Design of Walking Gaits for TAO-PIE-PIE, a Small Humanoid Robot

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Abstract. This paper describes the methodology that we used to design and implement balancing and walking gaits for TAO-PIE-PIE, a small 30cm tall humanoid robot. TAO-PIE-PIE is a fully autonomous robot with all power, sensing, and processing done on-board. It is also a minimalistic design with only six degrees of freedom. Nevertheless, its performance is comparable to that of other more complex designs. The paper describes three patterns: (a) a straight walk, (b) a turn on the spot, and (c) a kicking pattern. Sensor feedback is provided by two gyroscopes that provide angular velocity in the left-right and forward-backward plane and a CMOS camera providing vision information. The feedback from the gyroscopes is not used to directly control the walking gait, because the signal is noisy and it would be computationally too expensive for the current processor hardware. Instead, coarse feedback from the gyroscopes is used to monitor the transition from one phase of the pattern to the next. This feedback is used to: (a) determine when a phase has completed successfully, and (b) when to change the endpoints of certain phases. TAO-PIE-PIE proved to be a successful design winning a number of honors at international competitions.

1 Introduction

This paper describes the design and implementation of a stable walking gait, a turning motion, and a kicking motion for TAO-PIE-PIE, the third generation humanoid robot developed in our laboratory.

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 expensive.

Nevertheless, 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 to minimize the energy required in walking, or what are the trade-offs between walking speed and stability.

This is one of the reasons why Kitano and Asada presented humanoid robots as a millenium challenge for robotics. There are currently two large international competitions for humanoid robots.

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 FIRA HuroSot competition is part of the FIRA International robotic competition. The competition consists of a triathlon (robot dash, penalty kick, and obstacle run) and the robot with the best summary score over all three events is declared the winner.

This paper describes our work on designing TAO-PIE-PIE, a small humanoid robot. One of the design goals of TAO-PIE-PIEwas a minimal design; using only as many degrees of freedom as necessary to achieve a stable walk.

The paper describes related work in section 2. The design requirements for our humanoid robot are shown in section 3. Section 4 gives details of the mechanical and electronic design of TAO-PIE-PIE. The methodology used to develop and details of the implementation of the walking gaits are given in section 5. We implemented three different walking patterns: a straight walk, a turn, and a kick. The paper concludes with section 7. This section also critically evaluates the performance of TAO-PIE-PIE against that of other robots.

2 Related Work

Many teams worldwide have also developed small humanoid robots. 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.

2.1 Viki

Viki was developed by Prof. Lund's team from the University of Southern Denmark. Similar to TAO-PIE-PIE, Vicki is a minimalistic 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 can not 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 Viki (both based on minimalistic design philosophies) were by far the smallest robots in the competitions. 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.

2.2 Pino and Morph

Pino and Morph are a humanoid robots developed by the Kitano Symbiotic Systems group [8]. 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.

2.3 Robo Erectus

Robo Erectus is a series of small humanoid robots developed by Changjiu Zhou at Singapore Politechnic, Singapore [9]. 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.

2.4 Kaist Robot

Prof. Kim from KAIST, Daejon, Korea developed a 50cm tall robot which uses DC motors and timing belts. The robot performed superbly during the 2002 FIRA HuroSot competition and won first prize. [5].

2.5 Johnny Walker

Johnny Walker is a 40cm tall humanoid robot developed by Dr. Thomas Bräunl from the University of Western Australia [2]. 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.

2.6 Development of walking gaits

There is a rich literature on the design of walking gaits for specific humanoid robots (see for example [7, 6]). 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 saggital 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 [4]. 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.

3 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 FIRA HuroSot. Among other, this meant that TAO-PIE-PIE had to be able to balance, walk, run an obstacle course, dance, 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.

For example, most teams in the small sized league use a camera mounted directly overhead. Since the viewing field is limited with a standard lens, most teams purchased wide angle lenses and expensive cameras. In contrast, our small size league team, the All-Botz [1], mounted the camera with a side view. This made the vision problem harder but resulted in the development of more complex and robust camera calibration routines.

However, this effort is now paying off since the development system is flexible and robust enough to handle the newer larger playing fields introduced in 2002 as well as even larger playing fields planned for the future.

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.

4 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. 1). Both model provided important stepping stones and insights into the design of a small humanoid robot.

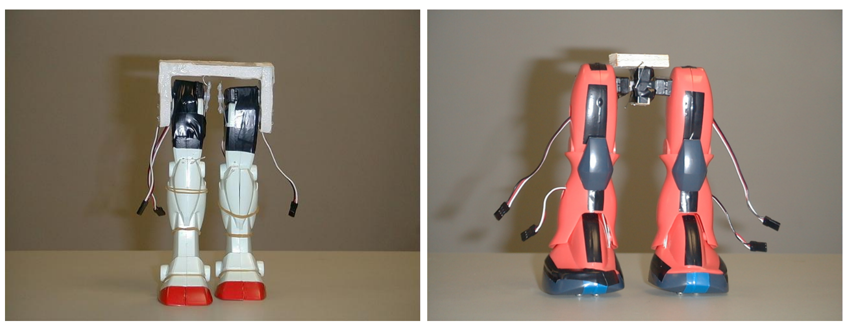

Fig. 1. Front views of RX-78 (left) and Zaku (right).

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

Firstly, 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.

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 saggital 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 saggital 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 2 shows the mechanical construction of TAO-PIE-PIE.

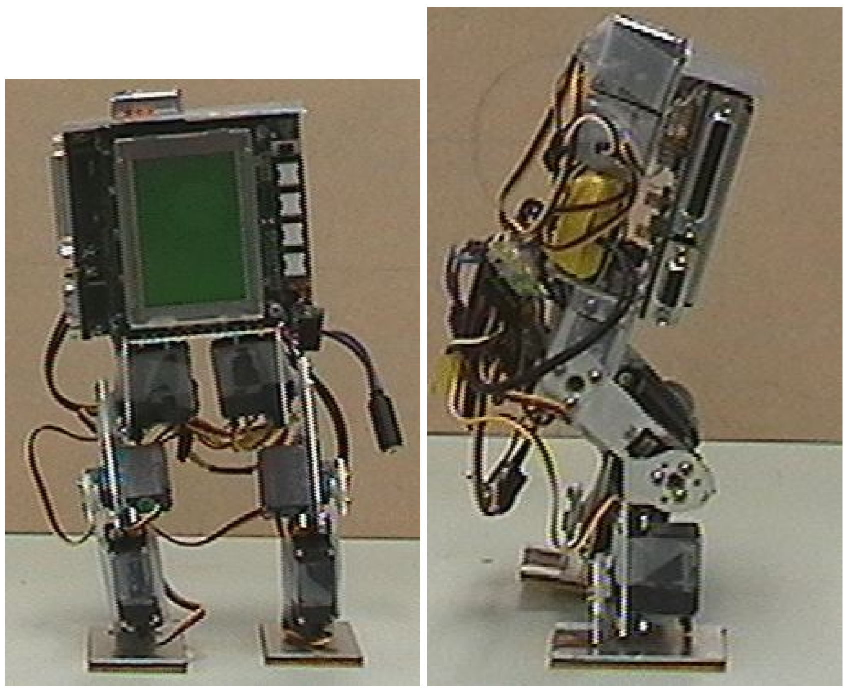

Fig. 2. Front and side view of TAO-PIE-PIE.

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

The Eyebot controller ([3]) 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 Figure 3. The mechanical design was done in conjunction with Dr. 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.

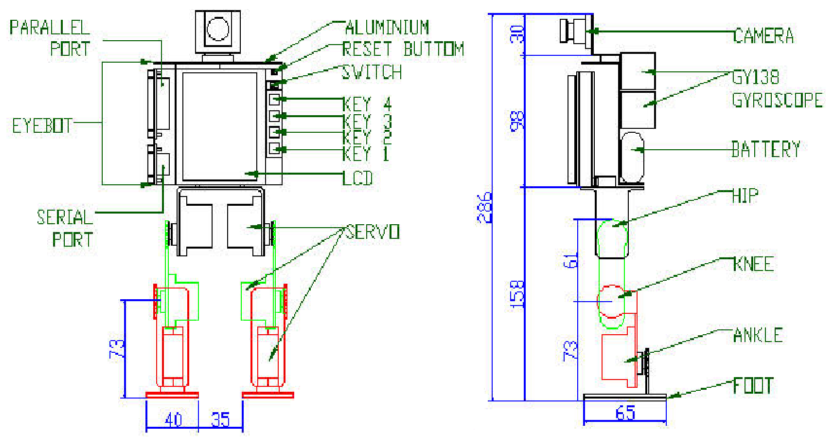

Fig. 3. CAD Drawing of TAO-PIE-PIE.

5 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.

5.1 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 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.

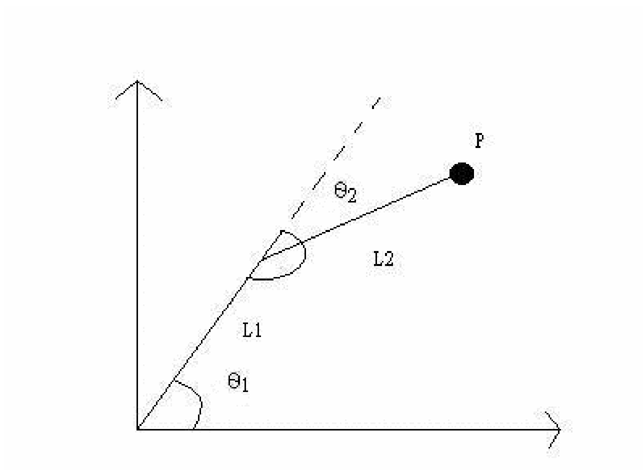

Fig. 4. Inverse Kinematics model of the robot. P, represent center of mass. $L2$ - hip joint link, $L1$ - knee joint link.

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.

$$\theta_2 = \frac{\cos(x^2 + y^2 - {L_1}^2 - {L_2}^2)}{2L_1L_2}$$

$$\theta_1 = \frac{-(L_2 \sin(\theta_2)x + (L_1 + L_2 \cos(\theta_2)y)}{(L_2 \sin(\theta_2)y + (L_1 + L_2 \cos(\theta_2)x)}$$

5.2 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.

5.3 Pattern for Straight Walk

The walking pattern for a straight walk is shown in Figure 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.

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.

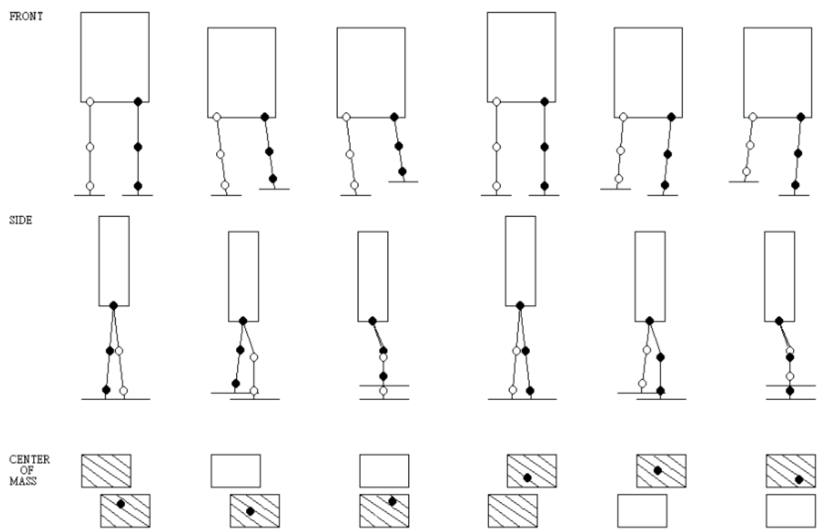

Fig. 5. Walking Pattern of TAO-PIE-PIE.

5.4 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 Figure 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.

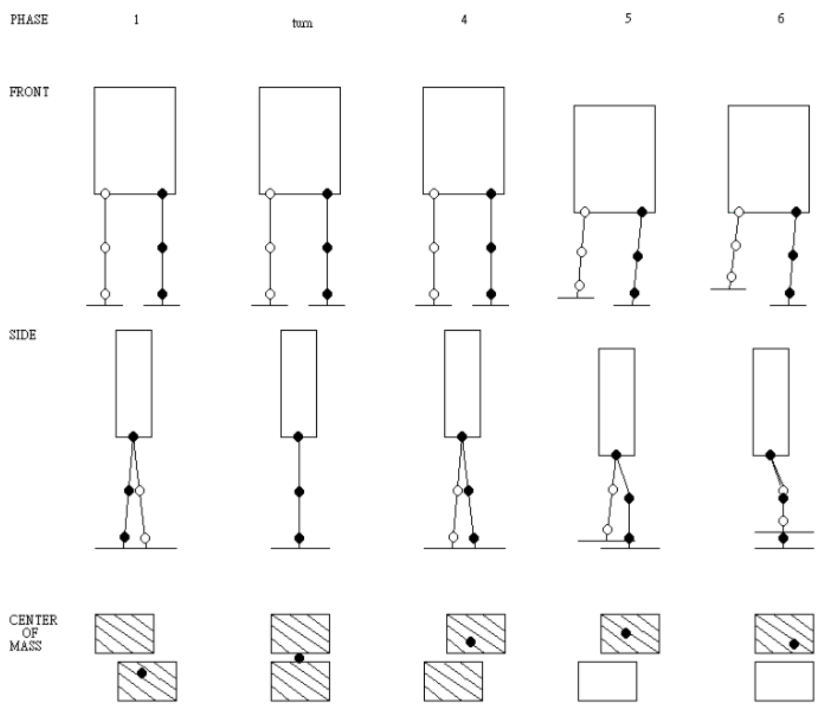

Fig. 6. Turning Pattern of TAO-PIE-PIE.

5.5 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 Figure 7 is similar to the walking pattern.

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.

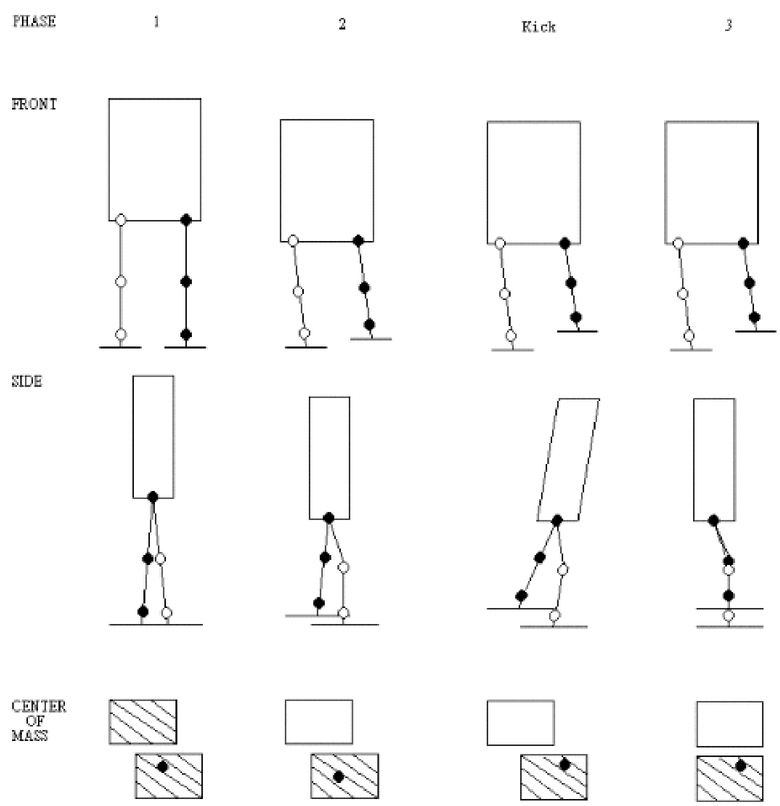

Fig. 7. Kicking Pattern of TAO-PIE-PIE.

5.6 Sensor Feedback

The only feedback about the motion of TAO-PIE-PIE is provided by two gyroscopes that provide information about the angular velocity in left-right and forward-backward plane respectively.

However, the computational requirements of on-board computer vision are large for the Eyebot embedded processor (MC 68332). Furthermore, the data from the gyroscopes is noisy and without significant pre-processing unsuitable to control the motion during the transition from one phase to another. Figure 8 shows the angular velocity readings for phase 1 (One Leg Stand) and phase 2 (Ready for Landing) over a series of steps.

Instead, only large changes in the output of the gyroscopes are used to recognize when a certain phase has been entered successfully. For example, the robot listens for a sudden change in the angular velocity in the left-right plane to determine when the free leg has landed in phases 1 and phases 4 of the straight walking pattern.

The feedback from the gyroscopes is also used to detect abnormal behavior. For example, if the robot's foot is caught on the carpet and 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 putting both feet on the ground as quickly as possible and straighten up its upper body. The motion will then stop until both gyroscopes show little angular velocity.

6 Evaluation

It is difficult to quantitatively evaluate the performance of different walking gaits and humanoid robots. Many factors that are not directly related to the walking gaits (e.g., size of the feet of the robot) can influence the performance of a humanoid robot. Furthermore, all humanoid robot designers attempt to find a balance between the stability and speed of the walking pattern. A robot that walks quicker usually has a higher chance of falling. Therefore, not only the maximum speed, but also the probability that the robot will fall at any given speed needs to be considered.

Therefore, this section will provide anecdotal evidence based on observations during the 2002 RoboCup and FIRA HuroSot competitions to highlight TAO-PIE-PIE's strength and weaknesses.

TAO-PIE-PIE competed at two international competitions for humanoid robots in 2002: FIRA HuroSot and RoboCup. It performed well in the competitions winning a

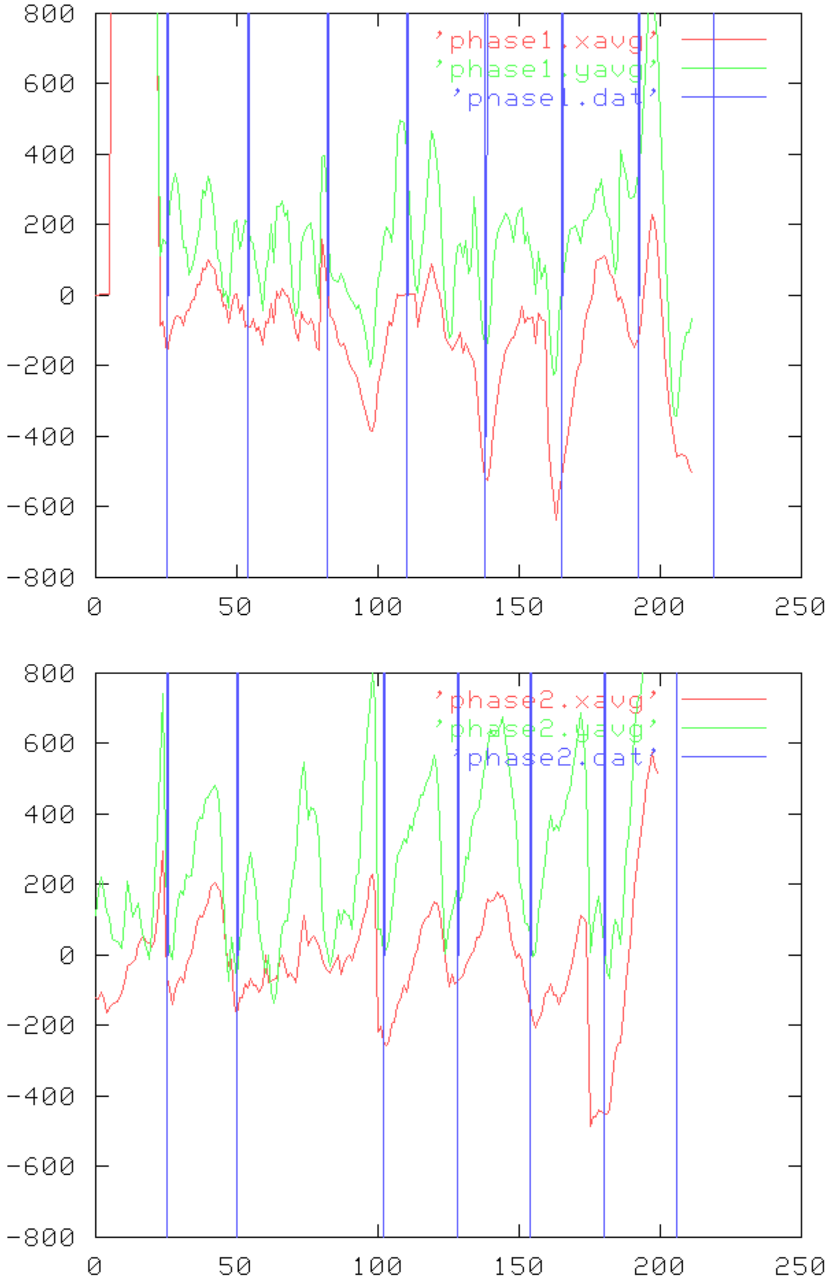

Fig. 8. Gyroscope readings for phase (One Leg Stand) and phase 1 (Ready for Landing) over a number of steps. The readings are the angular velocities in the left - right and forward - backward plane.

technical merit award for fully autonomous operation at FIRA HuroSot and second and third places at RoboCup.

More importantly, TAO-PIE-PIE's walking gaits have proved themselves to be very robust. TAO-PIE-PIE walked for a combined time of over an hour and only fell ones during the FIRA HuroSot competition. A similar result was achieved during RoboCup.

TAO-PIE-PIE also was the only robot in the small robot class that demonstrated during the RoboCup 2002 penalty kick competition, that it could quickly turn on the spot and kick a ball into either the right or left part of the goal. This strategy was successful up until the final against Footprints. After having been scored on by TAO-PIE-PIE in the preliminary rounds, the Footprints goal keeper moved quickly out of the goal in a straight line and thus covered the angle.

This highlights the biggest shortcoming of TAO-PIE-PIE at the moment. Its walking gait is slowed compared to that of other robots. It moved at an average speed of only 1cm/s. This is comparable to the performance of Vicki, the only other very small robot in the competition, but is very slow compared to robots in the 40cm class. The fastest robot in this class was Robo Erectus which walked at about 10cm/secs.

7 Conclusion

TAO-PIE-PIE has shown itself to be a powerful and flexible platform for research into humanoid robotics. It has proven itself during international competitions winning a second place in the RoboCup and a technical merit award in the FIRA 2002 competitions.

We have learned important lessons in the design of humanoid robots from TAO-PIE-PIE, which we will use in the design of the next generation humanoid robot HIRO. HIRO will use four additional DOFs (two in the hip and a pan and tilt camera). It also features a faster embedded processor (Intel Stayton), which allows us to implement better onboard computer vision algorithms. One of the main goals of the HIRO platform will be to investigate methods for augmenting the balancing of the robot using visual feedback.

Currently, only limited feedback from the gyroscopes is used to control the motion of the robot. With the addition of a more powerful embedded systems, finer grained control over the motion is possible.

8 Acknowledgements

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