17

Advancing Artificial Intelligence through Minimalist Humanoid Robotics

Jacky Baltes and John Anderson

Autonomous Agents Laboratory, Department of Computer Science, University of Manitoba, Winnipeg, Manitoba, Canada R3T2N2
andersj@cs.umanitoba.ca

Abstract. While the robots that most quickly come to mind to the general public are those with the most elaborate features and movements, those that are most useful in advancing the state of the art in artificial intelligence (AI) are very different. Minimalist robots are inexpensive and therefore more broadly available for research and educational purposes, but also force the researcher to rely on good, adaptable solutions to hard AI problems rather than relying on expensive specialized hardware that will only work under strict conditions. This chapter describes our work in minimalist humanoid robots, focussing mainly on Tao-Pie-Pie, a robot that competed successfully in numerous RoboCup and FIRA competitions. The chapter describes our motivations in designing minimalist robots and our rationale for working with humanoid robots, and describes the development of Tao-Pie-Pie, including contrasting this robot with other work and developing its walking gait and balancing reflexes. We then describe some issues in evaluating humanoid robots, and describe ongoing work.

17.1 Introduction

The robotics examples that best capture the imagination of the general public are generally those that are the most elaborate physically - those that can accomplish the most elaborate movements and appear the most human, even if the movements are preprogrammed and non-adaptable. In contrast to this, we believe that the best examples of robots from the standpoint of advancing artificial intelligence are much more minimal in nature: in our work, we always attempt to design a robot with the most minimal features necessary to accomplish the task at hand.

There are a number of important reasons for this. One is affordability, and the practical benefits that working with affordable research platforms brings to a laboratory. More broadly affordable robots means being able to support research more broadly, such as being able to explore issues in teamwork as opposed to being limited to individuals. It also means being able to equip more students and better support education and research in general. A second reason is practicality: even in cases where robots have a great expensive additions, such as gyroscopes, accelerometers, and other forms of sensing, these are in many cases not used in robotics competitions, either because particular devices are not crucial for the task at hand, or because of the complexities of integrating numerous senses and control [7]. In cases such as this, the additional features of the robot serve no purpose.

D. Liu, L. Wang, and K.C. Tan (Eds.): Design and Control of Intel. Robotic Systems, SCI 177, pp. 355–376.
springerlink.com

A much larger but less obvious advantage, however, is the fact that a minimalist approach serves to force a grounding on researchers, requiring them to provide more generally intelligent and adaptable approaches to any given problem. This is because the difficult parts of any problem cannot be overcome simply by using specialized hardware. For example, a robot whose sole goal is to play soccer on an even surface can use specialized rubber feet and mechanics to improve its performance. While such a robot might be an excellent soccer player, it would not be able to walk at all over uneven terrain or a gravel road. On the other hand, a researcher that does not have access to this specialized hardware must instead provide better solutions to basic problems such as localization and balancing, and these solutions are applicable to both the soccer problem and a broad array of problems that a solution requiring specialized hardware would not be. More general solutions require additional effort on the part of the researcher, but serve to greatly advance the state of artificial intelligence (AI), since we rely more on AI than specialized hardware.

In the same fashion, inexpensive equipment generally does not guarantee standards of precision. Even using similar mechanics and control, a system that uses cheap motors would still need to adapt to situations such as the right leg motor being stronger than the left leg motor. However, because of its inherent need to adapt to variations, such a system is much more robust when deployed in a real world environment.

Similarly, a robot whose walking gait is not precise due to hardware limitations forces the designer to rely on better balancing and better localization techniques, for example. All of these are the kinds of solutions that we see humans adapting to problems: not optimal, but sufficiently well in a wide range of situations.

The human form itself is an example of this: a humanoid robot cannot traverse flat ground faster or with less effort than a wheeled robot, for example. In fact, any individual activity in a specific setting can be performed faster or better using a less general form than a humanoid. Even in the biological world, other species can outperform humans in any area (e.g., horses can run faster, dolphins swim better, and monkeys climb better than humans), but humans are among the top five performers in all categories. The form itself has evolved not to do any one task well, but to perform adequately and adaptably to a huge range of tasks.

In addition to having similar benefits to minimalist robotics generally, a focus on the humanoid form brings about important side benefits. Robots of any kind will have to function in a world that is designed for humans, and while the humanoid form is not optimal, it does not require specialized environmental adaptations that wheeled robots require. In addition to being able to interact with the wide variety of equipment designed for humans, humans can also relate more easily to a robot in a human form: we anthropomorphise devices that look more like us, and humans already have a set of expectations that fit the humanoid form, allowing these to be exported more easily to a machine.

We believe that a focus on the humanoid form combined with that of minimizing specialized hardware will ultimately be a significant advantage in improving research in artificial intelligence. . In recent years we have been working with humanoid robots of varying complexity, attempting to focus on the minimum necessary hardware to support various forms of intelligent interaction with the world.

This chapter focuses in detail on our experiences designing and working with one minimalist humanoid robot: *Tao-Pie-Pie*, which competed in a number of RoboCup and FIRA HuroCup competitions, and became well-known for both its small size and the degree of functionality it displayed despite its minimalist nature. The first part of the chapter discusses the methodology used to create stable walking, turning, and kicking motions for Tao-Pie-Pie. The second part of the chapter describes the addition of balancing reflexes to allow Tao-Pie-Pie to traverse uneven terrain. The last part describes how the lessons learned on Tao-Pie-Pie were used in the implementation of *Blitz*, a much more complex humanoid robot designed to participate in the new HuroCup challenge. In addition, this chapter also discusses issues in evaluating humanoid robots in a competitive setting.

17.2 Tao-Pie-Pie

This section describes the design and implementation of a stable walking gait, a turning motion, and a kicking motion for Tao-Pie-Pie, a minimalist humanoid robot developed in our laboratory. We begin by comparing the design goals for Tao-Pie-Pie with those of other well-known humanoids.

Recent advances in material science, control engineering, robotics, and Artificial Intelligence has enabled researchers to build fully autonomous humanoid robots that can walk, dance, climb stairs, and other functions.

For the first time, these robots are not limited to academia and research laboratories, but have been developed as commercial products. Recently, several companies have developed commercial humanoid robotic platforms, for example Honda, Fujitsu, Mitsubishi, and Sony. These designs have many degrees of freedom and are very complex mechanical and electronic systems. Correspondingly, they are very expensive.

Despite the existence of these mechanically-advanced robots, many research questions about humanoid robots remain unanswered. Apart from the general problems of localization, computer vision, path planning, motion planning, and task planning, these also include some problems that are specific to the control of humanoid robots. For example, what is the minimum set of actuators needed for stable walking? What sensor information is necessary to walk over uneven terrain? How can we minimize the energy required in walking? Despite visually impressive demonstrations, these advanced models have not yet answered these or many other open questions.

Dealing with these many questions is part of the reason why Kitano and Asada presented humanoid robots as a millennium challenge for robotics [4]. Since this time, humanoid robotics competitions have become well known and well covered in the popular media. The two major competitions in particular are also of strong academic interest:

1. The RoboCup Initiative included a humanoid challenge for the first time in 2002. Humanoid robots competed in three events: walking, penalty kicks, and a free demonstration.
2. The HuroCup competition is part of the FIRA International robotic competition. The competition has become more elaborate each year, and currently consists of a octathlon (robot dash, penalty kick, lift and carry, weightlifting, basketball,

climbing wall, and obstacle run) and the robot with the best summary score over all events is declared the winner.

Tao-Pie-Pie competed in RoboCup events from 2002-2005, and in FIRA HuroCup events from 2002-2005. While Tao-Pie-Pie was then retired, mainly due to its aging framework, it could still compete at a favourable techical level in RoboCup events today. The broad array of events at current FIRA HuroCup competition is beyond the capabilities of Tao-Pie-Pie (in part because some of the events require arms), Tao-Pie-Pie led us to develop later robots that do currently compete in these events, and are equally minimalist for their expanded tasks. One of these later robots, *Blitz*, will be introduced later in the chapter, and we will also examine issues in evaluating robots, using the RoboCup and FIRA HuroCup events as examples.

We begin our overview of Tao-Pie-Pie with a brief summary of related work, both in terms of other similar robotics projects and background on walking gaits. We then describe the design of the robot, the development of its walking gait, and its balancing reflexes.

17.3 Related Work

Many research groups worldwide have also developed small humanoid robots for scientific exploration and competition. This section gives an overview over other small humanoid robot designs. This section attempts to give an overview over the different types of designs rather than trying to be exhaustive.

17.3.1 Viki

Viki [6] was developed by Hendrik Lund's team from the University of Southern Denmark. Like Tao-Pie-Pie, Vicki is a minimalist design approach. It embodies a bottom up approach focusing on the interaction between physical properties and control.

Viki uses only five motors. Two motors are used to turn the legs sideways, one motor moves the hip, and one motor moves the upper body. Another motor is used to control the arms of the robot.

Viki only uses four motors for the walking motion compared to Tao-Pie-Pie's six RC servos. However, Viki's mechanical design is significantly more complex including a gear box and timing belts. It is difficult to compare the kinematic abilities of the two robots. Viki has the ability to turn either leg sideways, but cannot kick a ball straight forward. Tao-Pie-Pie can not turn its hips sideways, but it can kick with the right or left foot.

It is also interesting to note that Tao-Pie-Pie and Viki (both based on minimalist design philosophies) were by far the smallest robots in the competitions they entered. Tao-Pie-Pie is 28cm tall, whereas Viki is about 25cm tall.

Viki does not include any sensors for balancing and walking. Rather it seems to have been developed primarily for the RoboCup Junior competition, since it has a set of infrared sensors that can detect an infrared emitting ball over long distances.

17.3.2 Pino and Morph

Pino and *Morph* are a humanoid robots developed by the Kitano Symbiotic Systems group [9]. Pino is approximately 50cm tall. It uses high torque servo motors to control 26 DOF (6 DOF in each leg, 5 DOF in each arm, 2 DOF in the trunk, and 2 DOF in the head). Pino includes a vision sensor, posture sensors, joint angle sensors (using the potentiometers of the servos), and force sensors in the feet.

Morph is a next generation humanoid robot. It is similar to Pino's design, but smaller.

17.3.3 Robo Erectus

Robo Erectus is a series of small humanoid robots developed by Changjiu Zhou at Singapore Polytechnic, Singapore [10]. It is a approximately 40cm tall and has 12 DOFs. It uses standard RC servos as actuators.

Although its walking gait is not as stable as that of other robots, it can move at an amazing speed of approximately 10cm/sec. Robo Erectus was the fastest of the small sized robots in the RoboCup competition achieving a second place finish in the robot walk even against taller robots.

17.3.4 KAIST Robot

Jung-Hoon Kim from KAIST, Daejon, Korea developed a 50cm tall robot which uses DC motors and timing belts. The robot performed superbly during the 2002 HuroCup competition and won first prize. [3].

17.3.5 Johnny Walker

Johnny Walker is a 40cm tall humanoid robot developed by Thomas Bräunl from the University of Western Australia [1]. It also uses the Eyebot controller. It has four DOFs in each leg. Feedback is provided by a vision cameras as well as two accelerometers, two gyroscopes, and force sensors in the feet.

17.3.6 Development of Walking Gaits

There is a rich literature on the design of walking gaits for specific humanoid robots (see for example [8, 5]). However, much of this work was done in simulation only, and those using real robots succeed only by constraining the range of motion of the robot (e.g., through the use of oversize feet, or by restricting the motion in the sagittal plane).

The representation of the walking gait is also important. A smooth control curve is needed, since otherwise the motion of the robot will be too jerky. Jerking introduces unwanted forces into the motion of the robot, is not energy efficient, and introduces even more noise into the output of gyroscopes and accelerometers. Ijspeert describes the walking gaits with a set of differential equations [2]. The differential equations describe a set of attractors using Gaussian kernel functions. A walking gait is represented as a set of weights on the kernel functions, and thus an attractor landscape.

17.4 Design Requirements

Tao-Pie-Pie was intended as a research vehicle to investigate methods for deriving control methods for stable walking patterns for humanoid robots. Stable walking, especially over uneven terrain is a difficult problem. One problem is that current actuator technology (RC Servos, DC motors) generate less torque in comparison to their weight than human muscle. Another problem is that feedback from gyroscopes and actuators is very noisy. The necessary smoothing of the input signals makes it hard to use it in actively controlling the walking motion.

Another research direction was the investigation of computer vision based methods for balancing and walking. Humans use vision when balancing. This can be demonstrated convincingly by having a person balance on one leg and then ask them to close their eyes, which makes balancing much harder for people. The idea is to use the optical flow field of the camera to control the robot's walking motion. This requires fundamental scene interpretation since to extract a motion vector (in general, a six dimensional vector representing translation in the X, Y, and Z plane as well as pan, tilt and swing angles) from an image sequence requires knowledge of the geometry of the scene. This problem can be simplified by making assumptions about the world and limiting the amount of

Furthermore, Tao-Pie-Pie was intended to compete at international humanoid robotic competitions such as RoboCup and HuroCup. Among other, this meant that Tao-Pie-Pie had to be able to balance, walk, run an obstacle course, and kick a ball.

Cost was an important design criteria in Tao-Pie-Pie's development. Previous experience has shown us that the use of commonly available cheap components does not only help to keep the cost of a project down and the Head of Department happy, but it also has lead to the development of novel, versatile, and robust approaches to problems in robotics.

Another design goal was to reduce the number of degrees of freedom (DOF) of the robot. This reduces the cost of the humanoid robot as well as increases its robustness. Each DOF adds extra complexity in the mechanical design and the design of the control electronics. Furthermore, reducing the number of DOFs in the robot allows us to exploit the dimensions of the humanoid walking problem. The minimum set of DOFs that allow a humanoid robot to walk is of interest since it leads to energy efficient designs.

17.5 Mechanical Design of Tao-Pie-Pie

Tao-Pie-Pie is the third generation of humanoid robots developed in our lab. The first two humanoid robots, *RX-78* and *Zaku*, were both based on commercially available toy model figures (See Fig. 17.1). Both model provided important stepping stones and insights into the design of a small humanoid robot.

A number of lessons were learned from RX-78 and Zaku and included in the mechanical design of Tao-Pie-Pie.

First, the plastic model kits were not strong enough to withstand the pressures and forces during walking and thus would often break. Therefore, Tao-Pie-Pie was constructed from aluminum.

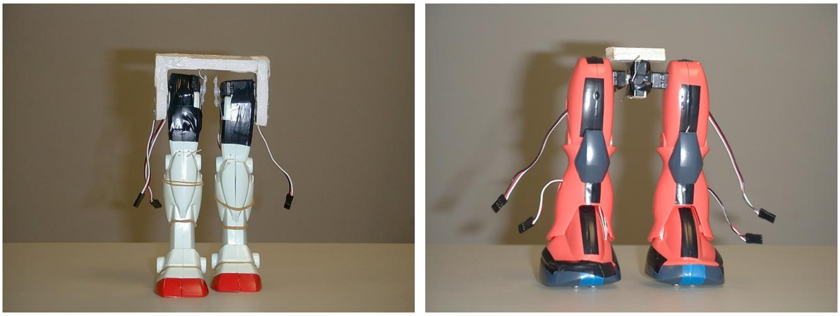


Fig. 17.1. Front views of RX-78 (left) and Zaku (right)

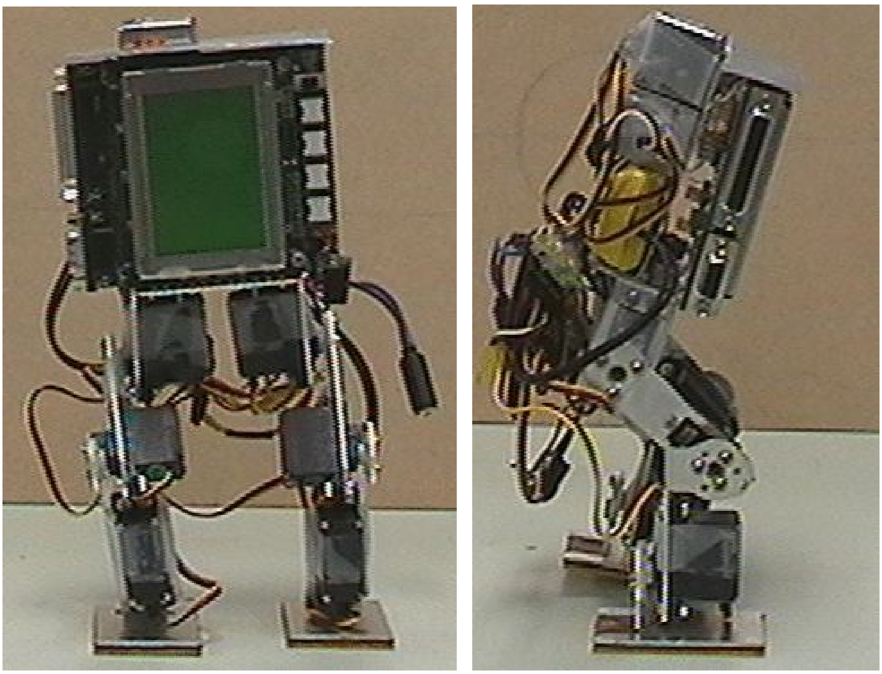


Fig. 17.2. Front and side view of Tao-Pie-Pie

Secondly, Zaku proved the need for a joint in the left-right (so-called sagittal) plane to shift the center of gravity from right to left. Although Zaku was able to shuffle in a straight line, the absence of a joint in the sagittal plane meant that it could not lift its feet of the ground and thus had a very short stride length. The only way for Zaku to shift the center of gravity from left to right was by bending its knees. Tao-Pie-Pie therefore had an extra DOF in each ankle which allows it to shift in the sagittal plane.

Thirdly, the importance of feedback in the control of humanoid walking was demonstrated by RX-78 which used a modified mouse as make-shift pitch and roll sensor.

Tao-Pie-Pie includes two gyroscopes to measure the angular velocity in the left-right and forward-backward plane.

Figure 17.2 shows the mechanical construction of Tao-Pie-Pie.

The actuators and sensors consist of widely available RC servos and RC gyroscopes for remote controlled cars and helicopters.

The Eyebot controller ([1]) was chosen as embedded processor, since it is relatively inexpensive, yet powerful enough to provide vision information. A small CMOS camera provides visual feedback for the robot.

The details of the mechanical construction of Tao-Pie-Pie are shown in Fig. 17.3. The mechanical design was done in conjunction with Nadir Ould Kheddal's robotics group at Temasek Politechnic, Singapore.

Tao-Pie-Pie is constructed out of 0.5mm aluminum. The RC servos are used as structural components in the design.

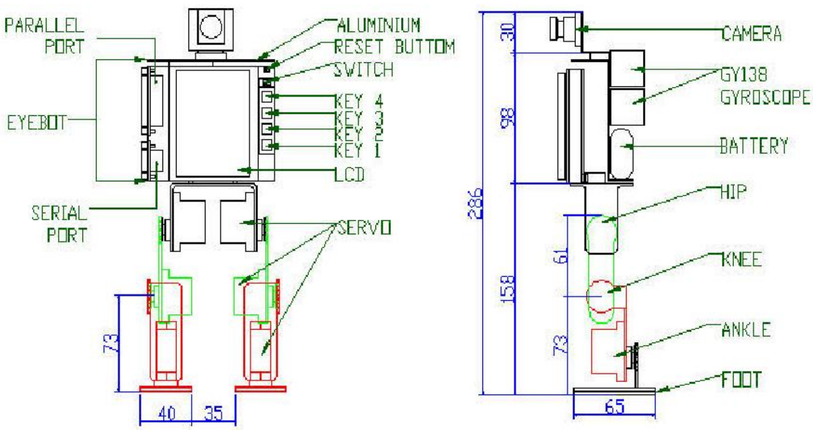


Fig. 17.3. CAD Drawing of Tao-Pie-Pie

17.6 Development of Walking Gaits

One of the fundamental problems in humanoid robots is the development of stable walking patterns. A walking pattern is dynamically stable if the COP is within the supporting area. A statically stable walking pattern also has the COM within the supporting area.

We used a divide and conquer approach and divided the walking gait into six phases: three for the right and three for the left leg.

The phases were selected in such a way that the robot is statically stable at the end of each phase.

17.6.1 Inverse Kinematics

Inverse Kinematics allow us to compute the correct joint angle to position a robotic link at a target position. After determining the desired location for the COM, we compute

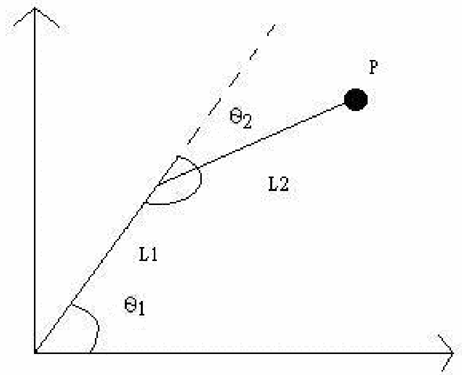


Fig. 17.4. Inverse Kinematics model of the robot. *P*, represent center of mass. *L*2 - hip joint link, *L*1 - knee joint link.

joint angles for all RC servos in the leg. By controlling the joints angles, we can control the stability during the motions.

To keep the humanoid balanced, we must keep the center of mass within the supporting region during the termination of all phases of the walking motion.

To solve the inverse kinematics model of the humanoid robot we use a simplified two link model of the robot.

Solving the equations for θ_1 first and then for θ_2, we can find a solution to the inverse kinematics problem. The solution for θ_1 and θ_2 are shown below.

$$\begin{aligned} \theta_2 &= \frac{\cos(x^2 + y^2 - L_1^2 - L_2^2)}{2L_1L_2} \\ \theta_1 &= \frac{-(L_2 \sin(\theta_2)x + (L_1 + L_2 \cos(\theta_2)y)}{(L_2 \sin(\theta_2)y + (L_1 + L_2 \cos(\theta_2)x)} \end{aligned} \tag{17.1}$$

17.6.2 Bezier Curves

The walking gait is based on a cyclical pattern generator. The walking patterns described in the next subsections are implemented using a set of control points.

There are many possible methods for interpolating points between the user defined control points.

During our work on RX-78 and Zaku, we used linear interpolation, similar to Bräunl. However, using linear interpolation the resulting curve is in general not differentiable around the control points. This leads to jerky motion of the robot, which introduces destabilizing forces into the motion. A smooth motion is much preferred since jerky motions are usually not energy efficient and more importantly aggravate noise in the sensors.

Instead, we used Bezier curves to interpolate setting between the control points. The advantage of Bezier curves are that they are simple cubic equations which can be computed quickly. Bezier curves are also versatile and generate smooth and natural gaits.

Another possibility is the use of cubic splines. Cubic splines seem especially suited to this problem since they guarantee that the resulting curve minimizes the second derivative (and therefore the acceleration in the robot). This greatly reduces unintended forces.

17.6.3 Pattern for Straight Walk

The walking pattern for a straight walk is shown in Fig. 17.5. The pattern is based on the control curves shown in the previous section.

The walking pattern consists of six phases. The walking pattern repeats itself after the sixth phase. The bottom row of images shows the approximate position of the COM.

Tao-Pie-Pie starts in phase 1 — "Two Leg Stand" — where the right leg is in front and the left leg is behind. Both legs are on the ground and the COM is between the two legs.

From phase 1, Tao-Pie-Pie moves to phase 2 — "One Leg Stand" —. In this phase, the ankle servo generates a torque which moves the COM to the inside edge of the right leg. This also results in the back (left) leg to lift off the ground.

During the transition from phase 2 to phase 3 — "Ready for Landing" — is in static balance. Tao-Pie-Pie moves the free left leg forward and positions it so that it is ready for land. The COM moves to the front of the supporting leg. This stabilizes the transition to phase 4.

During the transition from phase 3 to phase 4 — "Two Leg Stand Inverse" — the robot is in dynamic balance. The supporting leg extends its knee joint to shift the COM over the front edge of the supporting leg. The ankle servo of the supporting leg generates a torque to move the COM over the right side. The left leg will touch the ground in front of the right leg.

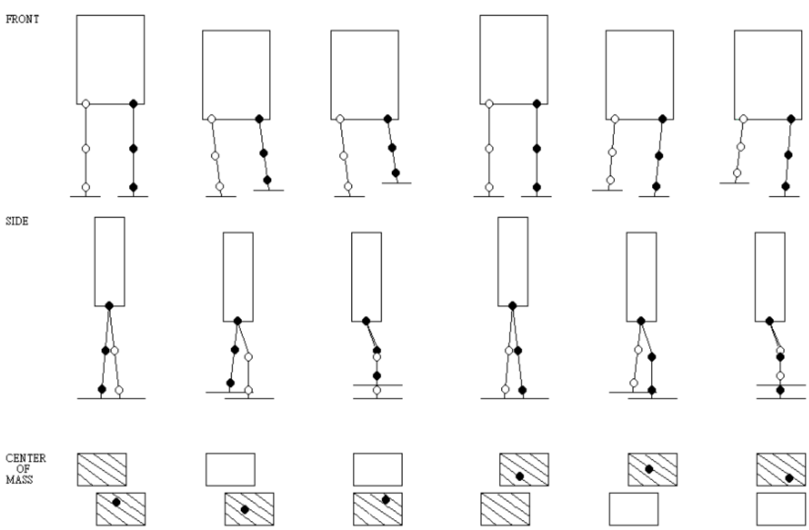


Fig. 17.5. Walking Pattern of Tao-Pie-Pie

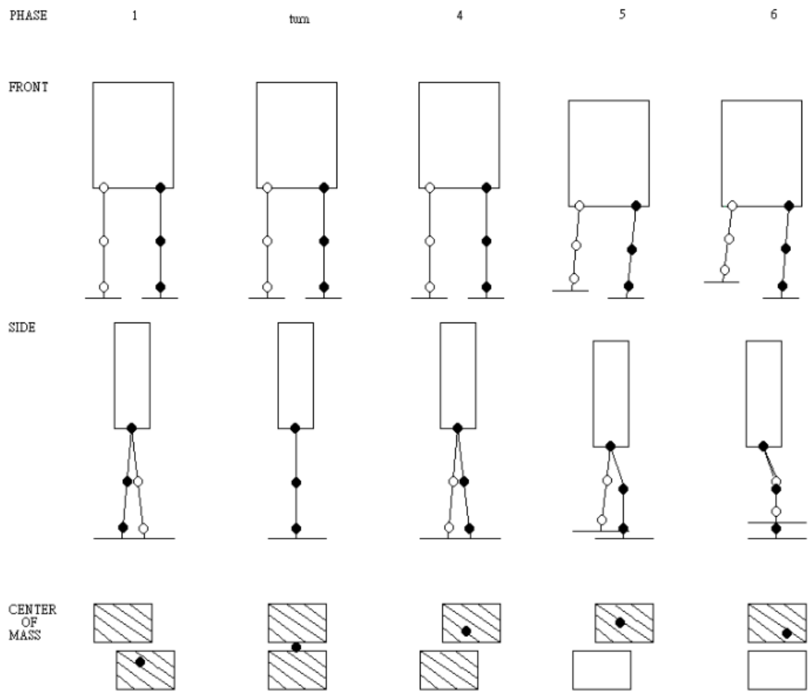


Fig. 17.6. Turning Pattern of Tao-Pie-Pie

Phases 5 to 6 are the mirror images of phases 2 to 3. After phase 6, the motion continues with a transition to phase 1.

17.6.4 Turning Patterns

Tao-Pie-Pie possesses two different patterns for changing the direction of its walk from a straight line walk: (a) varying the stride length, and (b) lower body twist.

By changing the speed at which Tao-Pie-Pie moves through phases 2 and 5 respectively, it can vary the stride length of the left and right part of the walking pattern which turns the robot into this direction. However, the turning rate is slow. Using this method it takes about 20 steps to turn by 45 degrees.

Instead Tao-Pie-Pie can turn on the spot by twisting its lower body, which is shown in Fig. 17.6. The turn occurs in phase "turn." In this phase, the front and back legs will swap position. During the turn, the COM and the COP are in the center between the two feet.

17.6.5 Kicking Pattern

The RoboCup competition also required our robots to kick a ball. Therefore, we developed a kicking pattern for Tao-Pie-Pie. The kicking pattern shown in Fig. 17.7 is similar to the walking pattern.

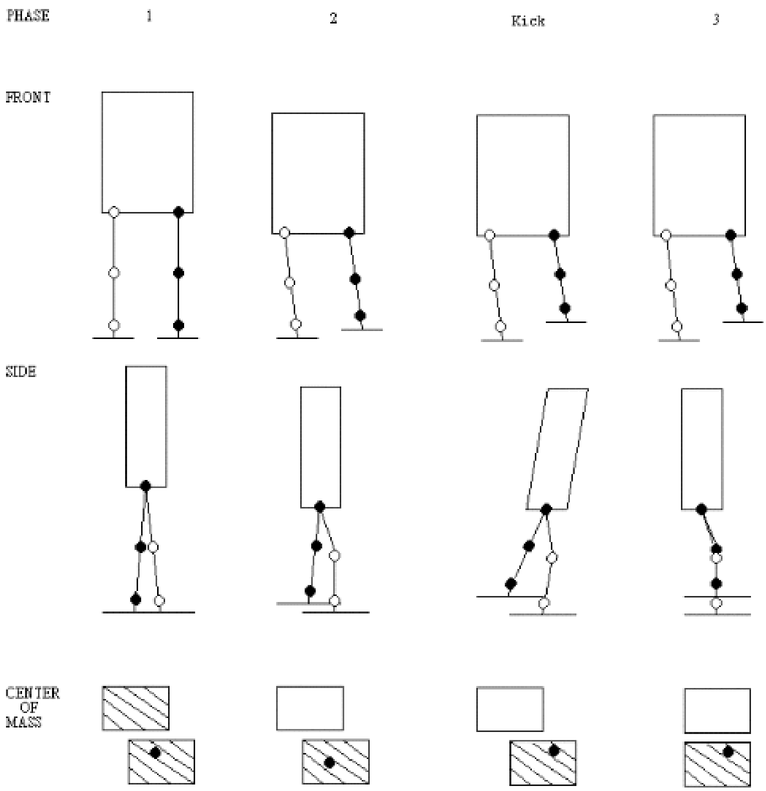


Fig. 17.7. Kicking Pattern of Tao-Pie-Pie

The difference is that in phase 2, the rear leg is moved back as far as possible. This increases the range of motion of the kick, which results in more energy for the kick. To keep the robot balanced, Tao-Pie-Pie leans the upper body forward by moving both hip joints.

This is necessary to keep the COM over the supporting area of the front leg.

Tao-Pie-Pie then snaps the back leg forward as quickly as possible. At the same time, it straightens out the upper body, which readies it for landing on the kicking foot.

17.7 Balancing Reflexes

The only feedback about the motion of Tao-Pie-Pie is provided by two gyroscopes that provide information about the angular velocity in the left-right (referred to as the *Y-plane* in the remainder of this chapter) and forward-backward plane (referred to as the *X-plane* in the remainder of this chapter) respectively.

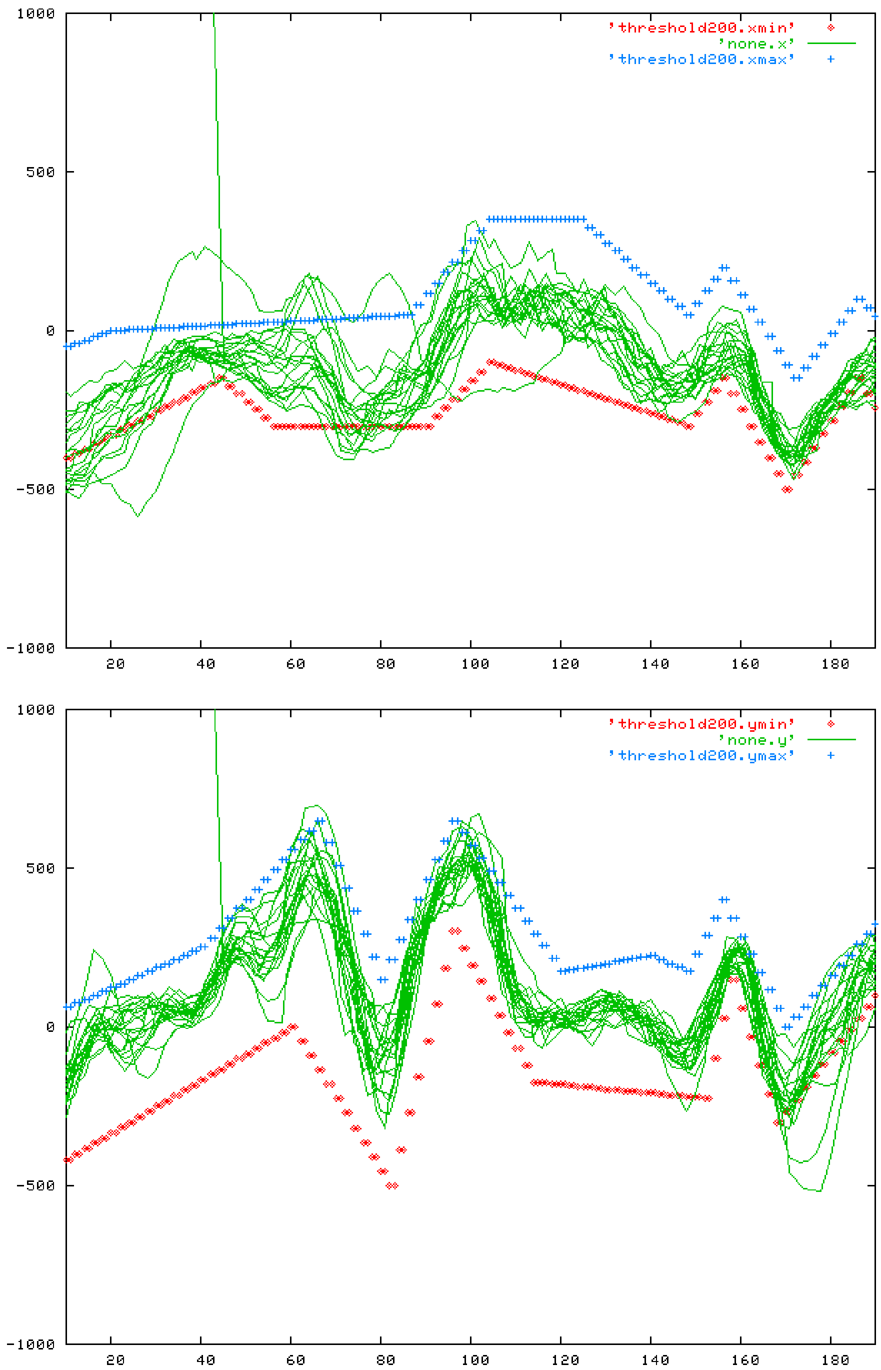


Fig. 17.8. Gyroscope Readings in the X and Y Plane over 10 Steps. Linear Approximation of the Safe Zone.

The raw sensor data of the gyroscopes is very noisy. We therefore compute a running average over five samples to smooth out the noise. Fig. 17.8 shows the gyroscope readings for the X and Y plane over approximately twenty steps.

Since Tao-Pie-Pie did not fall over during this extended walking trial, these gyroscope readings were used to determine a "safe zone" for the velocity feedback of the gyroscopes.

We then created a linear approximation of the "safe zone envelope" and generated minimum and maximum thresholds for the gyroscope readings. The approximation is shown using red and blue lines in Fig. 17.8.

17.7.1 Sensor Feedback in Detecting a Fall

Initially, we ran a series of experiments to verify the accuracy of the approximated "safe zone" by making Tao-Pie-Pie beep whenever the measured angular velocity was above or below the threshold in the X and Y plane respectively. The goal was to show that Tao-Pie-Pie would beep just before falling over. These experiments proved very successful. Tao-Pie-Pie detected a fall with 95% accuracy with few ($< 5\%$) false positives.

17.7.2 Balancing Reflexes

After verifying that the gyroscope data can be used to predict a fall for Tao-Pie-Pie, the next step was to develop a method for modifying the motion parameters to avoid a fall. There are three inputs to the active balancing algorithm:

1. X-plane gyroscope reading;
2. Y-plane gyroscope reading; and
3. the current phase of the walk.

Initially, the most common cause for Tao-Pie-Pie falling over was a fall to the right in phase 2 (see Fig. 17.5) or to the left in phase 5. This is due to the fact that because of the limited number of DOFs, Tao-Pie-Pie uses the ankle servo to move the COM over the right or left foot. Since the torso of Tao-Pie-Pie is fixed, Tao-Pie-Pie is precariously balanced at this point and the robot sometimes moves to far, resulting in a fall to the right or left respectively.

The first balancing reflex algorithm is active when the Y-plane gyroscope reading is larger/smaller than the maximum/minimum velocity threshold in phase 2/5 respectively. In this case, the robot tends to fall towards the right/left.

There are two ways in which the rotational velocity in the Y-plane can be controlled:

1. the set point for the right or left ankle servo can be changed to induce a torque in the opposite direction to the fall;
2. the robot can extend the knee and hip joint, resulting in a slowed down rotation. This effect is similar to the effect of slowing down the rotation of a chair while seated in it by extending one's arms.

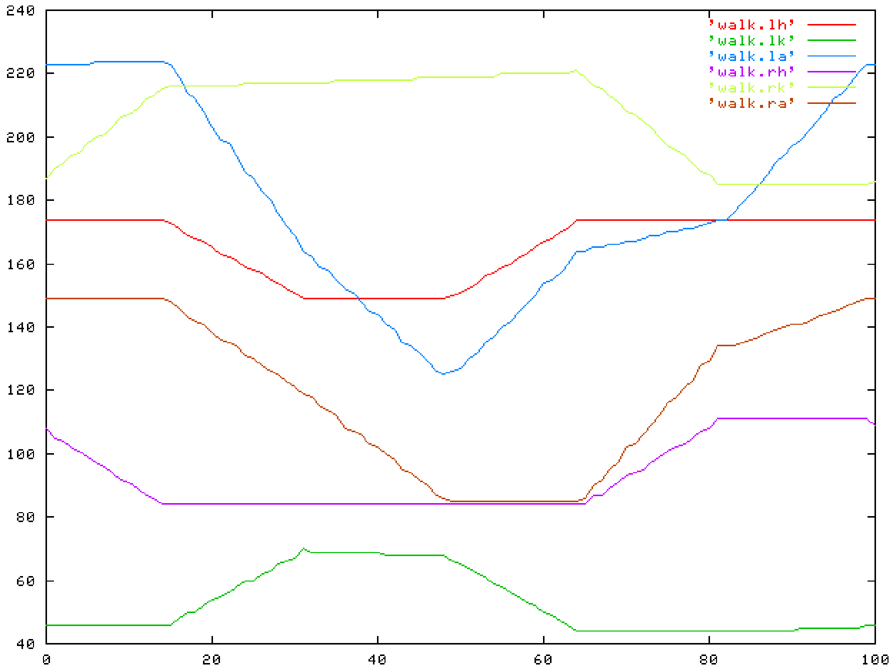


Fig. 17.9. Servo Settings for a Straight Walk

We focus on modifying the angular velocity through the first method, since during a straight walk, the left-right velocity is mainly generated through the ankle servos. The second method is disadvantageous in that it also modifies the forward-backward balance of the robot. The set points for the servos are based on linear interpolations between a set of control points.

If the angular velocity is too large, then the balancing reflex modifies the set point of the servo by moving it 10% closer to the start point of the pattern. Similarly, if the angular velocity is not large enough, then the set point is slightly extended.

The same approach is used when controlling falls in the sagittal plane. In this case, however, there is no single servo that is responsible for the angular velocity. Instead, both set points for the knee and hip joint are modified by 90% to prevent a fall.

The feedback from the gyroscopes is also used to detect abnormal behavior. For example, if the robot's foot is caught on the carpet, instead of moving the leg forward, the robot will fall onto the leg too early. If this abnormal feedback is detected the robot attempts to stabilize itself by constraining all movement within the phases, in essence putting both feet on the ground as quickly as possible and straightening up its upper body. The constrainment will continue until both gyroscopes show appropriate angular velocities.

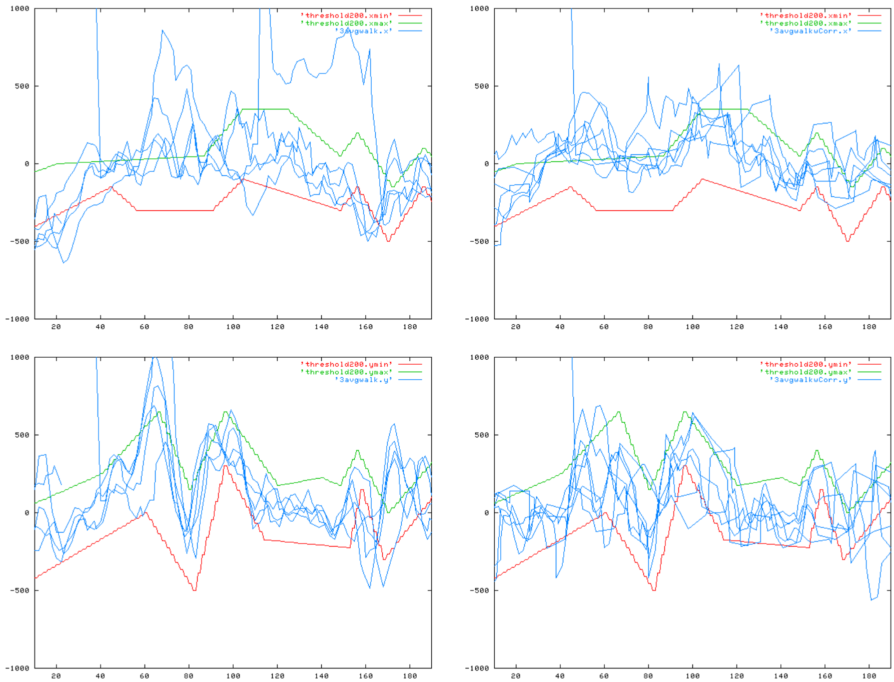


Fig. 17.10. Comparison of original walking gait (left column) and walking gait with balancing reflexes (right column) in the forward-backward (top row) and left-right (bottom row) plane

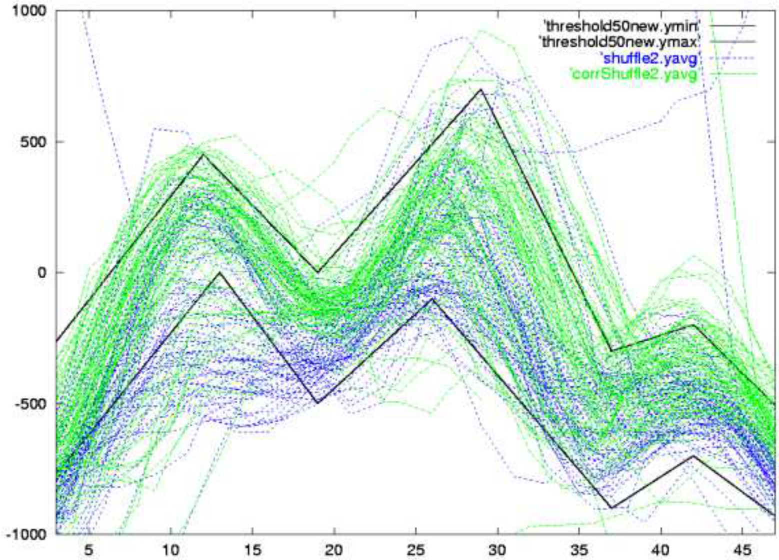
17.8 Evaluation of Balancing Reflexes

We evaluated the balancing reflexes algorithm by subjectively looking at the static walking pattern. The standard walking pattern of Tao-Pie-Pie is quite stable even without balancing reflexes. The robot did not fall during any of these experiments. However, the walking gait with balancing reflexes was more balanced resulting in a straight line walk. Without balancing reflexes, Tao-Pie-Pie would veer to the right significantly. The walking speed of the robot remains unchanged.

We also evaluated the balancing reflexes by subjectively by comparing the gyroscope feedback with and without balancing reflexes. The results of this comparison are shown in Fig. 17.10.

As can be seen from the plots, the balancing reflexes does constrain the walking gait so that the gyroscope feedback is more in the desired envelope. Most of the time, the walking gait remains in the desired velocity envelope.

Work is currently underway on developing a dynamic (shuffle-like) walk with correspondingly dynamic turns. When feedback correction was applied to walk, the walk covered more distance than without. Subjectively as well, the gyroscope feedback was not only better maintained within the desired envelope, but also formed a much more regular path, as shown in Fig. 17.11.



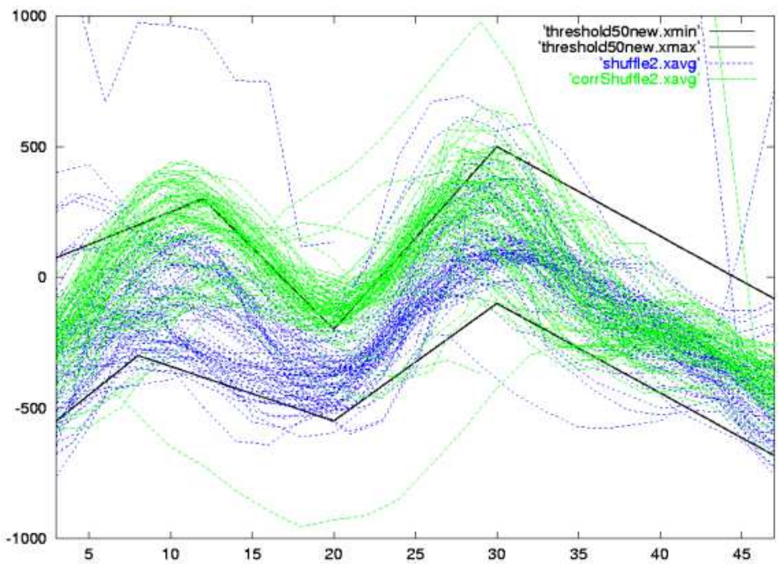


Fig. 17.11. Corrected and uncorrected dynamic walking gait in the forward-backward (top) and left-right (bottom) plane

17.9 Moving Forward: The HuroCup Competition

The balancing reflex algorithm used in Tao-Pie-Pie is simple, but works surprisingly well in practice. Tao-Pie-Pie has shown itself to be a powerful and flexible platform for research into humanoid robotics, and has placed numerous times in both RoboCup and FIRA competitions. As humanoid robots become more able, however, these competitions have become more challenging as well, moving from simple walking gaits and basic balancing, tasks which are the most basic for the human form, to the many skills that humans possess once walking and balancing are mastered.

These skills are currently best embodied in the FIRA HuroCup event, the most difficult competition for humanoid robots in the world (Fig. 17.12). The initial HuroCup competition took place in 2002 in Seoul, Korea and HuroCup has been an integral part of the FIRA Robot World Cup ever since. Even though exciting to watch for spectators, the HuroCup event is first and foremost a research event. It focuses on the three main research areas for humanoid robotics: (a) active balancing - humanoid robots must be able to traverse a vast variety of even and uneven surfaces quickly and efficiently under varying loads, (b) complex motion planning - humanoid robots must be able to manipulate various objects without loosing their balance. For example, a humanoid robot must be able to pick up a box from under a chair without falling down or colliding with the chair, and (c) human robot interaction - the hope is that a humanoid shaped helper robot is more acceptable to elder or disabled people. However, this implies that people want to communicate with such a robot in the same or similar way that they communicate with other humans.

The organizers of the HuroCup competition are aware of the fact that since there are no practical real world applications for small humanoid robots yet, competitions such as HuroCup act as a benchmark problem for research. It is thus very important that the benchmark problems are not biased but indicate true performance improvements in the real world. Even benchmarks for comparably much simpler domains, such as performance measurements for processore are fraught with pitfalls. For example, until the emergence of RISC processors, Million Instructions Per Second (MIPS) were considered a good processor benchmark. MIPS was a useful processor benchmark when the tested processors have a similar instruction set. Only the advent of RISC processors which had extremely high MIPS rating but in practice performed not much better than CISC processors with slower MIPS ratings lead to new benchmark problems.

Therefore, the HuroCup competition is using the following guidelines

- Full perception - action cycle: Even though it is sometimes desirable to isolate performance on very specialized tasks, there is a danger that competitors over-engineer their solutions to a particular problem without a resulting improvement on general purpose tasks. Instead, the competitions should include sensing, perception, reasoning, and execution cycle for all events.
- Unmodified environments: Simply providing uniform lighting would make many of the vision challenges much simpler. However, in practical tasks, we always must assume unstructured lighting and therefore should not base our research on unrealistic assumptions.

Fig. 17.12. Collection of images from HuroCup 2007. Top left shows the participants. Top right shows the robot dash event. Bottom right image shows the obstacle run with wall, gates, and step obstacles. The bottom right image shows our robot Blitz during the marathon run.

- Humanoid research: the competitions should focus on issues specific to humanoid robots.
- Evolution: as technology and research results improve the performance of robots, the competitions must be adapted (e.g., increasing the number of obstacles or moving from a coloured ball to a textured ball).
- Variability: the variability of the robot must be tested by requiring the robot to perform several tasks with a single robot. This reduces the possibility for teams to over engineer the robot by adding large feet so that it is easier to kick a ball, but much harder to walk.

Based on these considerations, the HuroCup competition was developed. In the HuroCup, a robot has to perform well in eight different events to win the overall crown. The list of HuroCup events for 2008 is:

1. Robot Dash: The robot dash is a sprint event where a robot must walk 1.2m forward and then backwards over an even surface. Teams must implement at least two different gaits (forward walk and backward walk). This event is an evolution of the original HuroCup events. The current world record for this event is 27 secs.

2. Penalty Kicks: A robot must approach a randomly positioned ball and try and score on a goal defended by a robot playing goal keeper. This is also an evolution of the original three HuroCup events.
3. Obstacle Run: A robot must cross a 1.2m wide zone without touching any of the randomly placed obstacles. In 2002, the obstacles consisted of circular obstacles. Continued improvements of teams led to increasingly more difficult setups. In 2007, obstacles consisted of walls, steps (i.e., a 2.5cm high obstacle that a robot may step over), and gates (i.e., an obstacle that has enough room for the robot to crawl under). Even though the obstacle run was one of the original three challenges, the change of obstacles has greatly increased the difficulty of the event in recent years.
4. Lift and Carry: Lift and carry was introduced in 2004. The robot must carry weights across a random uneven surface. The robot that can carry the largest load is declared the winner.
5. Weight lifting: Weight lifting is similar to the Lift and Carry event, but the robot walks on an even surface only. Furthermore, in 2008, the robot must detect and grasp the weight bar autonomously. This event was introduced in 2007.
6. Basketball: A robot must throw a table tennis ball into a basket ball hoop. The robot will score three points if the ball was thrown outside of the 40cm circle, otherwise 2 points. The robot with the most points after five throws wins.
7. Marathon: An endurance race for humanoid robots. The robots must cover 42.195m (1/1000th of the distance for a human marathon run) with a single battery charge. The track is marked with colored tape.
8. Climbing Wall: In 2008, the HuroCup competition will include for the first time a climbing wall event. The robot that can climb the highest on the climbing wall is declared the winner.

A robot receives points for its placing in the individual events (10 points for 1st place, 8 points for 2nd place, and so on) and the HuroCup winner is the robot with the most points over all eight events.

We believe the current organization of the HuroCup challenge is ideal for advancing the state of AI through minimalist robotics. The HuroCup champion must perform well in all events to win, which encourages the entrant's intelligent systems to be adaptable to a broad range of tasks, rather than being designed specifically for one. The nature of these challenges do mean that they are well out of the range of abilities of a robot such as Tao-Pie-Pie, however - the limited number of degrees of freedom precludes some of the necessary deformations, and the robot has no arms with which to participate in the throwing events.

The balancing reflexes demonstrated by Tao-Pie-Pie, and the focus on strong AI as opposed to specialized hardware, however, allow the basic principles embodied in Tao-Pie-Pie to be applied to new robots that are adaptable to tasks such as these, while being minimalist in their design. We currently embody these principles in our latest robot, Blitz, which will be described in the next section. Tao-Pie-Pie was retired in 2005, and currently is on display in the Heinz Nixdorf Museum in Paderborn, Germany.

17.10 Discussion: From Tao-Pie-Pie to Blitz

Tao-Pie-Pie had two main limitations, which made it unsuitable for the HuroCup competition: (a) the 68332 did not possess sufficient processing power for vision and motion control to deal with the much richer world of the 2007 FIRA HuroCup competition, and (b) Tao-Pie-Pie only had a very limited set of motions, since it was limited to six DOFs.

Rather than trying to extend the aging Tao-Pie-Pie platform, we decided to built a brand new platform. This platform still emphasizes the minimalist approach introduced in the beginning of this chapter.

In 2007, we developed Blitz as an intended entry into the FIRA HuroCup and similar events. Instead of being custom built as Tao-Pie-Pie and many of our humanoids are, Blitz is based on the affordable Bioloid robotics kit developed by Robotis of Korea. Because of its very low cost (about $1,000 US), its robustness, and its flexibility, the Bioloid kit has become very popular with both researchers and hobbyists.

Blitz has 18 DOFs, which means that it is able to perform many of the functions necessary to compete in HuroCup. It is able to walk, crawl, stand up, kick, pick up a ball, and lift a weight.

We are currently adding a 3 axis accelerometer to provide Blitz with more sophisticated feedback for active balancing, walking over uneven surfaces, and better recovering from falls.

Blitz also uses a Nokia 6600 mobile phone as its brain. The Nokia phone provides a fully programmable computing platform with a CMOS camera, bluetooth wireless communications, and a 160MHz arm processor. Similar development kits cost about $2,000CAD, but since mobile phones are produced in vast quantities and new models are released every 6 month, this and similar phones can be bought used for less than $100. We received the phones used on Blitz and Buster (Blitz's twin) as a donation from Prof. Kopatchek, TU Vienna, Austria.

This much larger set of motions means it is impossible to pre-program all motions. This introduces complex motion planning as a new research issue. In the simplest form, this means that several motions need to be combined. For example, a walking motion may need to be executed with the arms straight or while carrying a weight bar. Clearly, it is impractical to have to design different walking motions for all possible positions of the hands. However, the position of the hands, especially while carrying a weight influences the walk.

To solve this problem, we have developed a new representation for motions (based on the Fast Fourier transform), which allows us to overlay motions as sequences of cosine motions.

Secondly, we are currently working on a high speed, but sufficiently accurate simulation of the robot dynamics, which allows the robot to not just combine previous motions, but to generate new motions from scratch.

Consistent with our approach, the minimum platform was constructed to enable to do research on complex motion planning. As thus, Blitz is a clear evolution of work that began with Tao-Pie-Pie, but with a new focus. Instead of a small set of walking and kicking motions, Blitz is used to explore issues when trying to manage an almost infinite number of possible motions.

While Blitz is a much more sophisticated robot than Tao-Pie-Pie, it is true to our original design goals of minimalism. Adding an accelerometer, for example, is a minimal way to be able to perform diagnosis after a fall, in terms of knowing which direction the fall occurred in order to ensure the ability to recover from the fall. While the demonstrations provided by sophisticated commercial robots may be more visually interesting, we believe that the HuroCup approach of creating significant challenges, coupled with minimalist solutions to those problems, will go much further in answering the basic robotics questions laid out in the introduction to this chapter.

Acknowledgements

Most recently, this work has been funded through personal discovery grants by the National Science and Engineering Research Council of Canada (NSERC) to the authors.

The authors would also like to acknowledge the contribution of former and current students who implement and flesh out the ideas described in this chapter. We would like to especially thank Patrick Lam (MSc., University of Auckland, New Zealand, 2002), Sara McGrath (MSc., University of Manitoba, Canada, 2007), and Jonathan Bagot (MSc., University of Manitoba, Canada, ongoing).

References

1. Braunl, T.: Embedded Robotics. Springer, New York (2003)
2. Ijspeert, A.J., Nakanishi, J., Schaal, S.: Movement imitation with nonlinear dynamical systems in humanoid robots. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2002), Washington, DC, pp. 1398–1403 (May 2002)
3. Kim, J.-H., Park, I.-W., Oh, J.-H.: Design of a humanoid biped robot lower body. In: Proceedings of the 3rd International Workshop on Human-friendly Welfare Robotic Systems, Daejon, Korea (January 2002)
4. Kitano, H., Asada, M.: The robocup humanoid challenge as the millennium challenge for advanced robotics. International Journal of the Robotics Society of Japan 13(5), 723–726 (2000)
5. Kun, A.L., Miller, W.T.: Control of variable speed gaits for a biped robot. IEEE Robotics and Automation Magazine 6(3), 19–29 (1999)
6. Lund, H.H., Pagliarini, L., Paramonov, L., Jrgensen, M.W.: Viki humanoid: Towards an integrated approach. In: Proceedings of 2nd International Symposium on Adaptive Motion of Animals and Machines, Kyoto, Japan (March 2003)
7. McGrath, S.: Active reflex-based balancing for small humanoid robots. Master's thesis, Department of Computer Science, University of Manitoba, Winnipeg, Canada (June 2007)
8. Pratt, J., Pratt, G.: Intuitive control of a planar bipedal walking robot. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 1998), Leuven, Belgium (1998)
9. Yamasaki, F., Matsui, T., Miyashita, T., Kitano, H.: PINO the humanoid: A basic architecture. In: Stone, P., Balch, T., Kraetzschmar, G.K. (eds.) RoboCup 2000. LNCS, vol. 2019, pp. 269–279. Springer, Heidelberg (2001)
10. Zhou, C.: Linguistic and numeral heterogenous data integration with reinforcement learning for humanoid robots. In: Proceedings of the 1st IEEE Conference on Humanoid Robotics (Humanoids 2000), Cambridge, MA (September 2000)