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Toni: A Soccer Playing Humanoid Robot

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Abstract. This paper describes the humanoid robot Toni that has been designed to play soccer in the RoboCup Humanoid League. The paper details Toni's mechanical and electrical design, perception, self localization, behavior control, and infrastructure.
Toni is fully autonomous, has a low weight (2.2kg), and is much taller (74cm) than most servo-driven humanoid robots. It has a wide field of view camera, ample computing power, and wireless communication.
Toni possesses basic soccer skills. It walks dynamically in all directions (up to 20cm/s in forward direction) and turns on the spot. It perceives the ball and the goals and localizes itself on the field. Toni is able to approach the ball and to dribble it. It can kick the ball without falling.
We performed tests in our lab and penalty kick demonstrations at RoboCup German Open 2005. Toni's successors Jupp, Sepp, and Max performed well at the RoboCup 2005 Humanoid League competitions.

1 Introduction

The ultimate goal of the RoboCup initiative is stated as follows: 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 [9]. As one step towards this long-term goal, the RoboCup Federation added in 2002 a league for humanoid robots to their annual soccer championships.

Three competitions took place in the RoboCup Humanoid League so far. In preparation for real soccer games, the robots had to demonstrate their capabilities by solving a number of subtasks.

In the Humanoid Walk, they had to walk towards a pole, to turn around it, and to come back to the start. Scoring was based on walking speed and stability. In the Penalty Kick competition, two robots faced each other. While one robot tried to score a goal, the other defended. In the Freestyle competition, the robots had five minutes to show a performance to a jury. Each year, there is also a new technical challenge. In 2004, it consisted of an obstacle walk, a passing task, and balancing across a sloped ramp.

The RoboCup Humanoid League competition rules [11] require robots to have a human-like body plan. They must consist of a trunk, two legs, two arms, and a head. The only allowed mode of locomotion is bipedal walking. The robots must be fully autonomous. No external power, computing power, or remote control is allowed.

In the 2002 Humanoid League competition, the Nagara robot was the overall winner. A Honda Asimo prototype of team HITS Firstep [6] won in 2003. Team Osaka won the 2004 competition with the robot VisiON [17]. This robot used an omnidirectional camera as head. As a goalie it could defend against a shot by jumping to the ground. Afterwards, VisiON got up without help. Another highlight of the competition was the passing demonstration between two Hoap-2 robots of team Senchans A [14].

Despite these impressive achievements, the overall performance of the soccer playing humanoids is still far from perfect. Basic soccer skills, such as robust dynamic walking and kicking without loosing balance are not possessed by all robots. Even the best robots sometimes show instability while walking, fail to kick the ball, or defend against shots not taken. Consequently, further research is needed. Within the Humanoid League, the performance of smaller, servo-driven robots in general exceeds the performance of larger robots. The only convincing larger robot so far was the Honda Asimo prototype, out of reach for almost all researchers.

In the following, we describe the humanoid robot Toni, which has been designed by our team NimbRo for the 2005 RoboCup Humanoid League soccer competitions. We use servo motors to drive its 18 joints for their relatively low cost and for their good weight-to-torque ratio. Our design focused on weight reduction to make Toni agile. We used standard components for computing power and camera because of their high degree of integration and their relatively low cost.

This paper is organized as follows. In the next section, we review some of the related work. Section 3 describes Toni's mechanical and Section 4 its electrical design in detail. In Section 5 proprioception, computer vision, and self localization are covered. Section 6 describes how Toni is controlled using a hierarchy of reactive behaviors, and Section 7 details its infrastructure components.

2 Related Work

Humanoid robots are not only a good choice for playing soccer. The anthropomorphic body shape is also helpful for acting in environments that have been designed for humans, in particular for the interaction with people. In addition to speech, a humanoid robot can try to use the same means for intuitive multimodal communication that people use: body language, gestures, mimics, and gaze. Consequently, a number of research groups, especially in Japan, are constructing humanoid robots. A list of projects is maintained by Willis [22].

Among the most advanced humanoid robots developed so far is the 58cm tall Sony Qrio [16]. It contains three CPUs and has 38 degrees of freedom (DOF). Qrio is able to walk and dance. Research on map building and navigation, as well as on human-robot interaction is carried out inside Sony. Currently, it is unclear if and when this robot will be available to a larger research community, but the costs of Qrio have been compared to the price of a luxury car.

Unlike Qrio, Hoap-2 (25 DOF, 50cm tall), developed by Fujitsu [4], has been sold to some labs for about USD 50,000. It is used by the RoboCup team Senchans A, but never won the competition.

A taller humanoid, Asimo, has been developed by Honda [5]. The recently announced research version has 34DOFs and a height of 130cm. It can walk at 69cm/s and jogs at 83cm/s. It is possible to rent Asimo for about USD 162,000 per year for presentations.

Approximately the same size of Asimo has a trumpet playing humanoid robot which has been announced recently by Toyota [20]. It is displayed at Expo 2005 in Aichi, Japan.

While these humanoid robots are impressive, they are not available to researchers outside the industry labs or are too expensive for academic research. There are few publications about the details of humanoid robots developed by industry. Academic projects, like H7 of Tokyo University [7, 12] and HRP-2P [8] of the Japanese AIST are better documented.

Many existing humanoid robots are not adapted to the needs of soccer competitions. In soccer, the robots must survive a fall. Some robots even jump or lie down and get up by themselves again. The soccer robots must also be fully autonomous. Many existing robots have only limited senses. Some of them rely on external computers for behavior control. It might also prove difficult to get access to the lower levels of their APIs.

In addition to the expensive larger humanoid robots, which are usually driven by DC-motors and harmonic drive gears, some smaller servo-driven humanoid robots have been developed recently [10, 21, 23]. Some of these robots performed well at RoboCup competitions.

The servo-driven robots have up to 22DOFs and a size of 30-40cm. As the competition rules require the robots now to be fully autonomous, it becomes difficult for these small robots to carry a camera and sufficient computing power. The small body size also limits the walking speed of these robots.

To overcome the described limitations, we designed a taller servo-driven humanoid robot that keeps the low weight of the smaller robots. We added a wide-angle camera, ample computing power, and wireless communication to it.

3 Mechanical Design

Fig. 1 shows two views of our humanoid robot Toni, ready to kick the ball. As can be seen, Toni has human-like proportions and a slim appearance. Its mechanical design focused on weight reduction. Toni is 74cm tall and has a total weight of only 2.2kg.

The robot is driven by 18 servo motors: 6 per leg and 3 in each arm. The six leg-servos allow for flexible leg movements. Two orthogonal servos form the 2DOF hip joint and the 2DOF ankle joint. One servo drives the knee joint.

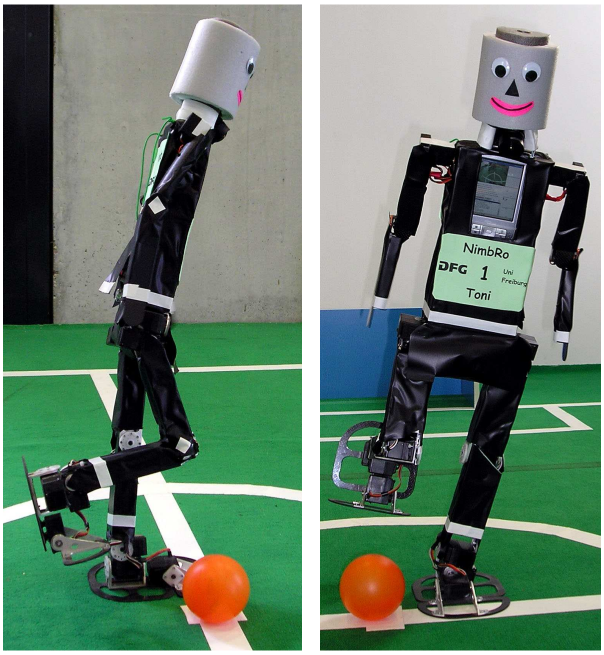


Fig. 1. Two views of the humanoid robot Toni, ready to kick.

A special feature of Toni is its active toes joint, located in the foot plate. It allows for over-extending the leg. This is needed for walking with a straight stance leg. Most humanoid robots shorten the stance leg by bending the knee joint to avoid singularities. This requires high-torque knee actuators and leads to an unnatural gait pattern. When the stance leg is kept straight, torques are reduced and the gait is more natural. However, when walking with large steps, it is now necessary to over-extend the other leg before toes-off in order to shift the weight to the stance leg. The extra segment between the ankle joint and the toes joint provides this extra leg extension [1]. The toes joint is also used when kicking the ball. To our knowledge, only the H6/7 robots of Tokyo University possess active toes joints [13].

We selected the S9152 servos from Futaba to drive the hips, the knees, and the ankles. These digital servos are rated for a torque of 200Ncm. They have a weight of only 85g. The toes joints need less torque. They are powered by JR 8511 servos (185Ncm, 66g). We augmented all servos by adding a ball bearing on their back, opposite to the driven axis. This made a stiff joint construction possible.

Toni's arms do not need to be as strong as the legs. They are powered by SES640 servos (64Ncm, 28g). Two orthogonal servos constitute the shoulder joint and one servo drives the elbow joint.

The skeleton of the robot is mostly constructed from aluminum extrusions with rectangular tube cross section. In order to reduce weight, we removed all material not necessary for stability. Toni's feet and its arms are made from sheets of carbon composite material. Its head is there for completeness only. It is made of lightweight foam.

4 Electronics

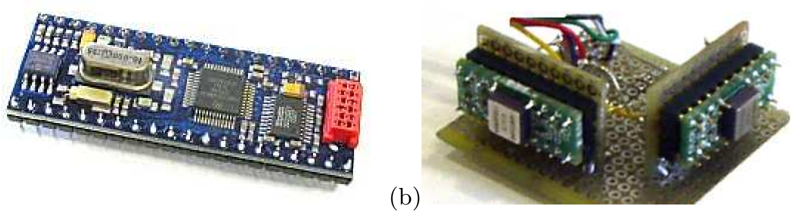
Toni is fully autonomous. It is powered by high-current Lithium-polymer rechargeable batteries, which are located in its pelvis. Two Kokam 2000H cells last for about 30 minutes of operation. They can be discharged with 30A and have a weight of only 110g.

The servos are interfaced to three tiny ChipS12 microcontroller boards, shown in Fig. 2(a). One of these boards is located in each thigh and one board is hidden in the pelvis. These boards feature the Motorola MC9S12C32 chip. This 16-bit controller belongs to the popular HCS12 family. We clock it with 24MHz. It has 2kB RAM, 32kB flash, a RS232 serial interface, CAN bus, 8 timers, 5 PWM channels, and 8 A/D converters. We use the timer module to generate pulses of 1...2ms duration at a rate of 180Hz in hardware. These pulses encode the target positions for the servos. Up to eight servos can be controlled with one board.

In order to keep track of the actual servo movements, the potentiometer voltages are digitized by the A/D converters and processed by the microcontrollers. By analyzing the temporal fine structure of these signals, we estimate not only the current servo positions, but also the PWM duty cycles of their motors.

In addition to these joint sensors, Toni is equipped with an attitude sensor, shown in Fig. 2(b). It consists of a dual-axis accelerometer (Analog Devices ADXL203, ± 1.5g) and two gyroscopes (ADXRS 150/300, $\pm 150/300$ deg/s). This attitude sensor is located in its pelvis. The four analog sensor signals are digitized with A/D converters of the HCS12 and are preprocessed by the microcontroller.

The microcontrollers communicate with each other via a CAN bus at 1MBaud and with a main computer via a RS232 serial line at 115KBaud.



(a) (b)

Fig. 2. Electronics: (a) ChipS12 microcontroller board featuring HCS12C32; (b) Attitude sensor consisting of a dual-axis accelerometer and two gyroscopes.

Every 6ms, target positions for the servos are sent from the main computer to the HCS12 boards. The microcontrollers send the preprocessed sensor readings back. This allows to generate smooth trajectories for the servos and to keep track of the robot's state in the main computer.

We use a Pocket PC as main computer, which is located in Toni's chest (see Fig. 1). The model FSC Pocket Loox 720 has a weight of only 170g, including the battery. It features a 520MHz XScale processor PXA-272, 128MB RAM, 64MB flash memory, a touch-sensitive display with VGA resolution, Bluetooth, wireless LAN, a RS232 serial interface, and an integrated 1.3 MPixel camera.

This computer runs behavior control, computer vision, and wireless communication. It is equipped with a Lifeview FlyCAM CF 1.3M that has been fitted to an ultra-wide-angle lens. The lens is located approximately at the position of the larynx. The wide field of view of this camera (vertically about 112°) allows Toni to see at the same time its own feet and objects above the horizon. The horizontal field of view is approximately 150°.

We also tested a Sony Vaio U750P PC as main computer, which is small enough to fit into Toni's trunk, as shown in Fig. 3(a). The PC has a weight of 550g, including batteries, and features an ultra-low voltage 1.1GHz Pentium M 733 processor, 512MB RAM, 20GB harddrive, a touch sensitive display with SVGA resolution, and wireless LAN.

This PC is interfaced to two ultra-wide-angle USB cameras, also visible in Fig. 3(a). They consist of webcam electronics, a 1/3" CCD imager, and a door viewer lens. Toni can see almost all objects around it when these cameras are pointed towards the front and the back. Two simultaneously captured images are shown in Fig. 3(b). The cameras deliver up to 30fps and the PC is fast enough to process the images and to localize the robot at this rate. The total weight of the robot in this configuration is only 2.7kg.

5 Perception

In order to play soccer, Toni needs information about itself and about the situation on the field. In particular, it must know where the ball and the goals are, localize itself on the field, and perceive other players.

We fuse the accelerometer and gyro readings to obtain an estimate of Toni's attitude. This is done by integrating the rotation speeds measured by the gyroscopes. The long-term readings of the accelerometers are used to provide a starting point for the integration. Furthermore, the biases of the gyros are compensated using the accelerometer readings. In combination with the measured joint angles, the attitude allows to reconstruct the camera pose.

The only source of information about Toni's environment is its camera. The wide-angle CF color camera allows seeing the ball at the robots feet, the goal, and poles simultaneously (see Fig. 4(a)). In RoboCup soccer, these key objects are color-coded. The ball is orange, the field is green, goals are yellow and blue, and poles contain magenta and a goal color.

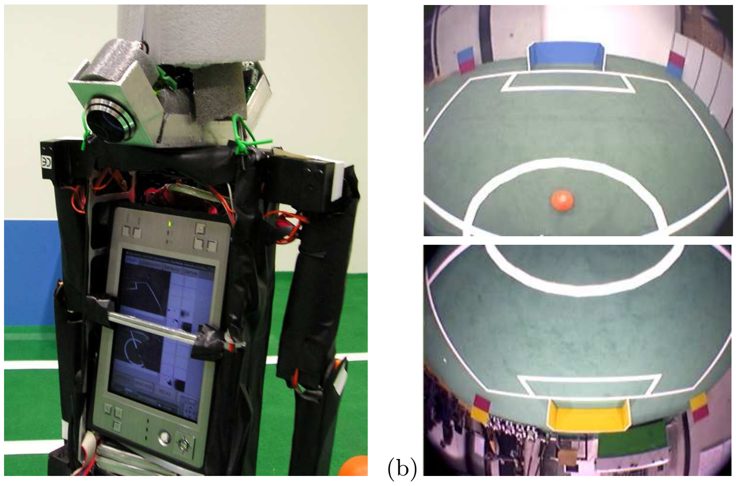
(a) (b)


Fig. 3. Toni with a small PC and two ultra-wide-angle USB cameras: (a) Picture of the robot's back and neck; (b) Pictures captured simultaneously from the two cameras.

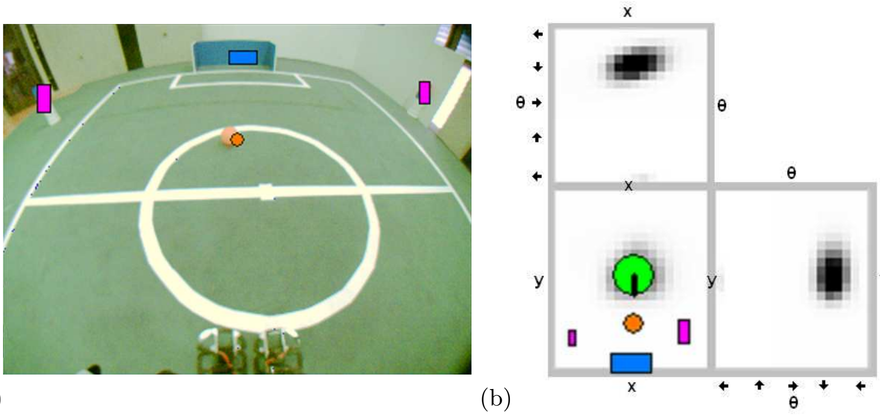
Our computer vision software converts the captured RGB images into the YUV color space to decrease the influence of different lighting conditions. The colors of pixels are classified with the pie-slice method [19]. In a multistage process insignificant colored pixels are discarded and the colored objects are detected. Their coordinates are estimated in an egocentric frame (distance to the robot and angle to its orientation), based on image position and object size. These relative coordinates suffice for many relative behaviors, like positioning behind the ball while facing the goal.

To implement global team behaviors, such as kick-off, we need the robot coordinates in an allocentric frame (position on the field and orientation). We estimate these using a probabilistic Markov localization method that integrates egocentric observations and motion commands over time. As proposed by Fox, Burgard, and Thrun [3] this method uses a three-dimensional grid (x, y, θ) to represent the probability distribution of robot poses. The grid is shown in Fig. 4(b).

6 Behavior Control

We control Toni using a framework that supports a hierarchy of reactive behaviors [2]. This framework allows for structured behavior engineering. Multiple layers that run on different time scales contain behaviors of different complexity. This framework forces the behavior engineers to define abstract sensors that are aggregated from faster, more basic sensors. Abstract actuators give higher-level behaviors the possibility to configure lower layers in order to eventually influence the state of the world.

The framework also supports an agent hierarchy. For Toni, we use three levels of this hierarchy: individual joint, body part, and entire robot. This structure



(a) (b)

Fig. 4. (a) Image captured from Toni's perspective while it was walking. Detected objects: goal (blue horizontal rectangle), ball (orange circle), and pole (magenta vertical rectangle); (b) Three 2D projections of the 3D grid representing the probability distribution of robot poses (x, y, θ). The green circle is drawn at the estimated robot location (x, y). The black line represents its estimated orientation θ. The detected objects are drawn relative to the robot.

restricts interactions between the system variables and thus reduces the complexity of behavior engineering.

The lowest level of this hierarchy, the control loop within the servo, has been implemented by the servo manufacturer. It runs at about 300Hz for the digital servos. We monitor target positions, actual positions, and motor duties.

At the next layer, we generate target positions for the individual joints of a body-part at a rate of 167Hz. We make sure that the joint angles vary smoothly. This layer implements an interface that describes the behavior of body parts. For example, the entire leg can be positioned using leg extension (the distance from the hip joint to the ankle joint), the leg angle (angle between the pelvis plate and the line from hip to ankle), and foot angle (angle between foot plate and pelvis plate).

Such a more abstract actuator space simplifies the implementation of dynamic walking on the next layer. A central pattern generator running in the trunk determines the step frequency. Both legs derive their own gait phase by shifting the trunk phase by $\pm\pi/2$. Based on this gait phase, each leg generates trajectories for its leg extension, leg angle, and foot angle.

The two key ingredients for generating dynamic walking are lateral shifting of the robots center of mass, and movement of the legs in walking direction. The swinging leg is shortened while it is moved quickly into the walking direction. At the same time, the supporting leg has maximal extension and is moved slowly against the walking direction. The resulting trajectories of leg angles and leg extension are shown in Fig. 5 for the case of walking in forward direction with small steps.

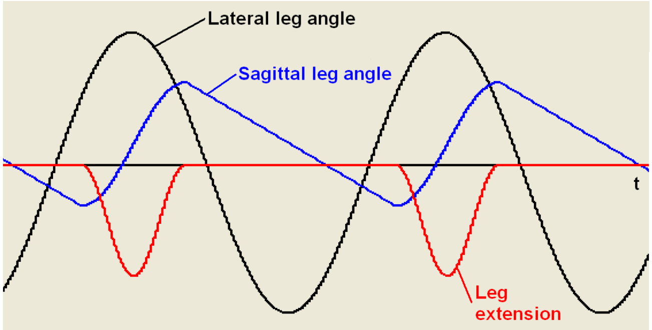


Fig. 5. Dynamic walking. Leg angles and leg extension of a leg while walking forward with small steps. The other leg moves in the same way, with a phase offset of π.

Toni's maximum walking speed is about 20cm/s. The robot is not only able to walk forward and backward, but it can also walk to the side. By blending these gait directions, we generate omnidirectional walking. Toni is also able to turn on the spot. We used this interface to implement higher-level behaviors, like approaching the ball, dribbling, and positioning for penalty kicks.

In addition to omnidirectional walking, we implemented a kicking behavior for Toni. Fig. 6 shows trajectories for the sagittal hip joints of both legs and the knee joint of the kicking leg. The kicking leg strikes out, accelerates smoothly until it hits the ball and decelerates again. Note that all three joints reach their maximum speed in forward direction when the ball is hit. The kicked ball rolls for approximately two meters on carpet. Afterwards, Toni goes back to a stable stand.

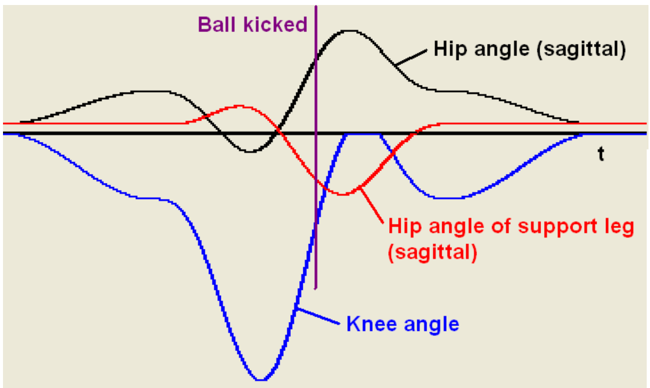


Fig. 6. Kicking. Joint angles of the knee of the kicking leg and the sagittal hip joints of both legs.

Toni's toes joints are used when walking with larger steps during the double-support phase. The unloading leg is over-extending to push the center of mass above the loading leg [1]. We also used the toes joints to balance Toni on the frontal part of the foot plate (toes).

7 Infrastructure

In addition to the robot itself, we implemented some infrastructure components to support behavior engineering.

• **Simulation:** In order to be able to design behaviors without access to the real hardware, we implemented a physics-based simulation for Toni. This simulation is based on the Open Dynamics Engine [15]. It is visualized in real time using OpenGL [18].

• **Communication:** Toni is equipped with a wireless network adapter. We use the wireless communication to transmit via UDP debug information to an external computer, where it is logged and visualized. This computer is also used to fuse local views to a team view when multiple robots are playing. We plan to use it to compute team behaviors, such as the assignment of roles to the individual players. We also plan to use the wireless network for transmitting the game state (kickoff, penalty ...) to the robots.

• **Test Behaviors and Remote Control:** On all levels of the behavior architecture, we implemented test behaviors that generate sequences for the abstract actuators in order to test the behavior of the lower layers. Similarly, the lower layers can also be tested by setting the actuators to the readings of a joystick. In this way, the user can determine an individual joint angle, a leg parameter, or the walking direction and speed of the robot.

• **Monitoring:** All variables of the system, such as joint angles, sensor readings, actuator values, and behavior activations, are logged. They can be visualized live or after an experiment. The analysis of not only the observable robot behavior, but also its internal state is extremely helpful when debugging behaviors.

8 Conclusions

This paper described the humanoid robot Toni, which was designed to play soccer. It detailed its mechanical and electrical design, perception, behavior control, and infrastructure.

Toni is fully autonomous, has a low weight of only 2.2kg, and is much taller (74cm) than most servo-driven robots. It has 18 DOFs, with toes joints as special feature. The robot is equipped with a wide field-of-view color camera, ample computing power, and wireless communication.

Toni possesses basic soccer skills. It can walk dynamically in all directions and is able to turn on the spot. It perceives the ball and the goals and localizes itself on the field. Toni is able to approach the ball and to dribble it. It is able to kick the ball without falling.

Fig. 7. Penalty Kick demos at RoboCup German Open 2005: Toni vs. Mr. DD.

We presented Toni for the first time to the public during the 21st Chaos Communication Congress (Berlin, Dec. 2004), where it was playing with a soccer ball. At RoboCup German Open (Apr. 2005), we showed penalty kick demonstrations against Mr. DD of Darmstadt Dribblers. Toni was able to approach the ball, such that the ball was located in front of its kicking foot and the robot was facing the goal. Toni slowed down when coming close to the ball and triggered its kicking behavior when positioned well enough. The robot smoothly stopped walking, reached out and kicked the ball strongly towards the goal.

For the RoboCup 2005 Competition, which took place in July in Osaka, Japan, we constructed three more robots, based on Toni's technology. Jupp and Sepp have a size of 60cm and played in the KidSize class. Max has a size of 70cm and played in the MidSize class. All three robots have an additional yaw-joint in the thigh, a pitch-joint in the trunk, and stronger arms. They can rotate easier on the spot and are able to get up after a fall. These robots performed well. Our team NimbRo got 2nd and 3rd in the Technical Challenge, next to Team Osaka. Max won the MidSize Penalty Kick final 3:0 against Aria (Iran). Sepp and Jupp reached the final in the 2 vs. 2 soccer games. They lost 2:1 against Team Osaka. They also scored the second highest number of goals in the Penalty Kick competition, next only to Team Osaka. In the overall Best Humanoid ranking, Osaka won, NimbRo KidSize came in 2nd, and NimbRo MidSize was 3rd.

Videos of the competitions can be found at: http://www.NimbRo.net.

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