# Control of a Heavy Weight Biped Robot in the Frontal Plane

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## Abstract

The advantage of legged locomotion in rough terrain and in confined spaces has been investigated extensively in recent years. It is anticipated that in the next decade or so, the prophecy that anthropomorphic biped robots will work side-by-side with humans will be realised. Recent successes in Japan have advanced the field substantially. However, little research has been conducted into the realisation of an industrial scale materials handling biped robot. Such a device presents challenges in terms of the magnitude of dynamic forces produced and of the systems required to control it in real-time. A 500kg, self-contained biped robot, called Roboshift, has been built to explore these challenges and to identify the significant aspects of control. This paper identifies issues associated with the control of the biped in the frontal plane. Results from balancing trials are presented which demonstrate the effect of ankle torque on the control of the biped. A model is then presented which demonstrates the effect of control forces and of geometry on the response of the biped in frontal sway. It is shown how the stiffness produced by control torque, a function of the gain of the control system and the response of the joint, affects the dynamic characteristics of the system.

## 1 Introduction

Mechanical walking machines have been proposed, patented and built from the beginning of the 20th century, but it is only since the advent of ready access to low-cost computing that electronically-controlled devices have become viable. The geometry presented by an anthropomorphic device and the inherent instability of bipedal locomotion increase both the complexity and cost of the device in terms of construction and control hardware.

Researchers involved in this field have tended to justify their endeavours in philanthropic terms, such as the suggestion that in the future biped devices may replace humans performing hazardous or degrading work [Golliday, 1977; Zheng, 1988]. While this goal may be worthy, the cost of a biped robot compared to that of a wheeled or tracked vehicle detracts from commercialisation. Other applications will need to be sought.

Like humans, biped robots possess the capability of turning in their own space and lifting heavy objects by adjustment of posture rather than by increasing their support base. Their support base can also be kept an order of magnitude smaller than that of any other lifting devices. Accordingly, we see the exemplar target application for a biped as being materials handling in confined, uneven terrain where a forklift or other lifting device would be unsuitable. Possible situations would be field handling in a military environment, on board a ship, or industrial applications in the field such as a geological or mining context.

Some attempts have been made to realise a bipedal walking materials-handling robot such as the General Electric Hardiman [Todd, 1987]. Research conducted in recent years has attempted to closely imitate the human form. Recent successes in Japan have advanced the field of Biped Robotics significantly. However, the ability of a human scale device to achieve heavy lifting is limited. Something larger is required.

This project endeavours to demonstrate that a biped robotic materials-handling device is feasible. It is suggested that the design criteria for such a device to be industrially practicable are as follows:

- Capable of lifting 500kg
- Completely self-contained
- Robust both physically and electronically
- Easily maintained
- Able to work for long periods

These design criteria have been taken for Roboshift – the biped robot that is the subject of this paper.

## 2 Structure of Roboshift

Roboshift is unconventional. Unlike any previous or current anthropomorphic scale biped, the body of Roboshift is located under the hips. In this configuration (See Figure 1) the stride length of the robot is nearly double that if the body were placed on top of the hips.

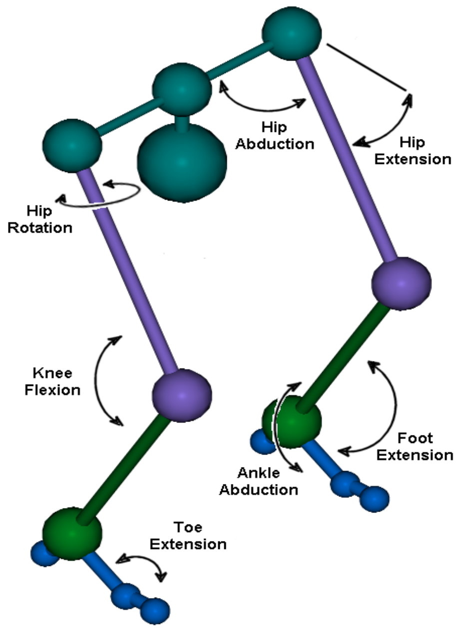



**Figure 1** Schematic of Roboshift showing degrees of freedom of the limbs.

This design requires the distance between the hips to be substantially increased so that the thighs can swing on either side of the body.

Roboshift is hydraulically driven, as was the biped robot developed by Waseda University and Hitachi [Kato, 1987], WH-11. However, unlike other larger scale robots such as WH-11 and the biped developed by Furusho et al [1986], Roboshift has been designed to be completely self-contained. A 16 kilowatt, LPG powered engine provides all hydraulic and electrical power. Only by cutting umbilical cords can problems associated with carrying the power source and all control systems on-board be identified in a prototype.

To satisfy the requirement that the device be easily maintained, the overwhelming majority of components must be available off-the-shelf. Also, by using standard, less specialised parts, the cost of the project has been reduced.

## 3 Biped Control

As recognised by Hemani [1977], the biped gait is periodic and symmetrical but unstable. The gait consists of falling from one leg, accelerating in the forward direction while decreasing potential energy, onto the other leg, decelerating in the forward direction while increasing potential energy. If disturbed from either trajectory, the system requires a force input to stabilise it.

Designers of biped robots have recognised these features of a biped control system. Furusho [1986], Shih [1992] and Gurfinkel [1981] have all used regular gaits that react to disturbances or feedback errors generated when actual trajectories fail to match computed ones. Also recognised by biped robot researchers is the complexity of the equations governing biped motion. Furusho [1986], for example, found that his 5 link biped model resulted in non-linear differential equations of order 10. Provided with sufficient processing power, ultra-reliable sensors, fast actuation and a structure with minimal deflection, it may be possible to use classical control methods to coordinate a biped robot in dynamic gait. But in practice it may be better to simplify the control model and focus available processing power on tasks that most influence stability.

Researchers have attempted to reduce the complexity of the control system by a number of methods. Vukobratovic [1970] suggests that designing the body so that limbs can be described as point masses eliminates or minimises secondary inertia terms. Using feed-forward control with local distributed negative feedback stabilisation has also proved popular and effective [Furushno, 1986; Gurfinkel, 1981; Shih, 1992].

Roboshift addresses the complexity of the control requirement by separating the processing of tasks, in a way inspired by the characteristics of the human system. In the human, force inputs to stabilise motion are generated by two systems. Firstly, as highlighted by Sias [1987], the nervous centres of the midbrain develop the feed forward data for gait motion. Sensory organs such as the vestibular system provide feedback error data for the midbrain to initiate course posture corrections. Learned functions such as walking are initiated by the midbrain in this way. Secondly, at a lower level, fusimotor and Golgi tendons provide propreoception and fine motor controls for precise positional control of individual joints. The twitch muscles that control these joint positions do so locally, without reference to the midbrain. An example of this would be a rotation of the foot to equalise the reaction force across it.

Figure 2 shows a schematic of how this concept is implemented in Roboshift. A primary control computer, representing the midbrain, computes the feed-forward control data and monitors the inputs from the artificial horizon and compass, which represent the vestibular system. It also receives force and positional data from local joint processors. The primary control computer communicates with the rest of the body through a communications computer, representing the spinal cord, which contains a 16-port RS232 expansion board. Local joint motion, propreoception and fine motor control, is controlled by 14 Motorola 68HC11 microprocessor and interface boards via analogue outputs and digital encoder position inputs. The microprocessors communicate with each other and with the control computer via the communications computer.

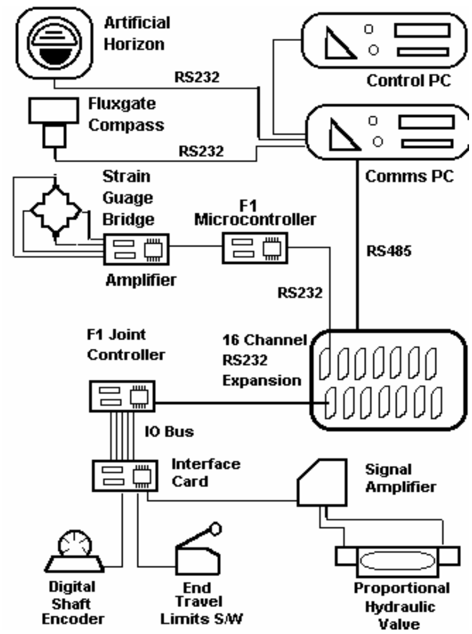



**Figure 2** Schematic of control System

**Figure 3** Robot being lowered in stance position.

## 4 Control of Frontal Sway

Sway in the frontal plane is fundamental to the walking process. The desired effect of frontal sway is to get the robot to lean far enough to one side so that the body is almost overbalanced. With the centre of gravity over the supporting foot, the free foot can be moved forward in readiness to take up the weight as the body falls onto it. The resulting motion represents an energy minimising gait because the system is operating at the natural frequency of oscillation. The disadvantage of such a gait is that fine control is required at the boundary of stability.

To explore the behaviour of Roboshift in frontal sway, the following test procedure was implemented.

1. With the robot suspended above the ground, instruct the control system to hold the joints in a predetermined configuration suitable for sustaining a rigid stance.
2. Lower the robot so that it balances on the ground, with the control system still maintaining a rigid stance position (see Figure 3). Note that due to clearances and tolerances in the joints and compliance in the joint members, the robot will lean slightly to one side of the frontal plane and either forward or backward in the sagital plane as it settles under its own weight.
3. Activate the active balancing program and observe the response.

The active balancing program attempts to reposition the robot's upper body so that the centre of gravity is maintained within a specified tolerance-band of a condition in which there would be equal load on each foot. The robot achieves this by abducting the hips equally but in opposite directions. The control input to the balancing software in the frontal plane is the proportion of weight on the left leg, as specified by a "trim" term that is defined as:

$$\text{Trim} = \frac{weight\_left\_leg}{weight\_left\_leg + weight\_right\_leg}$$

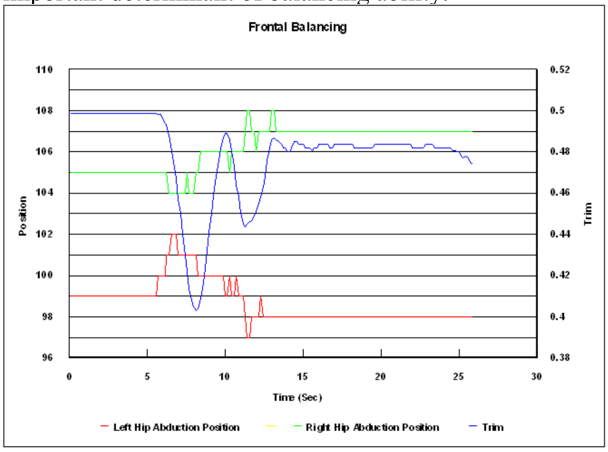
Initial results show the balancing routine to be sensitive to three variables;

- The tolerance-band set for balancing.
- The distance between the feet
- The gain of the control system.

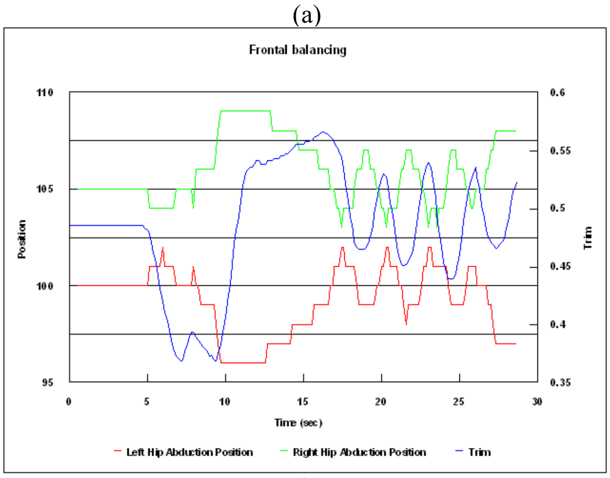
Figure 4a shows time-history data of the left and right hip position and the trim value as the robot actively balances. In this case, the limits for balance were set between 0.45 and 0.55. It can be seen that after an initial disturbance is applied, the robot balances successfully. When the limits were set between 0.48 and 0.52, see Figure 4b, the robot became unstable, continuously swaying in the frontal plane.

The robot balanced successfully when the trial was conducted with the same tightened trim limits as above, but with the valve control gain reduced i.e. a reduced proportional constant in the PI control loop. The corresponding increase in the time taken to respond could be seen in the decreases in the slope of the joint displacement curve. This demonstrated the relationship between balancing limits and the gain of the control system. When the gain was high, the robot generated substantial momentum by the time the trim fell between the set balance limits. While the proportional constant in the control loop might be expected to account for any potential overshoot, there is a lack of symmetry in the response because the robot has limited ability to decrease angular momentum when the centre of gravity is moving towards a position that brings it nearly over one leg (ie trim ≈ 0 or 1).

Under these conditions, when the stance width is less relevant, the width of the foot is likely to become an important determinant of balancing ability.




(a)




(b)

**Figure 4** Robot in active balance with trim limits set between (a) 0.45 and 0.55 and (b) 0.48 and 0.52.

Once a stable actively-controlled stance had been achieved, the next task was to generate controlled sway. by varying the hip abduction positions sinusoidally at a frequency close to that which could be expected during locomotion. Initial attempts to generate frontal sway in the biped have produced motion that is highly dynamic, as shown in Figure 5 which is taken from a video. From observation of the motion, it appeared that the robot was oscillating at a natural frequency.

**Figure 5** Biped in frontal sway.

Figure 6 shows the transfer of weight from one leg to the other as the robot commenced frontal sway from rest. The video of the event shows that the biped robot was swaying to the limit conditions discussed previously where the ground reaction force on the non-supporting leg approaches zero. Correspondingly, the reaction at the opposite foot approached the total weight of the robot. At this point, the non-supporting foot is seen to slide toward the supporting foot. This is caused by the moment created by the weight of the leg about the hip adducting the leg towards the supporting leg as the lateral friction forces at the foot approach zero because there is no weight on the non supporting leg. The biped then swayed back toward the non-supporting leg, now closer to the centre of gravity of the robot and subtending a larger angle at the hip, the corresponding increase in torque immediately reduced the amplitude of sway.

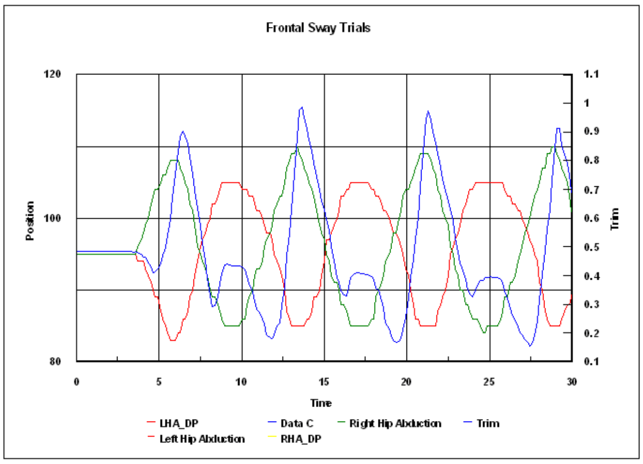



**Figure 6** Robot in frontal sway.

## 5 Effect of Ankle Torque

One of the issues facing the designer of a biped control system is the role of ankle torque in control of frontal sway. Hemani models both the case where no ankle torque exists and where ankle torque is available. He concludes that control in frontal sway is achievable in both cases. The advantage of ankle torque in the frontal plane is that it provides lateral stability during the swing phase of walking. As Hemani suggests, the disadvantage of ankle torque is that it must be measured or estimated and then controlled. In the case of Roboshift, the control system has been configured so that ankle torque may be controlled either centrally or locally.

From observation of the trials described above, it was determined that finer control would be required at the boundary of sway. To achieve this, it was decided that the width of the foot should be increased to provide additional ankle torque, which would help control the biped at the boundary condition. The foot width was increased from 150mm to 300mm which increased the calculated maximum available ankle torque from approximately 333Nm to approximately 667Nm[1]. Evidence of the increased torque capacity provided by the extension in foot width is the failure of the foot rotation cylinder connections, see Figure 7. Trials conducted in the new configuration produced unexpected results. It was observed that not only had the fundamental frequency of motion increased, as would have been expected, but an additional frequency had also been superimposed upon it. To determine the cause of the changes in frequency a dynamic analysis was begun.

## 6 Modelling Frontal Sway of Roboshift

Various methods have been used to dynamically model bipeds in the frontal plane. Hemani [1979, 1980] used Lagrangian dynamics to construct a constrained model and then linearised the system in the vicinity of the operating point. Hemani suggested that constraint forces could be calculated as functions of the state of the system. Therefore, his model allowed for the control of a biped in the frontal plane without the requirement for sensing of constraints, such as ground reaction forces. Roboshift uses an alternative approach in which these forces are measured and used in the control routine, thereby eliminating the need to calculate them. Thus the requirements for a model in the case of Roboshift are different.

**Figure 7** Failure of foot rotation cylinder connection

A dynamic model of Roboshift is being developed for motion in the frontal plane in order to provide insight into its dynamic characteristics. The simple version of the model shown schematically in Figure 8 was devised to explore natural, frequencies of vibration. It is of a three-link biped with parallel legs. Simplifications made during the derivation of the model include:

- $Cos(\theta) = 1$ for small oscillations in the vicinity of the vertical.
- $Sin(\theta) = \theta$ for small oscillations in the vicinity of the vertical.
- As there can be no rotation of the body, $\alpha_{body} = 0$
- The control torques $\tau_3$ and $\tau_4$ are equal and in the same direction.
- Ankle torques $\tau_1$ and $\tau_2$ are equal and in the same direction.

The equation of motion for the system is found to be;

$$\left(I_L + \frac{M_B L^2}{2}\right)\alpha + \left(k_A + k_B - \frac{M_B g L}{2}\right)\theta = 0$$

where:

$M_B$ = Mass of body
$L$ = Length of legs
$I_L$ = Moment of inertia of one leg about its foot
$g$ = Gravitational constant.
$\tau_B = k_B\theta$ = Control torque.
$\tau_A = k_A\theta$ = Ankle torque.

1 The maximum available ankle torque occurs at the instant prior to the edge of the foot lifting. It is calculated as the product of half the foot width and the vertical ground reaction at the foot

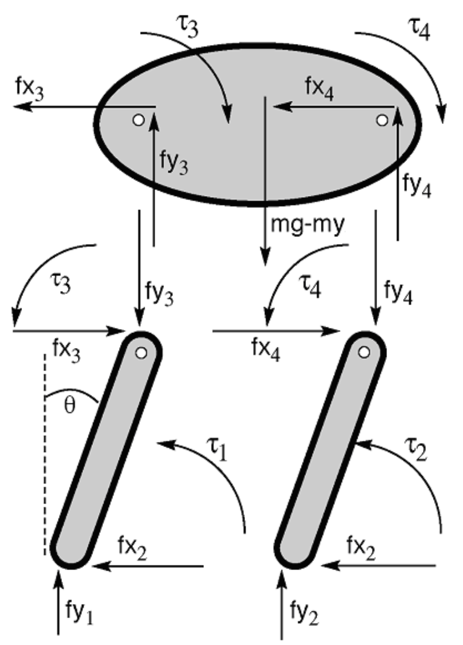



**Figure 8** Three link biped model

From this, the period of oscillation of the system is calculated as:

$$\omega = \sqrt{\frac{\left(k_A + k_B - \frac{M_B g L}{2}\right)}{I_L + \frac{M_B L^2}{2}}}$$

The equation shows that the dominating parameters of the biped are the length of the legs and the magnitudes of torques at the ankle and body.

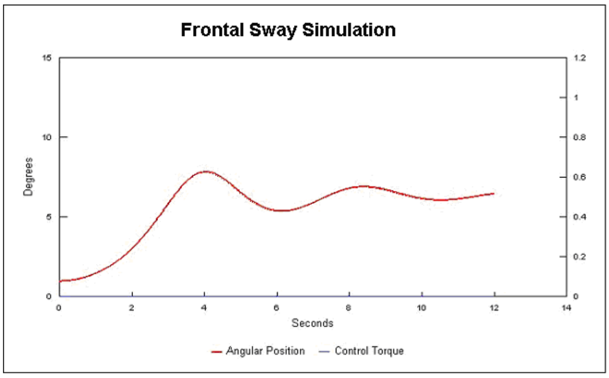
Data used for this model corresponded to the first trials of the biped which had been conducted with a foot width of 150mm. In this configuration, with full load on one leg, these feet could provide an ankle stiffness of approximately 7600Nm/radian with a maximum ankle torque of 333Nm. Hip abduction is controlled by a hydraulic cylinder that is mounted at the top of the body. For the purpose of the analysis, it will be assumed that these joints when locked possess a similar stiffness to that of the ankles. The remaining physical properties of the biped are listed in Table 1.

| | | |
|---|---|---|
| Length of Legs | 2 | m |
| Mass of Body | 300 | kg |
| Mass of legs | 80 | kg |
| Moment of Inertia of Legs | 33 | $kgm^2$ |
| Ankle Stiffness | 7600 | Nm/rad |
| Maximum Ankle Torque | 333 | Nm |
| Body-hip Stiffness | 2000 | Nm/rad |

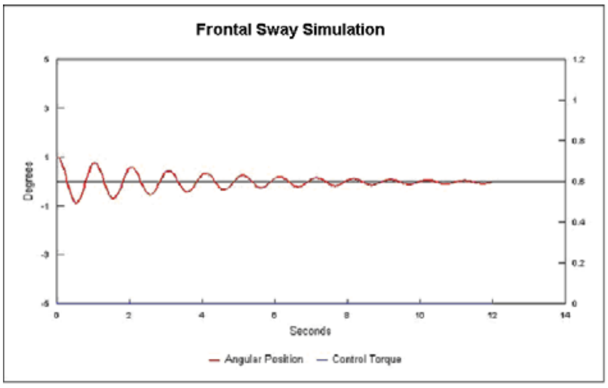
**Table 1** Input data for model

When input into the above equation, these values predict an oscillating frequency of 0.42 Hz corresponding to a period of 2.4 seconds. This may be compared with an observed period of 2.8 seconds in the video taken of the trials.

As previously discussed, when the biped is first lowered to the ground, it will lean toward one side or the other until the ankle torque becomes equal to the moment generated by the centre of gravity about the centre of support. Figure 9(a) shows the response of the simulated system as the model is allowed to lean from the vertical. In this case no control torques are included. Ankle torques are based on the original foot width and a damping coefficient has been added. The damping factor has been estimated from observed time taken for the robot to come to rest after a step input.




(a)




(b)

**Figure 9** Response of biped dynamic model when biped is allowed to lean uncontrolled from the vertical with maximum ankle torque = (a) 333Nm, (b) 667Nm

The simulation shows that without control forces, the biped displays a single natural frequency of oscillation, as expected. When the maximum available ankle torque is increased to a value associated with the wider feet, it can be seen that the natural frequency of the system increases as shown in Figure 9(b). As might have been expected with this increased torque capacity, the frequency of oscillation has been increased and the system has come to rest closer to the vertical.

The model was then expanded to include control torque at the hips. The control software makes incremental changes to the force acting on the hip cylinders based on the feedback error of the actual position versus the target position. A time-history plot of the control values for the hip abduction cylinders during frontal sway can be seen in Figure 10. Control torques are only active when the position error of the hip abduction cylinders exceed a set value. Once active, their values are proportional to angular displacement error; i.e. as the error increases, the restoring force of the hip control cylinders increase proportionally. Effectively the control torque acts as a torsional stiffness at the hips and can be modelled as a torque proportional to angular displacement.

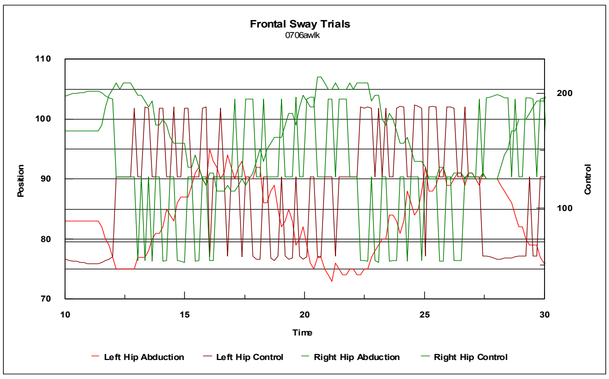



**Figure 10** Hip control values

The graph in Figure 11 shows the model used in Figure 9 (a) reacting to a simulated control torque after it starts from a displacement of 10 degrees. It can be seen that the additional stiffness of the control system changes the response of the system at the times when the control torque is acting. The greater the control torque the shorter the period of oscillation. Once the hip abduction torque (stiffness) is not acting, the frequency reverts to that of the natural system. The control torque is a function of the gain of the control system and the dynamic response of the joint being controlled. Further work will investigate the tuning of the control system.

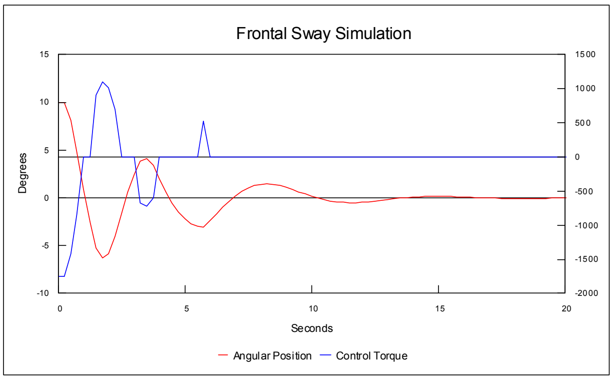



**Figure 11** Simulation with control torque.

An inverted pendulum can display harmonic motion only if the moment generated by gravity is overcome by a suitably large restoring torque. In the case of a biped robot in active control, it has been shown that the restoring torque is primarily a function of the torque generated by the control system. As the magnitude of that torque increases, the period of oscillation will decrease.

In its present form, the single degree of freedom model used to analyse the system could not, of course, explain the source of the additional frequency observed after the addition of wider feet. An alternate explanation is that this additional frequency is a function of the compliance of the joint. As the hip abduction cylinders move to reduce the error, the inertia of the system causes an amount of the movement to be taken up by compliance. This compliance then results in an increase in torque, which accelerates the joint in relation to the inertia of the system. Effectively, the mass of the system acts as a high-pass filter for the control system, which runs at a frequency of 7 Hz. The additional torque created by the addition of the wider feet increases the frequency response of the system decreasing the damping of the control frequency. Thus, as the width of the feet increases the stiffness of the system, higher order responses will become apparent. This aspect of the system will be investigated in future work.

## 7 Conclusions

Widespread research being conducted into anthropomorphic service robots is certainly fascinating but these robots are not yet cost effective for the roles on which the research has been justified. It is as an industrial scale materials handling platform that biped robots are more likely to be commercially viable.

An industrial scale biped robot, weighing 500kg, has been built, which is completely self-contained with on-board motive and electrical power.

The research presented in this paper demonstrates the large forces involved with the control of an industrial scale biped robot in sway in the frontal plane. It shows that the major control factors are:

- The geometry of the device
- The stiffness of its connection to the ground
- The stiffness of the control system at hip joints

The effect of ankle torque stiffness is demonstrated in data obtained from balancing trials of the robot and from a dynamic model of the system.

More trials are being conducted. Further areas of research will include an examination of how to manipulate the dynamic response of the system by controlling the active and passive stiffness factors. As well as additional experimentation, this understanding will require the development of dynamic models from which to gain the required insight.

Once the robot has been stabilised in frontal sway, walking will be attempted.

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