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Nao Devils Dortmund

Team Report 2014

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Contents

Chapter 1

Introduction

Competitions such as the RoboCup provide a benchmark for the state of the art in the field of autonomous mobile robots and provide researchers with a standardized setup to compare their research. Additionally the RoboCup *Standard Platform League* does not only provide researchers with a common setup, but also with the same hardware platform to use. This renders increased importance to publications of those teams, since extensive documentation and especially releasing source code allows other researchers to compare results and methods, reuse and improve them, and to further common research goals.

In the course of this report some of the points of the robot software and current the research approach of the RoboCup team *Nao Devils* are described. An overview about the Nao Devils software is given in section 1.2.

Stable motions are of crucial importance in the context of biped robots. Thus, the following chapter of the document will describe the motion control process emphasizing the *Dortmund Walking Engine* which has been the first closed loop walking engine applied to the Nao in RoboCup 2008. The version of RoboCup 2010 was able to reach walking speeds of up to $44cm/s$, which is, to our knowledge, the highest speed yet achieved with the robot Nao. Due to smaller enhancements of the existing walking algorithm for 2014 it is now possible to reach this speed in-game. Incidentally this speed exceeds the "theoretical maximum walking speed" given by Aldebaran in an earlier specification by almost 50%. For RoboCup 2011, a lot of effort was put into the development of a walk that is able to cope with a higher center of mass that results into the mitigation of the problem of quickly overheating joints. Another important task was to reduce the intensity of oscillations of the body that occur during the movement of the robot.

This system proved to be fast and stable. For RoboCup 2012 the system was therefore only slightly changed. Instead, we improved the dynamic kick introduced for RoboCup 2011, called instant kick. It is now possible to execute a kick within a motion cycle without interrupting or delaying the walking motion. For RoboCup 2014 we extended this kick by the ability to kick in an arbitrary direction. One positive side effect is that the kick is also stabilized by the walking engine. The kick will be introduced in chapter 2.2.2.

The work for 2014 aimed to improve the reliability of the self localization and the behavior as well as the extension of the instant kick.

This report is organized as follows. Chapter 2 describes the motion including the walk and the instant kick. Chapter 3 focuses on the perception processes of the Nao

while section 4 presents the concepts and ideas for the implementation of the robots behavior. In each of those chapters 2, 3 and 4 the solutions currently in use are described in detail and further references supplied when appropriate, but also the current research is presented. Chapter 5 gives a brief introduction to the tools used by our team in RoboCup 2014. Chapter 6 summarizes our current research topics and the development process for 2015.

We are happy to announce a code release including all software and tools used by team Nao Devils in 2014. It is available on our website[1].

1.1 Team Description

The *Nao Devils Dortmund* are a RoboCup team by the Robotics Research Institute of TU Dortmund University participating in the *Standard Platform League* since 2009 [1] as the successor of team BreDoBrothers, which was a cooperation of the University of Bremen and the TU Dortmund University [2]. The team consists of numerous undergraduate students as well as researchers. Previous team members of *Nao Devils Dortmund* have already been part of the teams *Microsoft Hellhounds* [3] (and therefore part of the *German Team* [4]), *DoH! Bots* [5] and senior team members have been part of *BreDoBrothers*.

The Team was actively participating in the RoboCup events during the last range. Major successes were the 3rd places in RoboCup 2009, GermanOpen 2009/2012 and the 2nd place in RoboCup 2011. The Team also participated in most of the *technical challenges* in these years while reaching the 3rd in RoboCup 2009 and RoboCup 2013. Additionally the team ranked second and third in the Drop-In challenge 2013 and 2014 respectively. Besides official RoboCup competitions the *Nao Devils* regularly participate at other international events such as the *Festival della Creatività* in Florence, Italy, the *RoboCup Exhibition and Engagement Event* in Eisteddfod of Wales, UK, and the *Athens Digital Week* in Greece. It is also planned to take part in the *Standard Platform League* of RoboCup 2015 in Hefei, China.

1.2 Software Overview

The software package used by team *Nao Devils* consists of a robotic framework, a simulator and different additional tools.

The framework, running on the Nao itself, is based on the German Team Framework [6]. Since 2013 our Software is based on the Framework released by the team *B-Human*[2] in 2012. The framework communicates with *NaoQi* using the *libBHuman*, completely separating it from Aldebaran's software modules. For an introduction and overview on the framework see [7]. We exchanged most of the vital modules in the motion, cognition and behavior sections. These modules are the subject of this report in chapter 2, 3 and 4 respectively.

Since *B-Human's* team report 2011 [8] covers the basics and usage of the simulator in great depth, a detailed description in exclude from this report. For further details please refer to [8] chapter 8.

[1] http://www.irf.tu-dortmund.de/nao-devils/download/2014/NDD-CodeRelease2014.zip

[2] `https://sibylle.informatik.uni-bremen.de/public/bhuman12_coderelease.tar.bz2`

To test developments in simulation, the software *SimRobot* was used instead of commercial alternatives, such as *Webots* from Cyberbotics[3]. Being open source offers great advantage, allowing to adapt the code to own developments. In addition having the feature to directly connect to the robot and debug online is very convenient during development. SimRobot [9] is a kinematic robotics simulator developed in Bremen which (like Webots) utilizes the Open Dynamics Engine[4] (ODE) to approximate solid state physics. Using update steps of up to 1 kHz for the physics engine enabled the possibility of realistic simulated walking experiments closely matching the gait of the real robot. It also features realistic camera image generation including effects like motion blurring, rolling shutter, etc.

Together with the change of the underlying framework we switched to CABSL by Team *B-Human*, a variant of XABSL completely realized in C++. Since debugging behavior running on the real robot can be really difficult to comprehend, team *Nao Devils* developed a debug tool that can be utilized for different behavior specification languages, in our case CABSL. A logging mechanism records all CABSL decisions online during gameplay. With help of the debug tool these logs can be combined with a video file, to analyze and replay robots decisions. A detailed description of this tool can be found in section 5.1.

1.3 Recent Changes

Most important change for RoboCup 2014 is the enhancement of the walking engine including the ability to execute a kick during the walk that is able to kick in an arbitrary direction. Additionally the walk is extended by the execution of lunges that is crucial to walk for example on artificial grass. We demonstrated this ability on the Open Challenge 2014. In this demonstration the artificial grass is compared to the usual carpet thick. As a result the robot sinks with it feet into the grass that must be balanced by a modification of the foot steps. This modification can also stabilize a walk that is disturbed by collision where the robot would fall down without a modification.

We also exchanged the path planing method by a simple approach that is more robust compared to potential fields and leads to higher walking speeds in most conditions. This is described in section 4.2.

[3] `http://www.cyberbotics.com/`
[4] `http://www.ode.org/`

1.4 Getting started

This section describes the steps to set up a Nao robot to be ready to use with our code - to work with the Nao and manage your robots, see section 5.3.

- Download the code release from our website[5].
- Find out the last four digits of the robot's Body ID (e.g. by searching for 'bodyid' in the robot's memory via the web interface).
- Follow the instructions in 'Install/readme.txt' to set up your robots.
- Create a configuration folder for your robot with those 4 digits and 'Nao' as a prefix (e.g. 'Config/Robots/Nao3156/') and copy the contents of 'Config/Robots/Default' into it.
- Run 'installAlcommon' with the 'naoqi-sdk-1.14.5-linux32.tar.gz' file as argument (found in Aldebaran archives).
- Follow the instructions in the *B-Human* team report 2012 [7] to set up the code for compilation.
- For deploying the Code to the robots, you can use our deployment tool *NaoDeployer* (found in 'Util/NaoDeployer/').

[5] http://www.irf.tu-dortmund.de/nao-devils/download/2014/NDDCodeRelease2014.zip

Chapter 2

Motion

The main challenge of humanoid robotics certainly are the various aspects of motion generation and biped walking. Dortmund has participated in the Humanoid Kid-Size League during Robocup 2007 as *DoH! Bots* [5] and before in RoboCup 2006 as the joint team *BreDoBrothers* together with Bremen University. Hence there has already been some experience in the research area of two-legged walking even before participating in the Nao Standard Platform League of 2008 as the rejoined *BreDoBrothers*.

The kinematic structure of the Nao has some special characteristics that make it stand out from other humanoid robot platforms. Aldebaran Robotics implemented the HipYawPitch joints using only one servo motor. This fact links both joints and thereby makes it impossible to move one of the two without moving the other. Hence the kinematic chains of both legs are coupled. In addition both joints are tilted by 45 degrees. These structural differences to the humanoid robots used in previous years in the Humanoid League result in an unusual workspace of the feet. Therefore existing movement concepts had to be adjusted or redeveloped from scratch. The leg motion is realized by an inverse kinematic calculated with the help of analytical methods for the stance leg. The swinging leg end position is then calculated with the constraint of the HipYawPitch joint needed for the support foot. This closed form solution to the inverse kinematic problem for the Nao has been developed in Dortmund and used since RoboCup 2008 when other teams as well as Aldebaran themselves still used iterative approximations.

2.1 Walking

In the past different walking engines have been developed following the concept of static trajectories. The parameters of these precalculated trajectories are optimized with algorithms of the research field of *Computational Intelligence*. This allows a special adaption to the used robot hardware and environmental conditions. Approaches to move two legged robots with the help of predefined foot trajectories are common in the Humanoid Kid-Size League and offer good results. Nonetheless with such algorithms directly incorporating sensor feedback is much less intuitive. Sensing and reacting to external disturbances however is essential in robot soccer. During a game these disturbances come inevitably in the form of different ground-friction areas or bulges of the carpet. Additionally contacts with other players or the ball are partly unpreventable and result in external forces acting on

the body of the robot.

To avoid regular recalibration and repeated parameter optimization the walking algorithm should also be robust against systematic deviations from its internal model. Trajectory based walking approaches often need to be tweaked to perform optimally on each real robot. But some parameters of this robot are subject to change during the lifetime of a robot or even during a game of soccer. The reasons could manifold for instance as joint decalibration, wear out of the mechanical structure or thermic drift of the servo due to heating. Recalibrating for each such occurrence costs much time at best and is simply not possible in many situations.

The robot Nao comes equipped with the wide range of sensors capable of measuring forces acting on the body, namely an accelerometer, gyroscope and force sensors in the feet. To overcome the drawback of a static trajectory playback, team Nao Devils developed a walking engine capable of generating online dynamically stable walking patterns with the use of sensor feedback.

2.1.1 Dortmund Walking Engine

A common way to determine and ensure the stability of the robot utilizes the zero moment point (ZMP) [10]. The ZMP is the point on the ground where the tipping moment acting on the robot, due to gravity and inertia forces, equals zero. Therefore the ZMP has to be inside the support polygon for a stable walk, since an uncompensated tipping moment results in instability and fall. This requirement can be addressed in two ways.

On the one hand, it is possible to measure an approximated ZMP with the acceleration sensors of the Nao by using equations 2.1 and 2.2 [11]. Then the position of the approximated ZMP on the floor is (p_x, p_y). Note that this ZMP can be outside the support polygon and therefore follows the concept of the fictitious ZMP.

$$p_x = x - \frac{z_h}{g}\ddot{x} \tag{2.1}$$

$$p_y = y - \frac{z_h}{g}\ddot{y} \tag{2.2}$$

On the other hand it is clear that the ZMP has to stay inside the support polygon and it is also predictable where the robot will set its feet. Thus it is possible to define the trajectory of the ZMP in the near future. The necessity of this will be discussed later. A known approach to make use of it is to build a controller which transforms this reference ZMP to a trajectory of the center of mass of the robot [12]. Figure 2.1.1 shows the pipeline to perform the transformation. The input of the pipeline is the desired translational and rotational speed of the robot which might change over time. This speed vector is the desired speed of the robot, which does not translate to its CoM speed directly for obvious stability reasons, but merely to its desired average. The first station in the pipeline is the Pattern Generator which transforms the speed into desired foot positions $\mathbf{P}_{global}$ on the floor in a global coordinate system used by the walking engine only. Initially this coordinate system is the robot coordinate system projected on the floor and reset by the Pattern Generator each time the robot starts walking. The resulting reference ZMP trajectory p^{ref} calculated by "ZMP Generation" (see section 2.1.3 for details) is also defined in this global coordinate system.

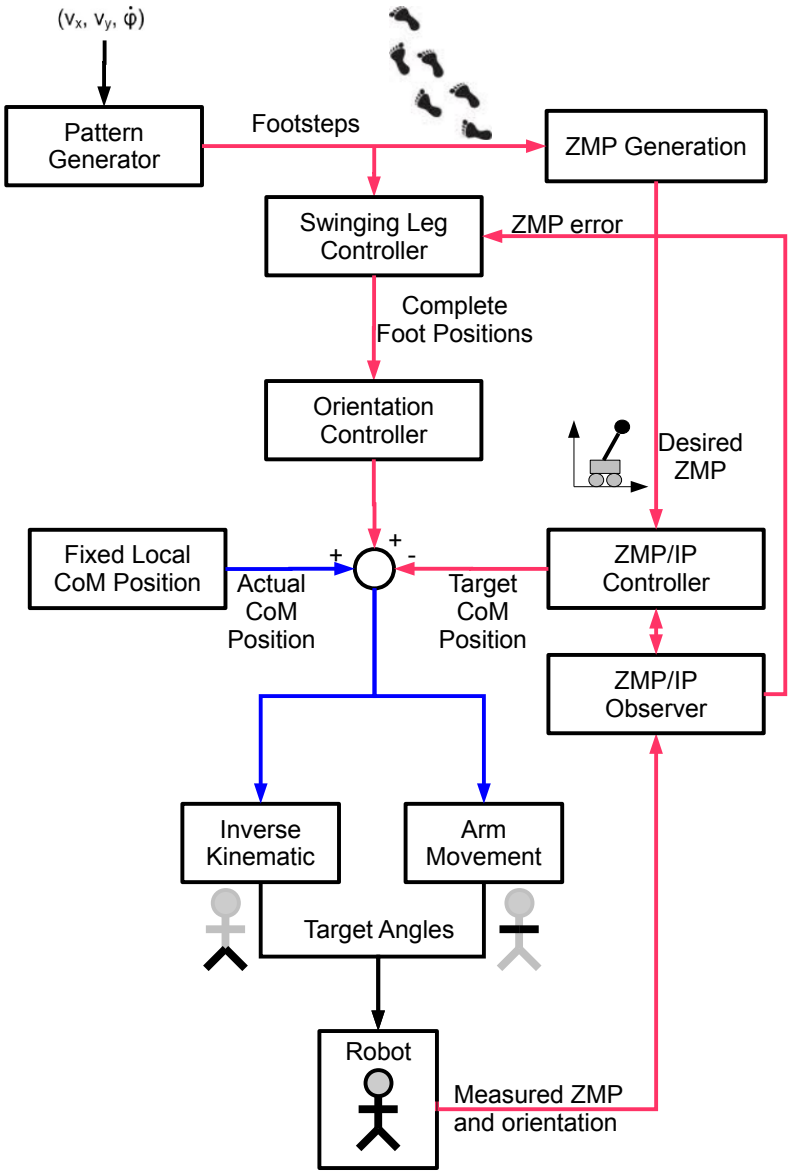


Figure 2.1: Control structure visualization of the walking pattern generation process. Data expressed in the robot coordinate system are represented by a blue line and data expressed in the global coordinate system is represented by a red line.

The core of the system is the ZMP/IP-Controller, which transforms the reference ZMP to a corresponding CoM trajectory ($\mathbf{R}_{ref}$) in the global coordinate system as mentioned above. The robot's CoM relative to its coordinate frame ($\mathbf{R}_{local}$) is given by the framework based on measured angles during the initial phase of the walk. After this phase $\mathbf{R}_{local}$ is no longer updated since this would be another control loop which would cause oscillations [13]. Equation 2.3 provides the foot positions in a robot centered coordinate frame.

$$\mathbf{P}_{robot}(t) = \mathbf{P}_{global}(t) - \mathbf{R}_{ref}(t) + \mathbf{R}_{local}(t) \tag{2.3}$$

Those can subsequently be transformed into leg joint angles using inverse kinematics. Finally the leg angles are complemented with arm angles which are calculated using the x coordinates of the feet.

2.1.2 The ZMP/IP-Controller

The main problem in the process described in the previous section is computing the movement of the robot's body to achieve a given ZMP trajectory. To calculate this, a simplified model of the robot's dynamics is used, representing the body by its center of mass only. The ZMP/IP-Controller uses the state vector $\mathbf{x}=(x, \dot{x}, p)$ to represent the robot where x is the position of the CoM, $\dot{x}$ the speed of the CoM and p the resulting ZMP [11].

The system's continuous time dynamics can be represented by

$$\frac{d}{dt}\begin{bmatrix} x \\ \dot{x} \\ p \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{g}{z_h} & 0 & -\frac{g}{z_h} \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ p \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v \tag{2.4}$$

where $v = \dot{p}$ is the system input to change the ZMP p according to the planned target ZMP trajectory p^{ref}. Discretizing equation 2.4 yields the system equation

$$\mathbf{x}(k+1) = \mathbf{A}_0\mathbf{x}(k) + \mathbf{b}v(k) \tag{2.5}$$

where $\mathbf{x}(k)$ denotes the discrete state vector at time $k\Delta t$, $v(k)$ denotes the controller for the system and

$$\mathbf{A}_0 = \begin{bmatrix} 1 & \Delta t & 0 \\ \frac{g}{z_h}\Delta t & 1 & -\frac{g}{z_h}\Delta t \\ 0 & 0 & 1 \end{bmatrix} \tag{2.6}$$

describes the system's behavior. Details about the controller design can be found in [14].

One important fact about the controller is, that it needs a preview of the reference ZMP. As can be seen in figure 2.2, it is not sufficient to start shifting the CoM simultaneously with the ZMP. Instead the CoM has to start moving before the ZMP does. Therefore a preview of p^{ref} is needed to be able to calculate a CoM movement leading to a stable posture.

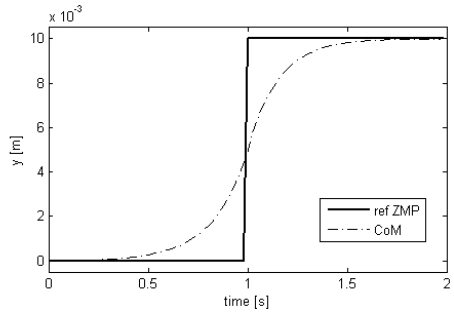


Figure 2.2: CoM motion required to achieve a given ZMP trajectory.

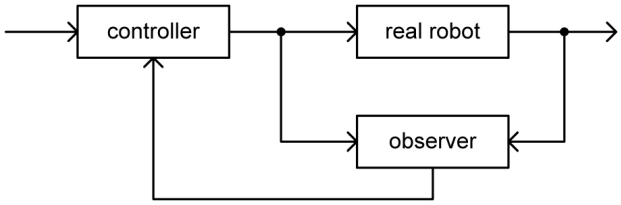


Figure 2.3: Control system with sensor feedback using an observer.

Sensor Feedback Sources

A humanoid robot like the Nao has multiple sensors to measure the dynamical and kinematical state. Using only one of those, e.g. the ZMP measured by the foot pressure sensors or the acceleration, has some disadvantages, like noisy data or measurement delays. A common way to cope with these problems is to implement a sensor fusion using a kalman filter. Looking at the control structure of the ZMP/IP-Controller reveals that parts of the state vector can be measured, namely the position of the center of mass $x^{sensor}(k)$ and the actual ZMP $p^{sensor}(k)$. The first can be calculated using the center of mass positions c_i of each link expressed in the coordinate frame of link i:

$$x^{sensor}(k) = T_s^w(k) \cdot \left(\frac{1}{\sum_l m_l} \cdot \sum_i T_{O_i}^s(k) \cdot c_i \cdot m_i \right) \tag{2.7}$$

where

- s is the coordinate system of the support foot.
- w is the world coordinate system.
- O_i is the coordinate system of link i.
- m_i is the mass of link i.
- $T_i^j(k)$ is the homogeneous coordinate system transformation matrix from coordinate system i to j.

The later is the weighted average of the data measured by each pressure sensor in the feet. In case of the Nao robot the CoP for the left $p_{left}^{sensor}(k)$ and right foot $p_{right}^{sensor}(k)$ are given by the API and must be combined:

$$p^{sensor}(k) = \frac{f_l(k)}{F} \cdot T_{O_l}^{w}(k) \cdot p_{left}^{sensor}(k) + \frac{f_r(k)}{F} \cdot T_{O_r}^{w}(k) \cdot p_{right}^{sensor}(k) \tag{2.8}$$

where

- O_l, O_r is the coordinate system of left and right foot respectively.
- $f_l(k)$, $f_r(k)$ is the force exerted on the left and right foot respectively.
- $F = f_l(k) + f_r(k)$ is the overall force exerted on the robot.

This kind of ZMP measurement has the same limitation as the definition of the ZMP, it is bounded to the supporting area. As a result, the ZMP will be measured at the edge of the support area when the robot tilts. The measurement of the center of mass position is limited in a similar way. The result of flexibilities and tolerances in the joints can be measured, but not the result of the tilt of the robot. This is not necessarily a disadvantage, since it limits the reaction of the robot to disturbances to securely executable movements, especially if the robots falls down. The limitation of the CoM measurement also corresponds to the ZMP measurement limits.

Regarding the coordinate system transformations, there is one noticeable point. The transformations to the world coordinate system $T_{O_i}^{w}(k)$ and other transformations are seperated. The reason for that is the way of calculating. The transformations between the coordinate systems of the links are calculated using forward kinematics and measured angles. However, the position and orientation of the feet in the world coordinate system cannot be measured directly. Possible sources would the self localization or the odometry calculated by integrating the acceleration sensor, both combined with forward kinematics. But these sources are inaccurate and lead to large noise in the measured CoM and ZMP positions. Measurable errors during a walk are much lower than these measurement errors and it would be not possible to react correctly. Therefore the target foot positions and orientations given by the Pattern Generator are used for $T_{O_i}^{w}(k)$.

Integration of the Measurements, a Sensor Fusion

In the last chapter two measurable values of the state vector $\mathbf{x}(k)$ are presented. The measurable output of the system given by equation 2.5 can now be defined as

$$y(k) = \mathbf{c} \cdot \mathbf{x}(k) \hat{=} \begin{bmatrix} x^{sensor}(k) \\ p^{sensor}(k) \end{bmatrix} \tag{2.9}$$

with

$$\mathbf{c} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.10}$$

Since not the full state can be measured, an observer is needed. Figure 2.3 shows the overall system configuration. The observer is put in parallel to the real robot and receives the same output of the controller to estimate the behavior of the real system and

is supported by the measurements of the ZMP and the CoM. Derived from equations 2.5 and 2.9 the observer can be defined as follows:

$$\widehat{\mathbf{x}}(k+1) = \mathbf{A}_0\widehat{\mathbf{x}}(k) + \mathbf{L}\left[\mathbf{y}(k) - \mathbf{c}\widehat{\mathbf{x}}(k)\right] + \mathbf{b}\mathbf{u}(k). \tag{2.11}$$

It can be shown, that this system is observable.[1]

The controller in this equation is defined as:

$$u(k) = -G_I \sum_{i=0}^{k} \left[\mathbf{C}\mathbf{x}(i) - \vec{p}_i^{ref}\right] - \mathbf{G}_x\mathbf{x}(k) - \sum_{j=0}^{N} G_d(j)\vec{p}_{k+j}^{ref}. \tag{2.12}$$

To calculate the gains in equation 2.11 and 2.12 a performance index must be defined:

$$J = \sum_{j=0}^{\infty} \left\{ Q_e \left[p(j) - \vec{p}_j^{ref}\right]^2 + \Delta\mathbf{x}^T(j) Q_x \Delta\mathbf{x}(j) + R\Delta u^2(j) \right\}. \tag{2.13}$$

The idea is to minimize the difference between the reference and the actual ZMP, to ensure a smooth trajectory and to lower the reactivity of the system.

The gains can then be calculated as follows:

$$\mathbf{B} = \begin{bmatrix} \mathbf{Cb} \\ \mathbf{b} \end{bmatrix}, \mathbf{I} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \mathbf{CA}_0 \\ \mathbf{A}_0 \end{bmatrix}, \mathbf{Q} = \begin{bmatrix} Q_e & 0 \\ 0 & \mathbf{C}^T Q_x \mathbf{C} \end{bmatrix}, \mathbf{A} = [\mathbf{I}, \mathbf{F}] \tag{2.14}$$

$$G_I = \left[R + \mathbf{B}^T\mathbf{P}\mathbf{B}\right]^{-1} \mathbf{B}^T\mathbf{P}\mathbf{I}, \quad \mathbf{G}_x = \left[R + \mathbf{B}^T\mathbf{P}\mathbf{B}\right]^{-1} \mathbf{B}^T\mathbf{P}\mathbf{F} \tag{2.15}$$

$$G_d(j) = -\left[R + \mathbf{B}^T\mathbf{P}\mathbf{B}\right]^{-1} \mathbf{B}^T \left[\mathbf{A}_c^T\right]^j \mathbf{P}\mathbf{I}, j = 0, 1, ..., N. \tag{2.16}$$

The closed-loop matrix $\mathbf{A}_c$ is defined as

$$\mathbf{A}_c = \mathbf{A} - \mathbf{B}\left[R + \mathbf{B}^T\mathbf{P}\mathbf{B}\right]^{-1} \mathbf{B}^T\mathbf{P}\mathbf{A}. \tag{2.17}$$

To calculate $\mathbf{P}$ the discrete-time matrix Riccati equation must be solved:

$$\mathbf{P} = \mathbf{A}^T\mathbf{P}\mathbf{A} - \mathbf{A}^T\mathbf{P}\mathbf{B}\left[R + \mathbf{B}^T\mathbf{P}\mathbf{B}\right]^{-1} \mathbf{B}^T\mathbf{P}\mathbf{A} + \mathbf{Q}. \tag{2.18}$$

Due to fact that $\mathbf{P}$ is constant this can be done offline using Matlab or Octave.

The gain $\mathbf{L}$ utilized for the sensor feedback can be calculated in the similar way just by executing the LQR method. This can also easily be done utilizing Matlab or Octave.

The effect of the sensor feedback is depicted in figure 2.1.2. As can be seen, if the CoM deviates from the optimal trajectory (either by measuring the CoM error directly or as a result of a measured ZMP disturbance) the controller accelerates the CoM towards

[1] A matlab script calculating the gains can be found in the Coderelease: /Utils/Matlab/writeParamNG.m.

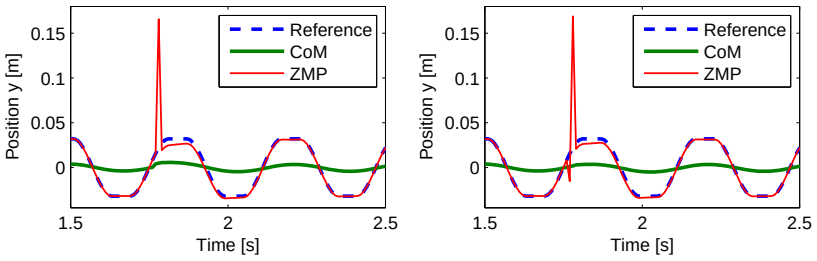


Figure 2.4: Reaction of the controller to different disturbances. On the left an error in the CoM position was measured, on the right a ZMP error.

the optimal trajectory. After the acceleration the CoM is decelerated until it follows the optimal trajectory again.

A more detailed presentation of our past approaches and algorithms is presented in [14, 15]. The current approach including a detailed description of the whole algorithm can be found in [13].

Experimental Sensor Feedback Methods

Besides the sensor feedback realized by the ZMP/IP-Controller there are two more methods implemented. While the ZMP/IP-Controller is responsible for controlling the translation of the center of mass, the orientation is expected to be 0. This assumption is not correct, and should be handled in another way. Therefore a module called GyroTiltController is implemented which realizes a PID controller using the output of the gyroscope directly to control the body roll and tilt. The gains of the controller are chosen such that it has a damping effect on an oscillating body.

Results and future work

On a real Nao the most important effect of the sensor feedback is damping since the Nao tends to an oscillation during a walk. To show this positive effect, an experiment was conduct where a beam of 5 mm width and height was fixed onto the ground [13]. The robot walked with the right foot over the beam such that it induces an oscillation. Without sensor feedback, the robot fell down in 10 of 10 trials. With sensor feedback in 0 of 10 cases.

The performance of the system was also observable on the RoboCup 2012. However, after many competitions, exhibitions and experiments some Naos of our team reveal highly worn-out gears. It can be observed that in this case the gains for the CoM error feedback must be selected very conservative. Otherwise this feedback can amplify the existing oscillation resulting in different gains for different robots.

Our future work is the integration of reactive stepping. This means that the foot positions are immediately modified in case of a disturbance. The theoretical part of this work can be found in [16].

Reactive stepping is usually for balancing large disturbances. Large disturbances lead to a tipping robot and CoM errors due to this cannot be measured with the FSR. We

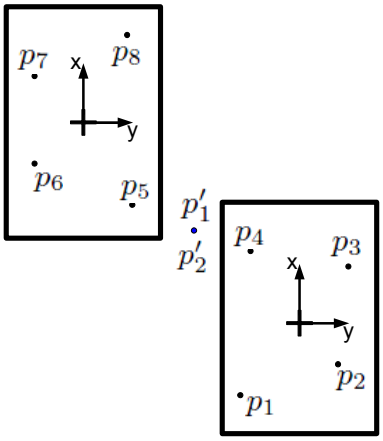


Figure 2.5: The control polygon consists of 4 points per foot with constants coordinates within the respective coordinate frame. In this example a positive x speed is assumed for a better visualization.

therefore utilize the CoM error for the step modification and the ZMP measured by the FSR for damping the oscillation.

Since the system was not advanced enough for application on a RoboCup the corresponding code parts are inactive. Together with the described issues because of worn-out robots we decided not to reactivate CoM measurements for the walk on the RoboCup 2013.

2.1.3 ZMP Generation

The ZMP Generation calculates a reference ZMP using the given foot steps. Within the support polygon the position can be freely chosen since every position results in a stable walk. On the x axis the ZMP proceeds with the desired speed. This results in a movement of the center of mass with constant velocity. On the y axis the ZMP is a Bézier curve with a control polygon of 4 points and dimension 1. The coordinate of each point is constant within the coordinate system of the respective foot. Figure 2.5 gives an example. In the right single support phase the control polygon is $P_r = \{p_1, p_2, p_3, p_4\}$. The same applies to the other single support phase. In the double support phase the control polygon consists of the points p_4, p'_1, p'_2, p_5, where p'_1 and p'_2 are the same point in the middle of p_4 and p_5. This leads to a smooth transition between the single and double support phases. Figure 2.6 shows the resulting reference ZMP along the y axis.

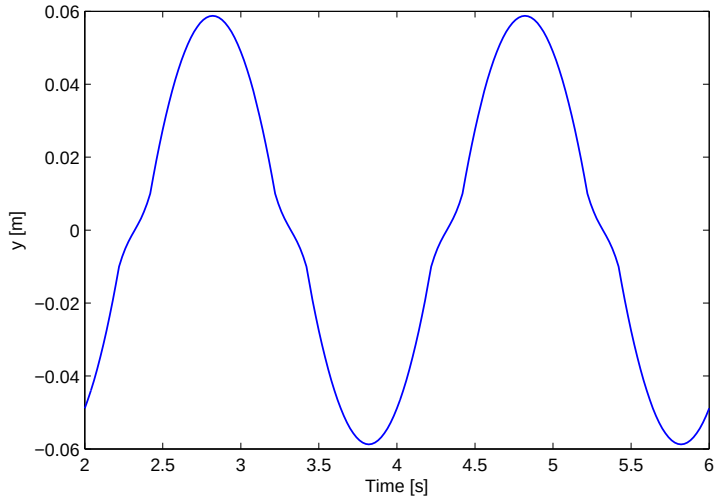


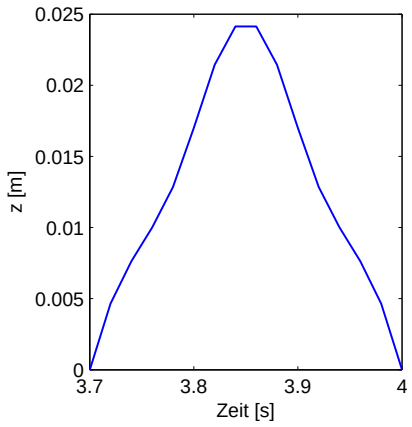
Figure 2.6: Resulting reference ZMP along the y axis.

2.1.4 Swinging Leg Controller

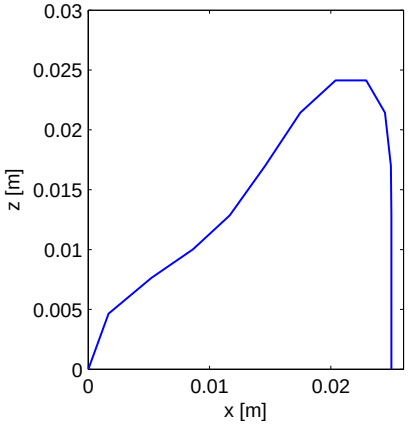
The PatternGenerator sets the foot positions on the floor. They could be imagined like footsteps in the snow. Therefore the footpositions of the swinging leg during a single support phase are missing. They are added by the Swinging Leg Controller which calculates a trajectory from the last point of contact to the next utilizing a B-spline. The control polygon consists of 9 points with 3 dimensions each. The x and y coordinates are set along the line segment between the start and end point. The z coordinates are increased and decreased respectively by $\frac{1}{6}$ of the maximal step height. The z coordinate over time can be seen in figure 2.7(a). To reduce the influence of the leg inertia the feet are lifted and lowered at the same speed. Figure 2.7(b) shows the z coordinate over x. The foot reaches its end position along the x axis some time before the single support phase ends. This reduces the error if the foot hits the ground too early.

2.1.5 Reactive Stepping

Even if the stabilizing effect can be shown, it is obvious that not every disturbance can be balanced this way. From observing human beings it can be followed that large disturbances can only be balanced by modifying the desired foot placement. This is also true for walking robots, but the derivation is different. In figure 2.8 at 1.7s a disturbance of the CoM trajectory can be seen. The preview controller balances this by accelerating the CoM to the original trajectory since it is optimal for the given ZMP reference. This acceleration causes a deviation of the actual ZMP trajectory that can be seen in figure 2.8. We can conclude that the reaction the disturbance can cause the robot to fall. So it is reasonable to say that not a disturbance causes a fall of the robot but an inappropriate reaction to it. An inappropriate reaction is for example to try to regain the originally planned walk in case of disturbances. Human beings modify the foot placement instead. For our ZMP based walk this means that the reference trajectory must be modified



(a) Step height over time.



(b) Stepheight over x for a walk along the x axis.

Figure 2.7: Movement of the swinging leg in the global coordinate system.

accordingly. In [16] we present a method to calculate the modification of the ZMP by calculation a simple matrix multiplication:

$$S(t, \mathbf{e}) = \mathbf{G}_{e,t}\mathbf{e}, \quad t \in \{1, \ldots, N\}.$$

Input of function S is the time T where the step is modified and the measured error $\mathbf{e}$ given by the ZMP/IP observer. Matrix $\mathbf{G}_{e,t}$ is constant and can be calculated in advance. The walk with the same disturbances but balanced with step modification can be seen in figure 2.8 on the right. The derivation and further details can be found in [16].

Besides the question about the mathematical realization of the step modification, the implementation of the robot must also consider various topics to realize modification that lead to a stabilization. A tilting robot must be raised after a lunge which requires

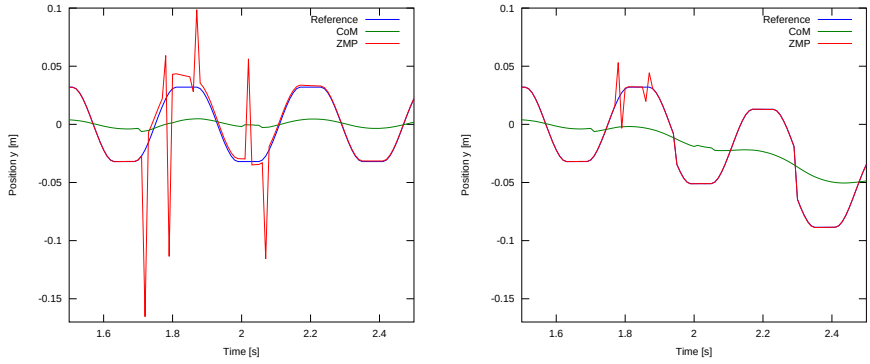


Figure 2.8: Balancing without lunges (on the left) and with lunges (on the right).

high torques. We therefore lower intentionally the CoM linear to the measured body tilt. Additionally the swinging foot is rotated around the stand leg to avoid undesired collisions with the ground.

While it can be proven in various experiments that this modification can stabilize the robot while it would fall down without, we currently investigate the advantage while walking with high speeds. However, the modification is clearly needed to be able to walk on problematic floors, like artificial grass etc.

2.2 Kicking

Kicking motions have different objectives. First the ball must be kicked as precise as possible with an adjustable power. On the other hand, the kicking motion should be as short as possible to avoid unnecessary delays during gameplay. As a consequence we have different kicking motions in use. One can be used for precise and adjustable kicks while the other is executed within a normal walk cycle.

2.2.1 Precise Kick Motion

In every SPL soccer match, whether it is for a pass or a shot on the goal, a precise kick that can be adjusted at the last possible moment, to cover up an imprecise ball model or a moving ball in an one on one situation, has become a necessity. Since covering all possible kick angles and strengths with Special Actions (see section 2.3) is simply not possible, a dynamic kick was needed.

Our current implementation uses the inverse kinematic from our walking engine to move the kicking foot towards the ball. With a fast kick execution time, the stability of the robot can hardly be ensured with any kind of reactive controller. Therefore we concentrated on a implementation that works without a controller and still is able to execute a stable kick with all desired angles and strengths. The kick motion needs only one input, the kick target: a field position relative to the robot.

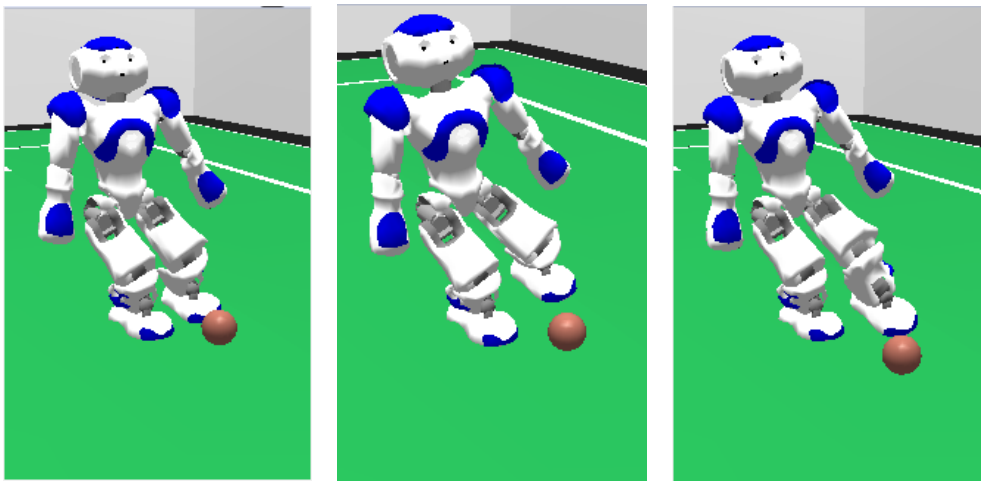
The main focus in the development for our kick was its stability while still being able to kick hard. Therefore the kick process is divided into several phases (see figure 2.9):

- lean - shift the robots weight to the standing foot
- prepare - move the foot to a point near the ball
- execute - a fast straight motion towards the ball
- prepare back - back to the position after lean
- lean back - back to the original robots position (standing)

The seperation into these phases allow a parameterization of the kick which can be adjusted and optimized easily. After the leaning process, our kick takes the relative ball coordinates from our ball model at the beginning of the prepare phase, moves the foot to a point in front of the ball so that the execute phase can kick the ball in one straight move of the foot in the desired direction. For this, the kicking foot origin is placed in a fixed distance to the ball on the the circle that this specific distance creates. Due to the different trajectories resulting from a sidekick compared to a frontkick, seperate leaning

angles for those motions are used and, since the foot of the Nao robot is not completely smooth or round, the kicking angle is not entirely free. Currently, the kicking angle is limited from 0 to 25 degrees for a frontkick and from 65 to 90 degrees for a sidekick, which is quite enough for almost any real game situation.

After the kicking foot has been brought into position, the kicking motion itself is done before the robot begins a reverse leaning process to again ensure its stability.



(a) Robot after the lean phase. (b) Robot after the prepare phase. (c) Robot after the execute phase.

Figure 2.9: The Robot in the three main phases of the kick, triggered from SimRobot.

2.2.2 Instant Kick

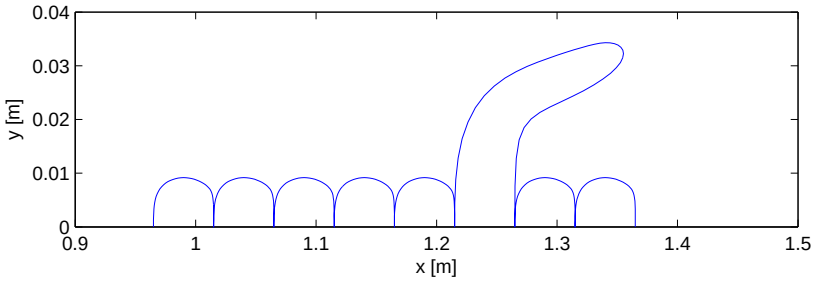


Figure 2.10: Visualization of the foot trajectory kicking a ball.

While all executed kicks should be as precise as possible, it is sometimes important to execute the kick as fast as possible. An illustrative situation is a near opponent challenging for the ball. Kicking precisely it no more necessary if the opponent reaches and kicks the ball before the own player has executed the kick. For this reason another kicking motion

exists, the "Instant Kick". This is not a motion separated from the walking engine like the Precise Kick or the older Special Action Kicks (see sec 2.3). It is executed during the phase where the Swing Leg Controller (see sec. 2.1.4) moves the swing leg from one position on the floor to the next. Instead of using a movement depicted in fig. 2.7 a curve is calculated that lifts of the foot, executes the kick and sets the foot on the target position on the floor where it would have set if no kick is executed, see fig. 2.10. The walk is therefore untouched and continues without a difference to a walk without kicking, besides the resulting instabilities. Since also all sensor feedback algorithms are still activated during kicking the motion is stabilized by the well proven walking engine.

To enable kicks straight forward and additionally kicks to the "inner"[2] side two separated set of parameters are utilized, one for kicking straight forward and one for kicking with the maximum angle. The actually used set of parameters is a linear interpolation of both depending on the desired angle.

A kick straight forward or with a low angle is calculated using the actual ball position. Faulty measurements of the ball position can lead to large leg movements causing a fall down especially when executing a kick to a side. If an angle larger than half of the maximum is desired, the ball is therefore assumed to be at a predefined position.

The kick is divided into three phases. During the first, the foot is moved to a start position, e.g. 8 cm in front of the ball. In the second phase, the foot is moved behind the ball and in the last phase, the foot is placed on the position for the next step. This three phases therefore replaces the normal movement of the foot during a single support phase. The distance in front of the ball, behind the ball and the duration of the phases can be configured as well as the fixed ball position for kicks to a side.

2.3 Special Actions

All movements except walking and kicking are executed by playback of predefined motions called *Special Actions*. These movements consist of certain robot postures called key frames and transition times between these. Using these transition times the movement between the key frames is executed as a synchronous point-to-point movement in the joint space. Such movements can be designed easily by concatenating recorded key frames.

[2] When kicking with left foot this is a kick to the left and vice versa.

Chapter 3

Cognition

From the variety of Nao's sensors only microphones, the camera and sonar sensors can potentially be used to gain knowledge about the robot's surroundings. The microphones haven't been used so far and are not expected to give any advantage. The sonar sensors provide distance information of the free space in front of the robot and can be used for obstacle detection. However, the usage of these sensors depends on maintaining a strictly vertical torso or at least tracking its tilt precisely since otherwise the ground might give false positives due to the wide conic spreading of the sound waves. Additionally, for certain fast walk types the swinging arms were observed to generate such false positives, too, and the sonar sensor hardware in general is currently unreliable and often does not recover from failure once the robot has fallen down. Thus for exteroceptive perception the robot greatly relies on its camera mounted in the head.

The following chapter describes the information flow in the cognition process starting from image processing and its sub-tasks in section 3.1. Special focus is given to new developments since 2011, meaning an image processing that does not rely on color tables. Also, the localization module based on a multiple-hypotheses unscented Kalman filter (see section 3.3).

3.1 Image Processing

In the past years the Nao Devils Team was using a color table based image processor which was based on the Microsoft Hellhounds' development of 2007 [17]. This image processing however, took at least several hours to calibrate and was very susceptible to lighting condition changes and color changes, for example when changing between two different fields. To address these problems, the currently used image processing was written with the idea to minimize this configuration process. Furthermore, due to the increased field size, the used resolution for each camera was increased from 320x240 for both cameras to 1280x960 for the upper and 640x480 for the lower camera.

The image processing in use still uses the color information from the color coded field, but does not need a specific calibration to get a good detection rate. To achieve this, the field color (green) is newly calculated every frame using a weighted color histogram based on pixel samples on the image. The key idea is to use as much a-priori information as possible to remove the need of color tables, reduce the scanning effort and minimize the

needed subsequent calculations. Since the limited cpu power does not allow for a scan of two whole images, we process only a small fraction of all pixels, scanning the images along fixed vertical and horizontal scan lines.

These scan lines search for changes within the y-channel to detect the white lines (if surrounded by the detected field color), and also detect possible ball locations based on the color channel changes. To reduce computation time, the detection of goals takes place only in the upper part of the images on the horizontal scan lines, also using the information about the field border detection.

All relevant objects and features are extracted with high accuracy and detection rates. Since the Nao SPL is the first RoboCup league (neglecting the simulation leagues and the Small Size League with global vision) that plays on a symmetric field, detecting features on the field itself becomes more important. The detection of those is described in more detail in the following section.

The current implementation allows us to play in natural lighting conditions and as shown in the open challenge for 2014, using auto camera settings, our robots continue to play and score even with huge lighting condition changes in games.

Since the image processor in use was implemented to adapt to different resolutions, the changes noted in the beginning did only result in a slightly slower runtime for both images and we were still able to process both images at 30 fps each.

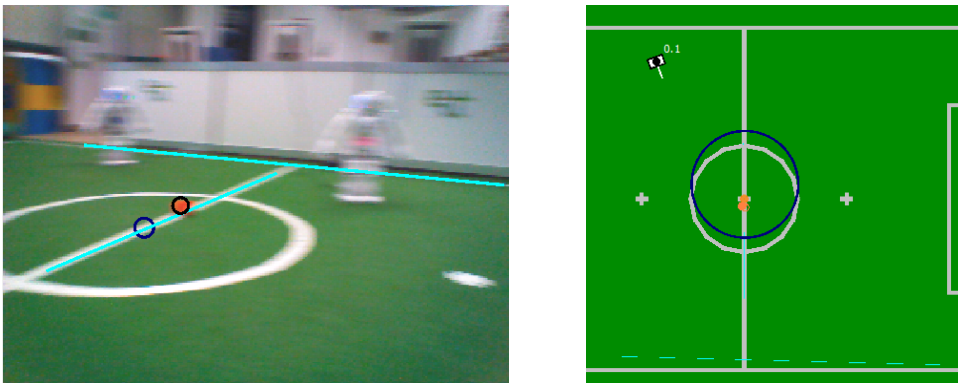
3.2 Line and goal detection

The line detection is using a similar approach to the last years. Based on line points detected on the scan lines, these points are connected to chains to determine possible lines and center circles. No gradient calculations are used since these calculations are susceptible to noise (especially on far away lines that have a width of 1 or 2 pixels) and also runtime was saved. Furthermore, especially using auto camera settings, the image is blurred in game on rapid head or robot movements (see figure 3.1), thus making gradient calculations even less accurate. The connected points are verified as lines with extra verification scans. Every detected line is then enhanced by scanning along the lines direction at its ends to maximize the lines length.

Since the field size was doubled last year, the used scan lines proved to be too few to detect the ball reliably in a distance of more than 5 meters. To adress this problem, several additional scan lines that scan specificially for the ball were added if the ball was not be found using the standard image processing. For the position of these scan lines, the ball model, including its prediction is taken into account. If the ball is still not found, since the ball is only expected to be lost at a certain distance, only the part of the upper image near the horizon then is scanned with randomly placed scan lines. This significantly increased the ball detection rate and helped to detect the ball in a distance of up to 9 meters.

3.3 Localization

One main focus of research is on Bayesian filters, where several enhancements for real time vision-based Monte Carlo localization systems [18] have been presented, and the approach based on the detection of field features without using artificial landmarks has



(a) Camera Image. (b) Field view.

Figure 3.1: Detection results on a blurred image.

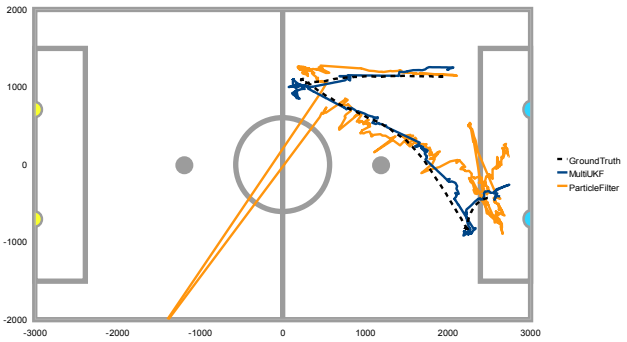
won the "almostSLAM" Technical Challenge at RoboCup 2005 [6]. The methods used up until RoboCup 2009 have all been based on those particle filters developed between 2005 and 2007. For RoboCup 2010 however a different approach has been developed and used in the competitions of 2010, and also in 2011 without any modifications [19].

Inspired by [20] the basic idea was to combine the smoothness and performance of Kalman filtering with a multi-hypothesis system. The latter is necessary to allow recovery from huge errors due to extended periods of integrated odometry errors without correcting through observations, or rapid unexpected position changes due to contact with other robots or "teleportation" by human intervention. All of those issues occur in robot soccer games and are amplified by the huge odometry errors inherent in fast biped walking.

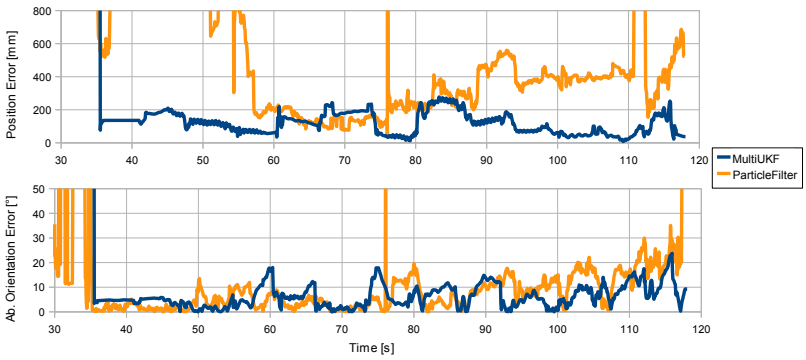
A classic Kalman filter applied to localization in a SPL scenario can only be used for position tracking, and only as long as the estimate does not deviate too much from the true positions. Most perceptions on a SPL field are ambiguous, so the sensor update will only be done with the most likely data association. At the same time, the perception of field features like field line crossings is often uncertain so that L- and T-crossings can not be distinguished. In such cases wrong associations tend to drive the estimation further away from the true position. Recovery from such situations is only possible when assigning huge weights (e.g. small observation covariances) to unique perceptions like observing both goal posts in the same frame which then decreases the robustness against false perceptions originating from the audience around the field.

This problem is addressed in [20] with a sum-of-Gaussians Kalman filter, where each Gaussian is split into several new ones representing the results of different association choices. Applying all possible data associations to every hypothesis generates exponential growth which needs cutting back shortly after by applying pruning heuristics and fusing similar Gaussians to prevent an explosion of computational complexity. Thus lots of processing time is wasted on creating and destroying new hypothesis which are either unlikely or very similar to the ones that already exist.

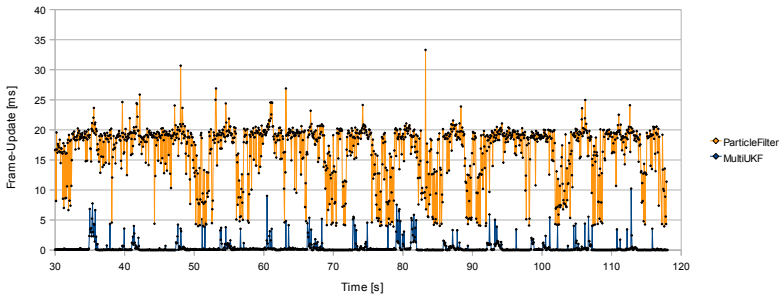
A different approach is implemented in the module *MultiUKFSelfLocator*. Only few new hypotheses are generated periodically at positions with high probability based only on recent sensor information. Those hypotheses are only updated using data that lies inside



(a) Estimated positions and ground truth on the field.



(b) Errors in pose estimation.



(c) Localization runtime.

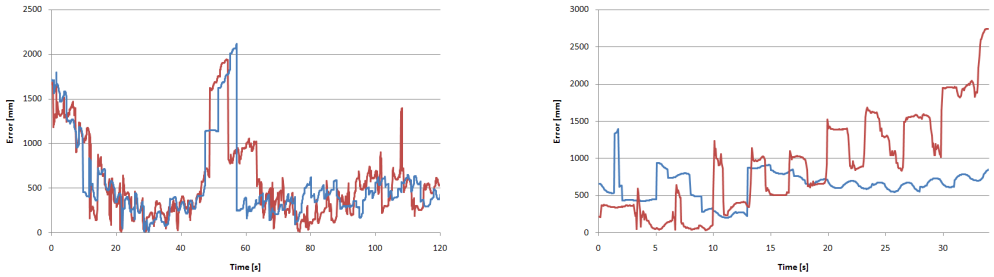
Figure 3.2: Localization of Multiple-Hypotheses UKF compared to previous particle filter solution (which was used in RoboCup 2009). Both are running in parallel on the Nao using the same perception as input. Ground truth is provided by a camera mounted above the field.

a certain expectation threshold. Non-linearity in the sensor model is addressed using the unscented transformation technique. Several other approximations and simplifications result in a localization method that is an order of magnitude faster than the previously used particle filter while providing superior localization quality and increased robustness to false positive perceptions (see figure 3.2). A more detailed presentation of the approach and its stochastic soundness is given in [19].

3.4 Distributed World Modeling

Current work includes robust cooperative world modeling and localization using concepts based on multi robot SLAM [21], as well as using probabilistic physics simulation and estimation to improve the robot's state estimation and odometry information [22]. Keeping track of the robot's dynamic environment opens the possibility for tactical behavior decisions beyond simple reactive behaviors which are currently in use.

The algorithm described in [21] estimates the robot's location and the surrounding dynamic objects simultaneously. In this joint modeling of the robot's state a particle filter estimates the robot's pose. Clusters of particles are combined into super-particles which map the dynamic environment using a number of Kalman filters. This represents an approximation of FastSLAM and both decreases the integration of odometry error compared to robot-centric local modeling (see figure 3.3) and allows resolving multi-modal localization belief states using shared information. The approach even preserves its SLAM functionality and is able to maintain a robot's localization based on mapped dynamic obstacles only. A detailed presentation of the approach is presented in [21].



(a) No gain for frequently observed robots.

(b) Tracking of infrequently observed robots significantly improved.

Figure 3.3: Advantage by unified (blue) compared to separate robot-centric modeling (red).

By specifically addressing the heterogeneity of the perceived information and the need to synchronize the estimation between the team of robots the task's complexity can be reduced to be in the range of applicability on limited embedded platforms. This module's average runtime on the Nao in the configuration used on the RoboCup 2010 would have been slightly above 20 ms which would not have allowed to keep a frame rate of 15 Hz or even 30 Hz. Especially the switch to a motion frame rate of 100 Hz made its application impossible. Additionally the system is based on the outdated particle filter localization

of previous years.

For 2011 parts of this distributed world modeling approach have been integrated with the new localization system described in section 3.3. Since the UKF localization concept does not allow the transformation of a combined estimator according to the Rao-Blackwell theorem, the SLAM aspect can not be transferred in this case directly. In the 2011 code used in the competitions, the SLAM aspects were not fully implemented. The ball and robot modeling is still done in a cooperative way using the approximations described in [21], but there has been no feedback into the localization and only a single maximum-likelihood hypothesis is maintained at each time.

In the code release accompanying this report there is the possibility to choose between local models, which are the result of the local aggregation of percepts (percept-buffering, but without periodically flushing the results into the global model, and the global model itself, which is a fusion of all distributed information. Due to the lack of feedback into a robot's own localization there are situations where the local model is still to be preferred. Precisely approaching close balls for example requires accurate robot relative information instead of the precise global position of the ball on the field. In the global model, the ball is more precise in global coordinates, but moderate errors in a robot's localization would have a major impact on the relative positioning, as long as the robot's pose is not corrected by the distributed information, too.

Chapter 4

Behavior

Nao Devils as well as previous Dortmund teams implemented behavior mostly by utilising state machines such as XABSL (*Extensible Agent Behavior Specification Language*). XABSL was developed in its original form in 2004 using XML syntax [23] in Darmstadt and Berlin and adapted in 2005 to its current C-like syntax and a new ruby-based compiler by the *Microsoft Hellhounds*. Since 2013, we use CABSL which was developed by team B-Human, and implements XABSL as C++-Macros allowing for easy access to all data structures (i.e. representations) required for decision making.

To this end, behavior is specified by option graphs. Beginning from the root option, subsequent options are activated similar to a decision tree until reaching a leaf, i.e. an option representing a basic skill like "walk" or "execute_special_action" which are parameterized by the calling option. Each option contains a state machine to compute the activation decision based on a number of values stored in the representations (see section 3.1).

While it is possible to design complex behavior using CABSL, several tasks may prove difficult or impossible to specify using CABSL alone, e.g. robust and efficient path planning including obstacle avoidance and also any strategic team behavior. Hence, the remainder of this chapter is structured as follows: Section 4.1 describes our team behavior which was successfully applied during the RoboCup 2013 and was extended for RoboCup 2014 competition. Additionally the head control is described which is of crucial importance to feed the localization and world modeling modules with useful information. The last section 4.2 describes a path planning approach to augment CABSL.

4.1 Teamplay

Team Strategy

For 2013, there have been significant rule changes in the SPL: The size of the field has been doubled and the number of robots increased to five per team. Hence, major parts of the existing behavior code had to be adapted, especially dynamic positioning. This year's behavior is similar to the one used in 2013 and defines the roles of the field players by their location and takes the current positions of each team robot into account.

The assignment of those positions of the field players is divided into two parts:

- The robot that has the easiest (i.e. preferably no obstacles and good orientation for a kick) and shortest way to the ball attempts to go there. Once it has reached the ball, it may opt either for shooting to the opponent's goal or for passing the ball to a team mate. If its way is blocked by an opposing robot and no team mate is in position to receive a pass, the robot plays the ball around the opponent.
- The other field players either support the robot which is in charge of the ball, or defend the own goal. For that purpose, positions are calculated dynamically depending on the game situation, including own and opposing player models as well as the ball model. Each player is assigned to one of those locations. The decision which robot is going to a particular spot is taken based on a shortest path heuristic. This strategy, as seen in 4.1 also minimizes the collisions between team mates.

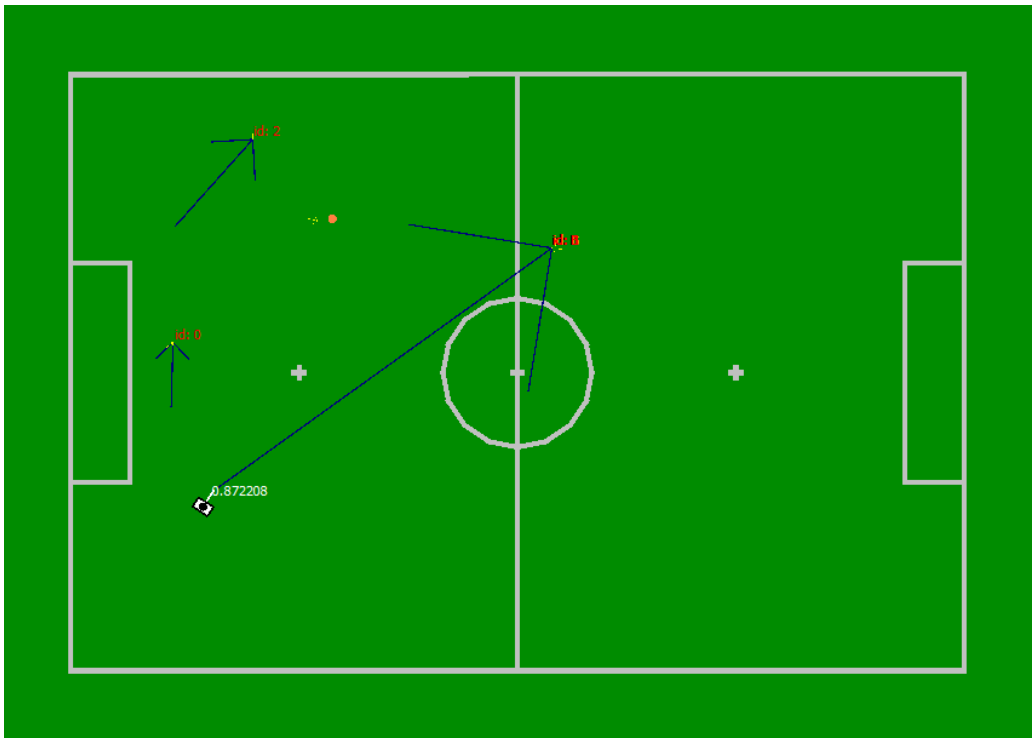


Figure 4.1: Example for the assignment of players to positions.

The task of assigning positions to players underlines the importance of having sophisticated distance metrics. To this end, we abstract from the Euclidian, and use a heuristic which includes penalties for obstacles, and adverse rotations (e.g. the robot is rotated opposite to a target position).

Apart from that, our behavior features:

- Five distinct roles: The *striker* always attempts to reach the ball. The *defender* is always acting in the own half. The *backup-striker* supports the striker in its vicinity.

The *supporter* moves to distinct positions in the offense, or defense, depending on the ball position. As those positions are located away from the striker, he might be able to pass the ball to the supporter. The *goalkeeper* is the only role that is fixed during the complete game.

- Dynamic, but constrained positioning for all roles. For example, the defender is not allowed to pass the center line.
- Configurable strategies allowing user to switch between more defensive and offensive play. The configuration affects specific positions of the field players that are not in charge of the ball.
- Kicking motions can be performed during the walk without stopping.
- A kick selection that decides in which direction the ball is shot. In case of obstacles in front of the robot, the ball is moved edgewise around the obstacle. If the robot is free, it might pass the ball to a team member or shoot to the goal.
- A goalkeeper which is capable to counter the ball by jumping or making a quicker block motion in case that the ball would pass near the keeper.
- Adaptation to the current number of team players during the game. If robots are taken out, roles in the following order are removed: supporter, striker-backup, defender.
- Kickoff positioning independent from the robot number (except goalkeeper).

One drawback of the proposed behavior is its reliance on the wireless network. This affects especially the distribution of percepts that are needed for the world model. There were major problems with the wireless (delays, framedrops) during the RoboCup competition in the past years. For 2014, a fallback strategy was introduced that does not rely on wireless communication. Instead, it uses fixed roles that prioritize the main role objective (e.g. defender), although every role would go to the ball if it is near enough. To avoid clumping of our robots in the latter situation, every robot uses the visual robot detection to check if another one of our robots is near the ball. This strategy was also used during the DropIn games, since the data of the team mates was in many cases considered unreliable.

HeadControl

In 2013, we decided to redesign the head control along with the behavior. In previous years, each separate behavior had customized head motions implemented in XABSL. We now introduced high level behavior commands that trigger head motions. For that purpose, a new module called *Head Control Engine* was added.

The engine provides five different head control modes:

- **ball**: A mode that fixates the ball. If this is physically impossible, a simple sweep along the walking path is executed. If the ball gets lost, a search for the ball is started.

- **localize**: This mode tries to improve the localization validity by sweeping the field, and looking at points of interest for localization. Such locations are goal posts, the ball, and line crossings.
- **opponents**: This mode is intended to be used by a stationary observer, sweeping the field for obstacles and verifying their positions.
- **soccer**: This is a high-level mode that is now being used by our team for the game play. It uses aforementioned functions. Additionally, while walking towards a target, the robot moves its head to keep path, walking target and obstacles on its way in sight.
- **direct**: This option allows the behavior engineer to directly set the target positions of the head joints.

4.2 Path Planning

The motion commands used in previous years have been based on desired speed vectors which were updated with every behavior execution. This mode of control dates back to the AIBOs which could be controlled like omnidirectional vehicles. Additionally for an AIBO it was sufficient to walk straight to the ball to grab and turn with it. For humanoid robots however the the omnidirectional characteristic of the walking generation is much less distinct, and at the same time a target position close to the ball has to be reached with a certain target orientation which increases the difficulty for trajectory control. While it is possible and also commonly done to generate omnidirectional walking patterns with the walking engine described in section 2.1, for a humanoid robot such as the Nao it is far more convenient to walk straight than it is to walk sideways. This is reflected in the possible walking speeds in each direction. Generating smooth path trajectories following the characteristics optimal for those described walking capabilities is obviously not possible in an intuitive way using a state-based behavior description language such as XABSL, or CABSL.

To overcome those limitations and ultimately to achieve more precision and speed in positioning close to the ball, a more advanced approach to path planning has been done for the *Nao Devils'* robots since RoboCup 2010. The utilized *Dortmund Walking Engine* is based on foot step planning (see section 2.1). In 2010, a basic behavior has been introduced to XABSL allowing the trajectory planning to be done by the walking engine which has much better control and feedback about the executed motion. The motion request has been adapted accordingly to accept a target position and orientation and different *go_to* commands have been implemented to cover common motion tasks while avoiding obstacles. In 2013, the command has been improved continuously by realizing a path planning through a potential field generated from static and dynamic obstacles.

Although the approach using a potential field worked, the robots were very cautious and inefficient, especially when avoiding dynamic obstacles. For 2014, a much simpler and more efficient approach has been implemented. The path starts with just two waypoints, the robot and the target position. Until there are no obstacles on any line between two waypoints, for each obstacles on such a line a new waypoint next to the obstacle is generated. For a more stable path, obstacles that are close to each other are merged. This approach, in contrast to the path which the potential field produced, allows fast and

predictive obstacle avoidance while minimizing the need to slow down when the robot is near such an obstacle.

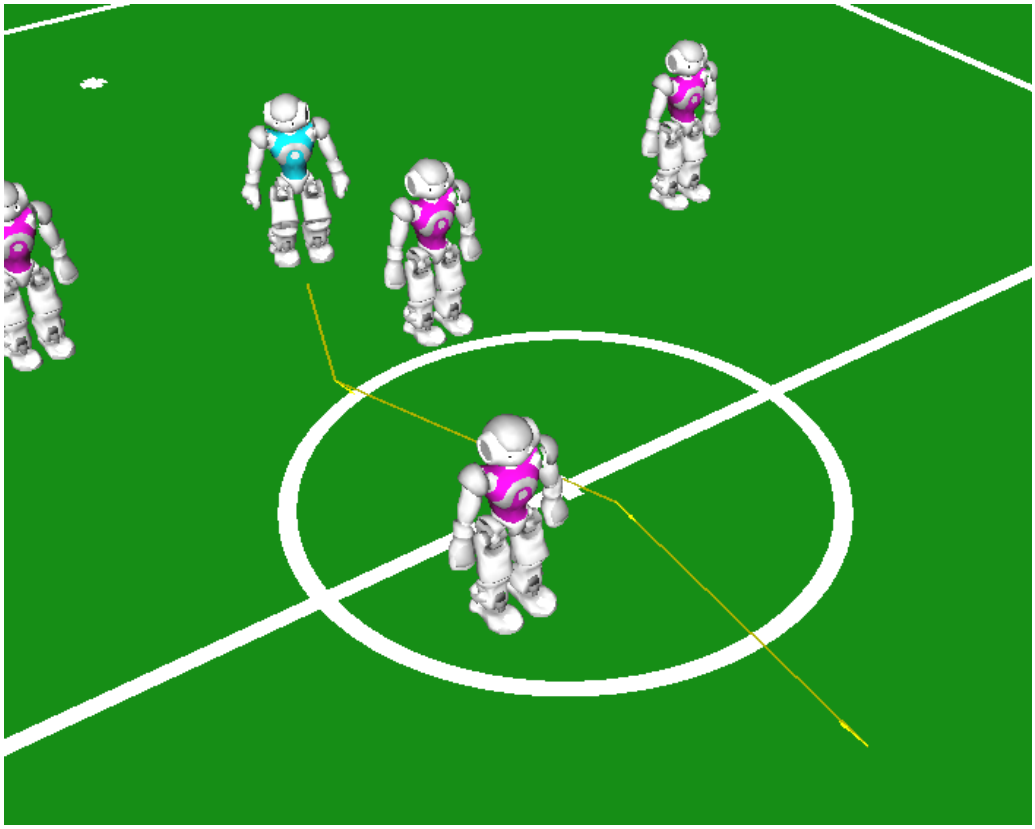


Figure 4.2: Example of a path around obstacles.

Chapter 5

Tools

Within the current year, a number of tools simplifying the work with the robots have been developed by team *Nao Devils*: Debugging is of crucial importance in the development of behavior for autonomous robots (see chapter 5.1). Helping referees doing their work in the course of a game has become more attendance due to rule changes regarding the field size and the number of the robots (see chapter 5.2). Moreover, automatic configuration and deployment tools support the game preparation and postpressing (see chapter 5.3). Team Nao Devils appreciates input and contribution to any of the tools.

5.1 Debugging

Debugging programmed code is essential to identify flaws and finding solutions to errors. This is not only true for the code of the robotic framework, but also for the behavior code written to decide which action is most suitable regarding the current situation. As described in section 4, team Nao Devils uses the CABSL programming language to implement the soccer behavior. The behavior code can be executed in a simulation environment or directly on the robotic hardware.

Different kinds of debugging tools are an essential part of every programming suite allowing to stop code during execution and get step by step information about the program state and variables. This concept is rather practical for debugging behavior using the simulator. Since the simulator runs both the robot code and the world simulation the whole simulation can be stopped to have a look at the current state and decisions. This allows to use the simulator to step frame by frame through the world state. To debug the behavior with the simulator SimRobot [9], a view the current CABSL tree containing CABSL symbols and variables (figure 5.1) can be displayed allowing a frame-by-frame forward simulation. Stepping back is not possible since the framework allows no rewind.

The used simulator is a physical simulation based on the Open Dynamics Engine (ODE). Therefore, the simulation of even one robot is a rather time consuming process resulting in a simulation slower than real-time on most modern standard PC platforms. Simulating a complete match including six robots decreases the framerate to numbers that make a user observation rather difficult. Even if the simulation would run in real time the physical simulation is insufficient to model the real world exactly. Since small situational differences can result in big differences in behavior decision the simulation model is not

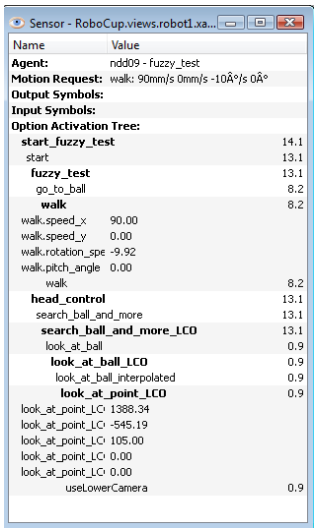


Figure 5.1: Example of a XABSL tree.

satisfactory enough to test soccer behavior more complex than basic behavior. Thus the most important behavior debugging can not be done in the simulator but on the real robot.

Debugging code on the real robot is quite different. The use of a breakpoint concept to stop the program during execution would stop the motion of the robot resulting most likely in a fall of the robot. Therefore most debugging in autonomous robotics involves monitoring rather than breakpoint approaches. The program execution is supervised with the help of a remote connection that broadcasts information about the program state, sensor input and decisions. In contrast to the breakpoint approach this method allows for a debugging in real game situations involving other autonomous robots but is prohibited during tournament game play. Unfortunately the nature of the supervision process results in a delay of information. Therefore the supervision cannot be matched exactly with the current field situation. In addition the broadcast connection results in an disturbance of the the normal code execution. In general the disturbance is minor in scope but can result in timing problems. The result would be a stuttering of the robot which changes the state that should only be monitored. Especially for debugging of robot behavior supervision of the written code is a rather inadequate solution.

Since execution directly onto the robot is of special interest for behavior development team Nao Devils developed a tool allowing a different debugging concept combining the convenience of simulator debugging with code testing on the real robot. The concept is based on logging each behavior decision during the execution. To allow a later analysis of the logged data the corresponding sensor information and the representation of the world state is also stored in addition to each decision. Since the complete sensor information, including the camera pictures, would result in an unmanageable amount of data, only the resulting information about the world model are saved.

With this stored data a playback of all behavior decisions and a debugging of decisions on given data can be done. An analysis of the world model is not possible since only the

modeled gamestate is stored and cannot be compared with reality. But to allow even that comparison a video camera can be used to record the real gamestate in a movie file.

Based on these concepts team Nao Devils developed a tool with following features:

- The debugging tool allows the organisation of the debug process in projects. For each project, several log files and one corresponding video showing the experiment or game with all participating robots can be analysed simultaneously.
- The video of the game can be loaded and displayed. While the time is synchronized within the logfiles automatically, the video has to be matched manually.
- The robot logs its internal state machine, the required symbols and hardware commands (motion, LED-Requests etc.) once per frame (see figure 5.2).
- Users are able to select symbols in order to plot the values as a time series (see figure 5.3).
- A 2D field view shows the modeled robot positions, trajectories and velocity, and the ball position (see figure 5.4).
- The behavior log can be played back, stopped, stepped through frame by frame and rewound to interesting positions.
- A graphical user interface allows for an easy reading of the logfile and shows the input/output symbols and current CABSL state tree (see figure 5.5).

The tool is implemented using Java as a platform-independent standalone tool. The written log (.xlg) is loaded line by line and a parser extracts the information of the symbols and the state machine. The parser is specialized to interpret CABSL logs but due to clearly defined interfaces between the interpreter and the different widgets an adaptation to another behavior language would be possible by changing the parser. Additional debug views specialized for other description languages can also be added easily.

All this is designed to enable a behavior engineer to replay all the states and analyze the decisions a robot made.

It is therefore easy to find out,

- whether a decision was based on a false perception: If the robot would have correctly seen a certain feature, it would have behaved correctly. This kind of error results from either a false perception or wrong interpretation and modeling.
- whether the decision was based on false decisions made on correct knowledge: The user observes a gamestate which resulted in an undesired decision. If the internal world model matches the real world the wrong decision is a result of a decision error or a coding bug.

The tool is at an advanced state of development. It has proven helpful in replaying gamestate decisions and allowing expert programmers to judge and debug errors thereby improving the written behavior code. The most useful information was thereby gained from actual tournament games which were otherwise impossible to supervise due to the given rules.

Nao Devils debug tool is free available at:
`http://nao-devils.de/downloads/behavior-debug-tool/`.

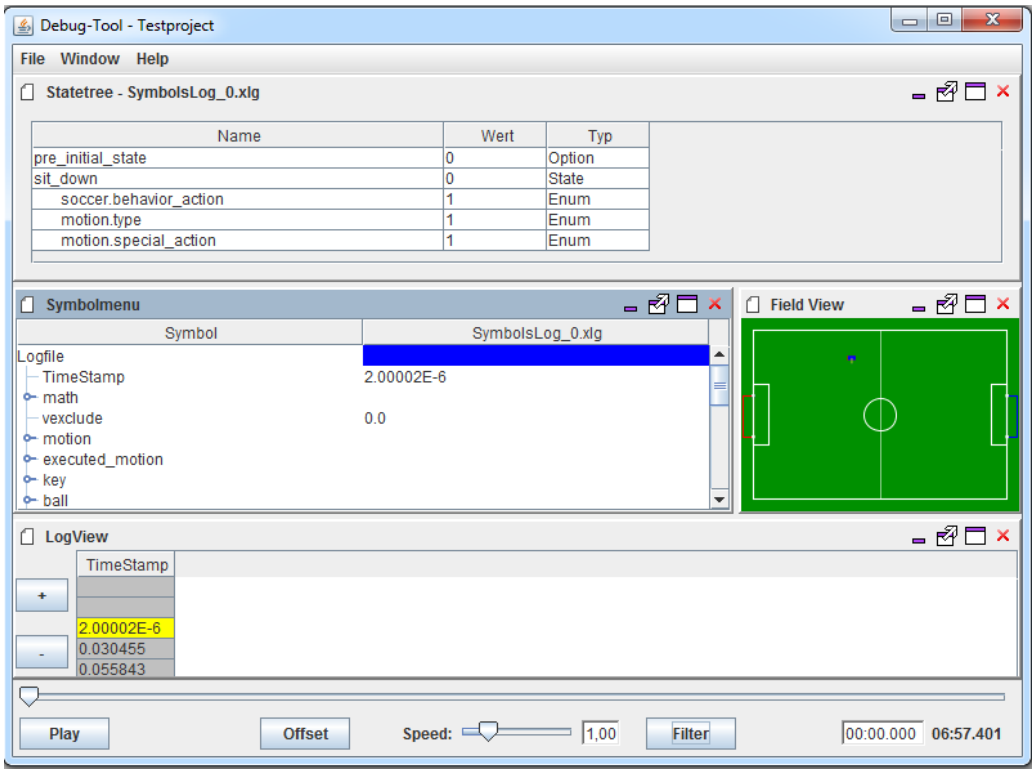


Figure 5.2: Logfile view of the Debug Tool.

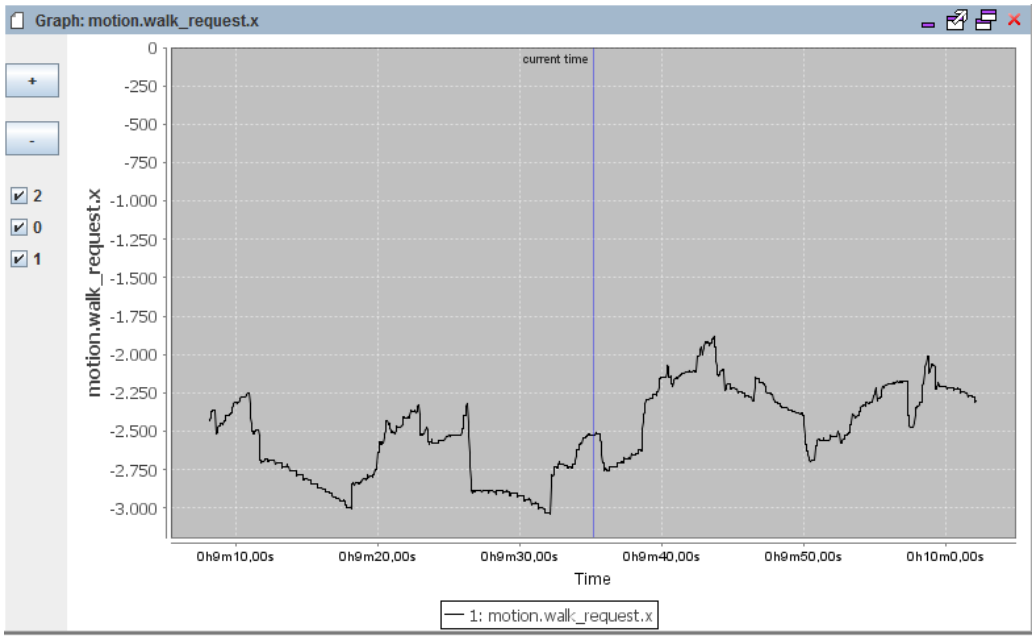


Figure 5.3: Example plot of a time series in the debug tool.

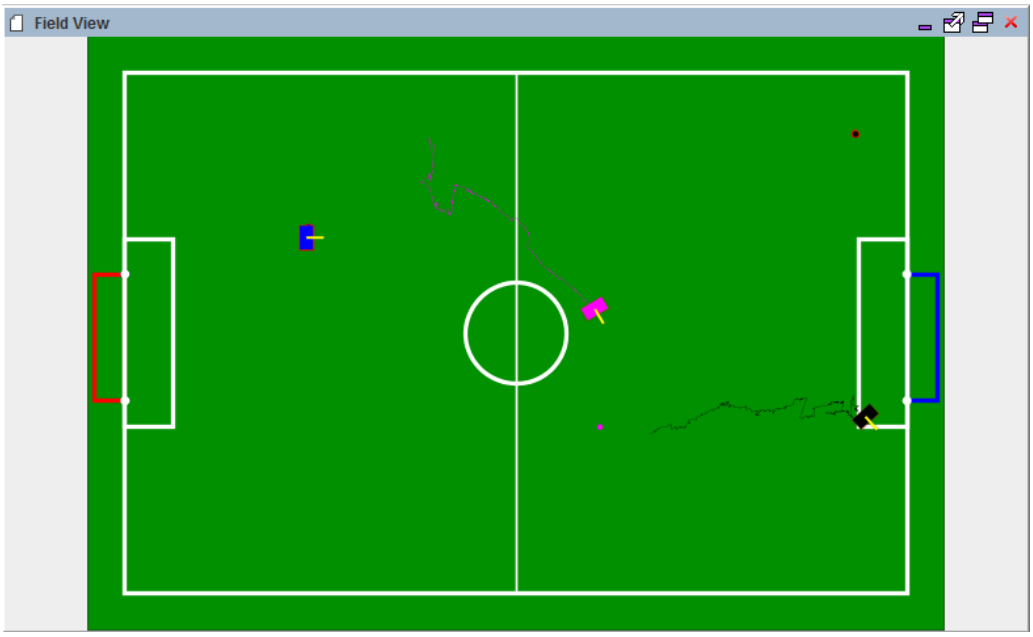


Figure 5.4: Example field view in the debug tool.

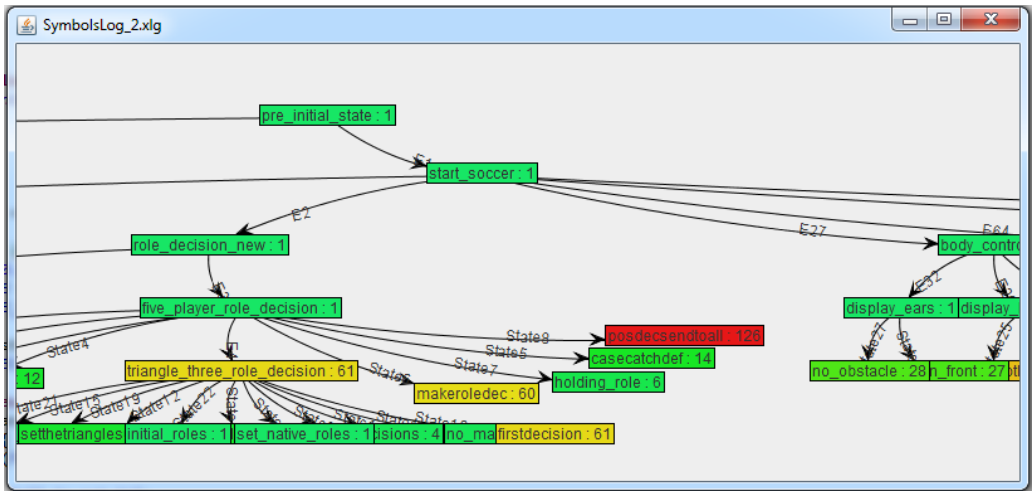


Figure 5.5: Example CABSL state tree in the debug tool.

5.2 SmartRef

Refereeing a game in the Standard Platform League (SPL) has become an increasingly demanding job over the past years. Robots are moving faster, there is more activity in the games, and finally the number of robots to constantly observe has increased to five per team.

Moreover, the environment during the games is challenging and imposes additional difficulties and problems on the referees to deal with. In this regard, the size of the SPL field has grown to $54m^2$, and the communication between the head and assistant referees is significantly impaired by cheering crowd, and noise from supporting team members.

Team Nao Devils decided to address this problem by developing a smartphone application that supports referees doing their work. The smartphone application is designed to smoothly integrate into the existing RoboCup software infrastructure. Thus, the application listens to the GameController and reacts on its commands. At the moment it is available for Android smartphones. On a mid-term perspective, it is intended to migrate the software application from the smartphone to smartwatches, and to other RoboCup disciplines.

The smartphone application SmartRef includes a context-sensitive graphical user interface and offers the following features:

- Specialised views for each stage of the game.
- Different views for head referees and its assistants (see figure 5.8(a)).
- Dynamic rule helper, e.g. for manual positioning, throw-in positions (see figure 5.6).
- Vibration in case of events (e.g. robots to be penalized, back in) (see figure 5.7(a)).
- Display of time limits (game times, kick off, all in play).
- Warnings at the end of each half-time.

- A timeout helper (see figure 5.8(b)).

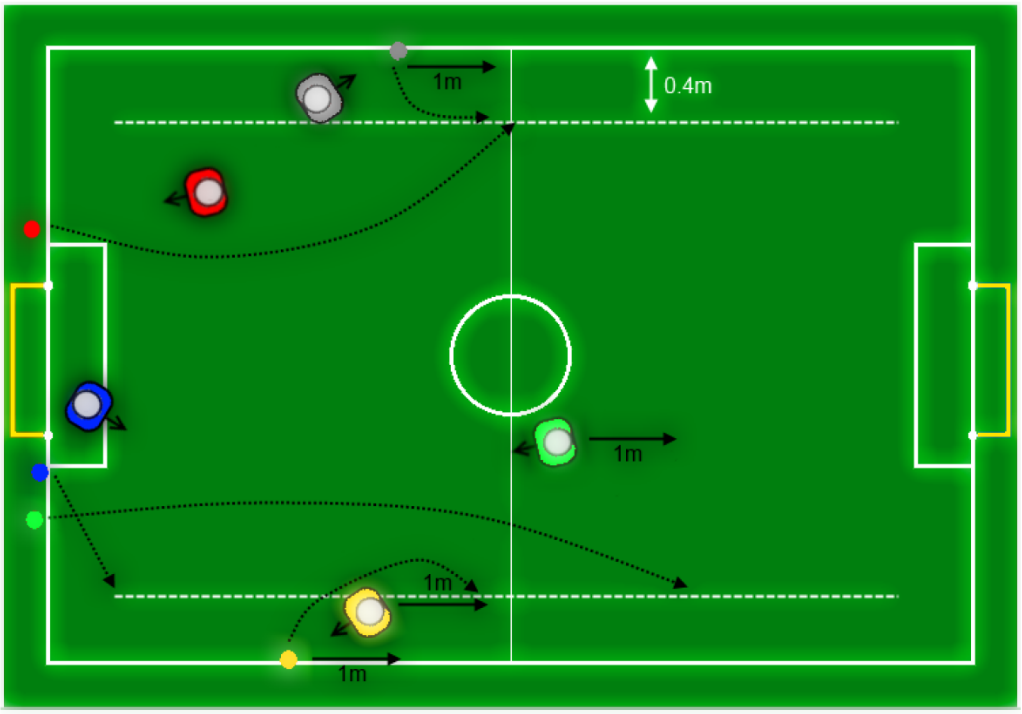
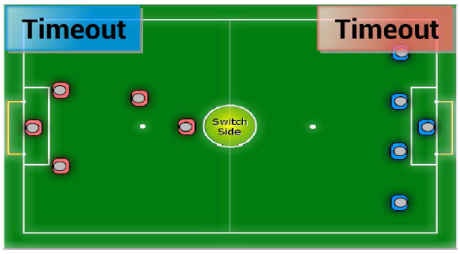


Figure 5.6: Rule helper view for throw-in positions.

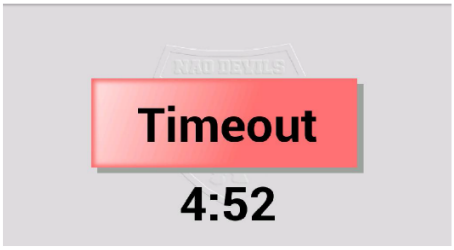
(a) Penalized robots with numbers and timer.

(b) Events during the game.

Figure 5.7: Penalties and events view.



(a) Field view with manual kickoff positions.



(b) Timeout helper.

Figure 5.8: Views for timeouts and manual kickoff positions.

5.3 NaoDeployer

Setting up robots for experiments and games usually requires a sequence of manual steps to be performed. This include modifications in configuration files and the deployment of the framework onto the robots. As those steps turn out as cumbersome and error-prone, our team provides a tool that simplifies software deployment, game preparation and post-processing. NaoDeployer is compatible with the Nao Devils and B-Human frameworks, and therefore usable for all teams relying on that codebase. The tool runs with Microsoft Windows, but migration to other operating systems is planned.

The graphical user interface of the tool is shown in figure 5.9. Users are able to select a number of robots from the listing on the left side for setup. Connection details of the robots are stored in the file "LAN.conf". The configuration of the robots' interfaces are depicted in listing 5.1. Comments are marked with '#', interfaces with '*'. The order of the robots in the listing on the widget corresponds with the order of the interfaces specified in the file.

Listing 5.1: LAN.conf

```
# This is robot Nao A
* 192.168.100.11
```

The button "setup robot" can be used to run copyfiles.cmd which is a script to copy all executables and configuration files onto the robots, and is part of the framework. The script can be parametrized via the GUI by a directory that specifies the location of the deployed files on the robot (username), by the build configuration to be used, and by the team number and robot numbers. Note that using a specific build configuration requires the compilation of the framework with the very build setting. The robot numbers are determined by the position of the Naos on the field in the middle part of the widget.

Moreover, the robot can be controlled rempotely. The tool allows to start and quit NaoQi and the framework; the OS which runs on the NAO can be rebooted and shutdown. It is possible to display and filter any outputs of the robots' shells, the SSH connections and deployment processes.

The tool allows to copy logfiles from the robots directly into a specified directory. NaoDeployer must be configured with the correct path to the framework version to be deployed. The tool is open source and available at GitHub: `https://github.com/NaoDevils/NaoDeployer`.

Figure 5.9: Nao Deployer.

Chapter 6

Conclusion and Outlook

The *Nao Devils Dortmund* is a team from the TU Dortmund University with roots in several other teams which have competed in RoboCup competitions over the last years. This team report covered a short overview of the main ideas and concepts that were employed and successfully used in RoboCup 2014.

At the Open Challenge 2014 we presented our current state in a way more complex environment, playing outside on artificial grass with direct sunlight with the same code we use for usual competition games. This is due to various enhancements we implemented in the past:

- An image processor without fixed color tables that works under varying lightning conditions using automatic camera settings.
- A walking engine that is not only tuned for a specific environment but utilizes various methods to stabilize a disturbed walking, especially reactive stepping.
- A flexible self localization.

For RoboCup 2015, beside integrating the new soccer rule changes, we plan to reintegrate a long distance kick and to develop a decision process that selects the best kick for every situation.

Appendix A

Walking Engine Parameters

In this section the most important parameters to control the Walking Engine are described. They can be found in the file <coderelease directory>/Config/walkingParams.cfg. Some parameters needed by the ZMP/IP-Controller are located in the file <coderelease directory>/Util/Matlab/NaoV3.m. The Matlab script writeParamsV3.m calculates the values used by the ZMP/IP-Controller using the parameters in this file and stores the results to <coderelease directory>/Config/Robots/<robot name>/ZMPIPController.dat. To execute the script open Matlab, change the current directory to <coderelease directory>/Util/Matlab and enter the following command:

```
writeParamV3(NaoV3('<robot name>'))
```

All values are expressed in SI units, unless otherwise stated.

A.1 File walkingParams.cfg

The file walkingParams.cfg consists of the following parameters:

footPitch

To avoid hitting the ground with the forward section of the foot an offset is applied to the foot rotation around the y axis. The added value reaches its maximum at the middle of the single support phase. The maximum can be set using footPitch.

xOffset

The center of the feet can be shifted along the x axis by setting this value unequal to 0. This offset is constant for the whole walk.

stepHeight

Maximum z position of the foot during the single support phase, see section 2.1.4.

sensorControlRatio

The sensorControlRatio is multiplied with the difference between the target ZMP and the measured ZMP. Legal values are $[0 \dots 1]$, where 0 means 'no sensor control' and 1 'full sensor control'.

doubleSupportRatio

Proportion of the double support phase during a step.

crouchingDownPhaseLength, startingPhaseLength, stoppingPhaseLength

These values define the duration of the transitions between a walk and special actions.

armFactor

The movement of an arm depends on the x coordinate of the opposite foot. The x coordinate is multiplied with armFactor and applied to the ShoulderPitch.

arms1

This value is the angle of ShoulderRoll for both arms. It is constant during the walk.

zmpSmoothPhase

To avoid hard sensor feedback during transitions from special actions to walk and vice versa the ZMP error is faded in and out. This parameters sets the length in frames of this phase.

maxSpeedXForward, maxSpeedXBack, maxSpeedYLeft, maxSpeedYRight, maxSpeedR, maxSpeedXForwardOmni

These values define the maximum speed. All requests sent to the Walking Engine are clipped to these values.

stepDuration

The PatternGenerator defines the footsteps based on two single support phases and two double support phases. The duration of all together is the stepDuration.

footYDistance

Distance between the feet.

stopPosThresholdX, stopPosThresholdY, stopSpeedThresholdX, stopSpeedThresholdY

Stopping a walk and executing a special action is only possible when the Walking Engine sets a flag which indicates that it does not compromise the stability. The Walking Engine uses this 4 indicators to check if the speed of the center of mass is low enough and the position within a stable range.

zmpLeft, zmpRight

Position of the target ZMP in the (left/right)foot coordinate system when the robot stands on one leg.

outFilterOrder

Before sending the angles to the robot they are low-pass filtered. This parameter defines the order of the filter.

tiltControllerParams, rollControllerParams

Gains for the tilt/roll PID controller params implemented in the module GyroTiltController.

sensorDelay

The sensor control relies on a good comparison between the measured ZMP and the target ZMP. In most cases the measurements are some frames old and must be compared with the target of the same frame.

halSensorDelay

Delay of the hal sensors used to measure the joint angles.

maxFootSpeed, fallDownAngle

The Walking Engine has an integrated check for instabilities to avoid breaking joints. Due to the sensor control the robot can react in an unexpected way resulting in very fast movements. The maximum speed of the feet can be limited by using maxFootSpeed. Additionally all movements are stopped immediately when the robot exceeds the maximum tilt or roll angle defined by fallDownAngle.

polygonLeft, polygonRight

As mentioned in section 2.1.3 the reference ZMP is calculated using a Bézier curve. This parameters define the y coordinates of the control points in the corresponding foot coordinate system.

offsetLeft, offsetRight

Due to high torques acting on the joints during the single support phase large angle errors can be observed. To compensate the effects a constant offset is added to each leg joint which can be configured using these parameters.

walkRequestFilterLen

To avoid abrupt speed changes a low-pass filter can be activated to filter the incoming speed requests. A value of 1 means deactivated.

accXAlpha

Gain controlling the acceleration sensor feedback (see section 2.1.2).

maxAccX, accDelayX, maxAccY, accDelayY, maxAccR, accDelayR

Besides the low-pass filter there is an other way to limit speed changes. If the acceleration resulting from the new speed request is higher than maxAcc only maxAcc is applied until accDelay frames are elapsed.

speedApplyDelay

This is the third way to limit speed changes. If a speed change has been detected further speed changes are ignored for speedApplyDelay frames.

legJointHardness

The stiffness parameter for the leg joints. The stiffness cannot be set for each leg separately.

heightPolygon

This five values are multiplied with stepHeight to get the z coordinates of the control polygon for the swinging leg as explained in section 2.1.4.

standRollFactor

A factor especially for standy on one leg. Instead of reaching he target center of mass position by translating the body, this factor allows to reach the target by rotating the body.

A.2 File NaoNG.m

The following parameters can be found in the file NaoNG.m:

g

The Gravity.

z_h

Target height of the center of mass over the ground.

dt

Length of one frame.

R

Controller-Parameter R [14].

N

Duration of the preview phase as explained in section 2.1.2.

Qx

Controller-Parameter Qx [14].

Qe

Controller-Parameter Qe [14].

Ql

Gain for calculating L [14].

RO

Gain for calculating L [14].

path

Path to the file ZMPIPController.dat.

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