Stabilizing Walking Gaits using Feedback from Gyroscopes

Jacky Baltes Sara McGrath John Anderson
Department of Computer Science
University of Manitoba
Winnipeg, Canada
jacky,andersj@cs.umanitoba.ca
http://www.cs.umanitoba.ca/~jacky
http://www.cs.umanitoba.ca/~andersj

August 6, 2003

Abstract

This paper describes methods used in stabilizing the walking gait of Tao-Pie-Pie, a small humanoid robot given rate feedback from two RC gyroscopes. Tao-Pie-Pie is a fully autonomous small humanoid robot (30cm tall). Although Tao-Pie-Pie uses a minimal set of actuators and sensors, it has proven itself in international competitions, winning honors at the RoboCup and FIRA HuroSot competitions in 2002 and 2003. The feedback control law is based solely on the rate information from two RC gyroscopes. This alleviates drift problems introduced by integrating the RC gyroscope feedback in the more common position control approaches.

1 Introduction

This paper describes our first attempts at using feedback control to balance the walking, kicking, and turning gaits of Tao-Pie-Pie, a third generation humanoid robot.

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: Honda, Fujitsu, Mitsubishi, and Sony, for example. 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, there are also 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 do we minimize the energy required in walking? What are the trade-offs between walking speed and stability?

We designed Tao-Pie-Pie to address some of these questions. Tao-Pie-Pie uses a minimal set of actuators and sensors to achieve a stable walk. Currently, the research work has been focused on flat, even terrain, but given the promising results of the methods described in this paper, we hope to be able to move to uneven surfaces in the near future.

The remainder of this paper is structured as follows. The design requirements for our humanoid robot are shown in section 3 describes the design requirements of Tao-Pie-Pie and supplies details of its mechanical and electronic design. The methodology used to develop and details of the implementation of the walking gaits are given in section 4, while Section 5 presents an evaluation of this approach. We begin by presenting some related work in humanoid robotics.

2 Related Work

Small humanoid robots have been developed previously by a number of different research teams. 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 [2] was developed at the University of Southern Denmark . Similar to Tao-Pie-Pie, Vicki employs 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 can not kick a ball straight forward. Tao-Pie-Pie cannot turn its hips sideways, but it can kick with either 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 recent 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 Morph3

Morph3 is a humanoid robot developed by the Kitano Symbiotic Systems group [3]. The goal of the Morph3 project is to develop a humanoid robot that is able to perform acrobatic motions such as sommersaults, aerobics, and complex dance motions. Morph3 is 38cm tall and has 30 DOFs (6 DOFs in each leg, 2 in the waist, 5 in each arm, 1 in each hand, 2 in the head, and 2 in the eyes). It also contains an elaborate array of sensors: 28 current sensors, 18 thermal sensors, two CCD cameras, 4 three axis force sensors mounted on each foot, a 3 axis gyroscope mounted in the waist, and one 3-axis and four 2-axis accelerometers are mounted at the waist as well as the arms and legs respectively. There is also a compass as well as an infrared sensor in the neck.

Morph3 is covered by eight tactile sensing shells at the hip, arms, elbows, and the back, allowing the robot to detect contact of one part of its body with the floor. The actuators can be controlled in either the traditional positional control mode as well as "current control mode," which allows stiffness control of a motion. To save energy, the actuators also support a "free mode," which allows passive control over the motion.

Morph3 is already able to perform a variety of acrobatic movements, including getting up after a fall and a forward roll.

2.3 Robo Erectus

Robo Erectus is a small humanoid robot developed at Singapore Politechnic [4]. 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 2003 RoboCup competition, achieving a second place finish in the robot walk even against taller robots.

3 Tau-Pie-Pie

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 possible motion models. This reduces the amount of computation so that it is managable in real-time.

Furthermore, Tao-Pie-Pie was intended to compete at international humanoid robotic competitions such as RoboCup and FIRA HuroSot. Among other things, 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 not only helps to keep the cost of a project down, but it also has led 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 allows us to exploit the dimensions of the humanoid walking problem. The minimum set of DOFs that allow a humanoid robot to walk is also of interest, since it leads to energy efficient designs.

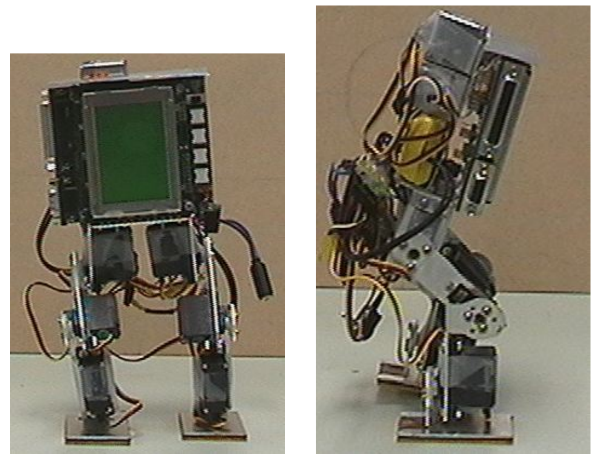

Figure 1: Front and side view of Tao-Pie-Pie.

Tao-Pie-Pie is the third generation of humanoid robots developed in our lab. Figure 1 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 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, with RC servos are used as structural components in the design.

4 The Walking Gait

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

We employ a divide and conquer approach and partition the walking gait into six phases: three for the right leg and three for the left. The phases were selected in such a way that the robot is statically stable at the end of each phase.

The six phases of the walking pattern for a straight walk is shown in Figure 2. The bottom row of images in Figure 2 shows the approximate position of the COM in each phase. We describe these phases moving from left to right in the figure.

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

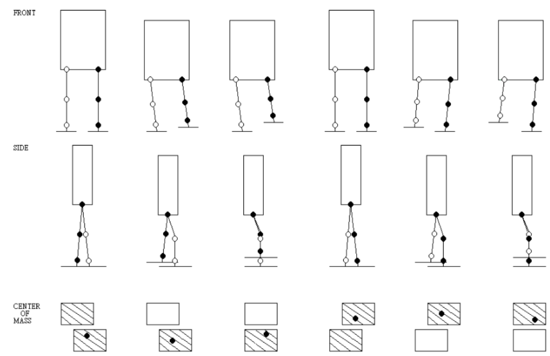

Figure 2: Walking Pattern of Tao-Pie-Pie.

4.1 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 the left-right (referred to as *Y-plane* in the remainder of this paper) and forward-backward plane (referred to as *X-plane* in the remainder of this paper) respectively.

The raw sensor data of the gyroscopes is very noisy. We therefore compute a running average over five samples to smooth out the noise. Figure 3 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. 3.

4.2 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

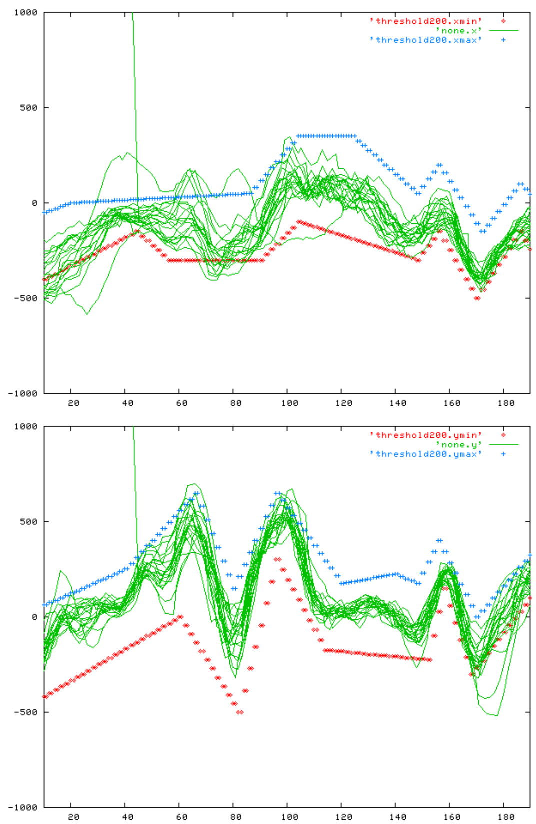

Figure 3: Gyroscope Readings in the X and Y Plane over 10 Steps. Linear Approximation of the Safe Zone.

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.

4.3 Motion Compensation

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 motion compensation 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. 2) 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 motion compensation 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.

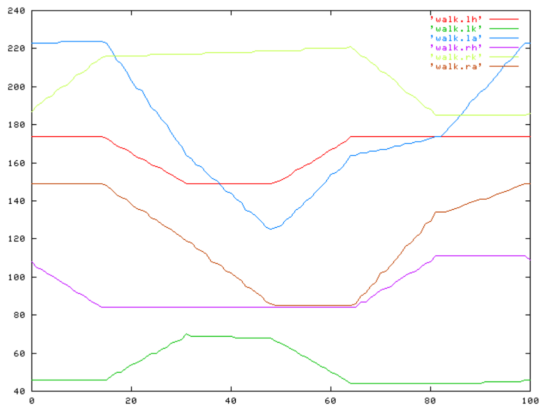

Figure 4: Servo Settings for a Straight Walk

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.

As can be seen in Fig. 4, 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 motion compensator modifies the set point of the servo by moving it 10% closer to the start point of the pattern. Similarily, 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 backward-forward direction. 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 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.

5 Evaluation

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

We also evaluated the motion compensation by subjectively by comparing the gyroscope feedback with and without motion compensation. The results of this comparison are shown in Fig. 5.

As can be seen from the plots, the motion compensation 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.

6 Conclusion

This paper describes our first experiments into the design of robust feedback control for walking of small humanoid robots. There is much work left to be done.

The current motion compensation algorithm is simple, but works surprisingly well in practice. We plan on investigating more complex methods for motion compensation and balancing in the future. For example, the motion compensation should not be a constant factor, but should be proportional to the current velocity.

We intend to extend this evaluation into more uneven terrains. The hope is that by using feedback, Tao-Pie-Pie is able to compensate for uneven terrain and adapt its walking gait.

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

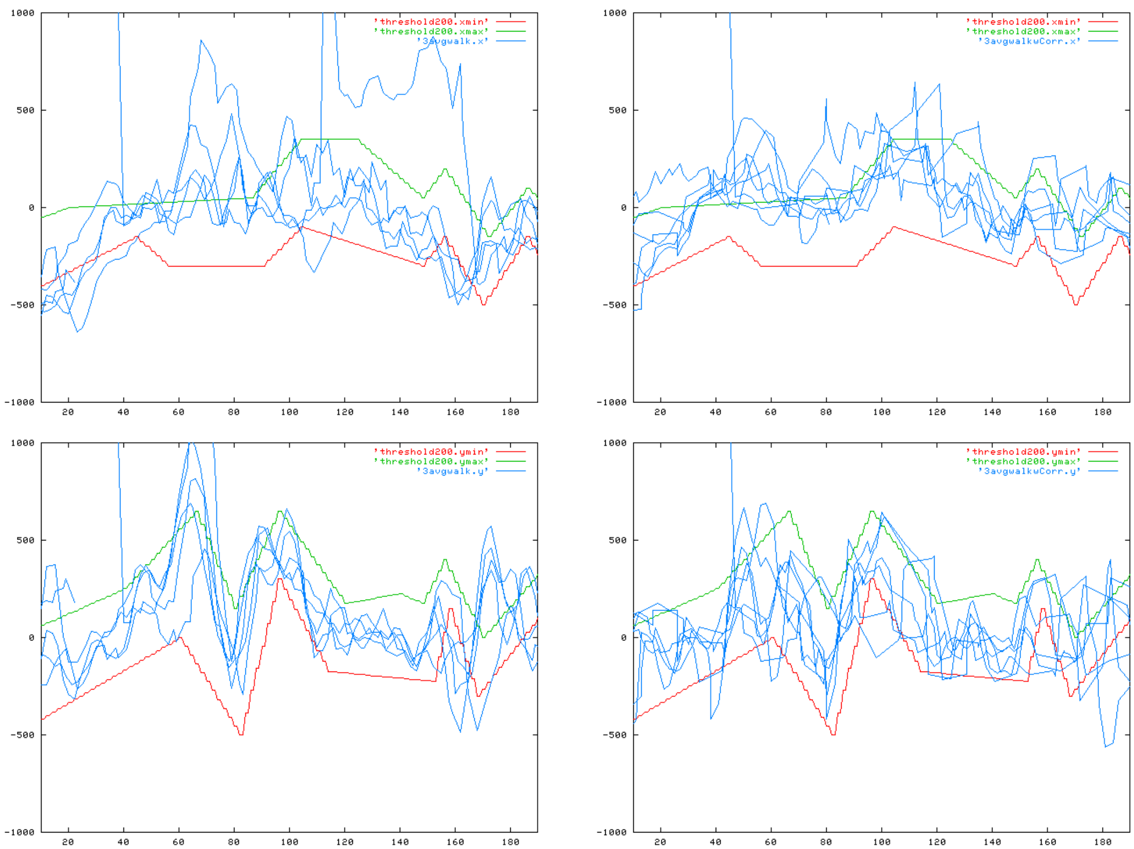

Figure 5: Comparison of original walking gait (left column) and walking gait with motion compensation (right column) in the forward-backward (top row) and left-right (bottom row) plane.

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 one for each leg). HIRO will also have more sensors, especially a set of force sensors in the feet. It also features a faster embedded processor (Intel Stayton), which allows us to implement better on-board 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.

References

[1] Thomas Bräunl. Thomas bräunl's homepage. WWW, November 2002. http://robotics.ele.uwa.edu.

[2] Leopold Paramonov and Henrik Hautop Lund. A minimalistic approach to humanoids. In *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*, 2001.

[3] Fuminori Yamasaki, Tatsuya Matsui, Takahiro Miyashita, , and Hiroaki Kitano. Pino the humanoid: A basic architecture. In Peter Stone, Tucker Balch, and Gerhard Kraetszchmar, editors, *RoboCup-2000: Robot Soccer World Cup IV*, pages 269–278. Springer Verlag, Berlin, 2001.

[4] Changjiu Zhou. Linguistic and numeral heterogenous data integration with reinforcement learning for humanoid robots. In *Proceedings of the 1st IEEE Conference on Humanoid Robots*, 2000.