software is higher than without the simulator. An other beneficial advantage is the fast setup of a simulation test because there is no need to start the robot or to synchronize source code. The scripts are flexible enough to start a full LLSF simulation as well as a prepared setup to test robot skills.

mla not so useful now but may become indispensable when multiple components are in development at the same time speed Expendability: hackathon problem test specific situation

6.1.4 Limitations

6.2 Multi-Robot Strategies

6.2.1 Dynamic Role Change

6.2.2 Recycling

digital optical distance sensor adjustment

6.2.3 Role Configurations

6.2.4 Different Abstraction Levels

bad network influence eval

realism: time error?

Chapter 7

Summery and Future Work

This is the conclusion.

7.1 Future Work

refactor gazebo plugins/split in more plugins for each sensor, actuator

7.2 Summery

seitenzahlen komisch angeordnet

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