Energy Efficient Bipedal Robot

A MASTER'S THESIS

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of the requirements for the award of the degree

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In

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Submitted by

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I do hereby declare that the work presented in this thesis entitled **"Energy Efficient Bipedal Robot"**, submitted in the partial fulfillment of the degree of Masters of Technology (M.Tech), in Information Technology at Indian Institute of Information Technology, Allahabad, is an authentic record of my original work carried out under the guidance of **Prof. G.C. Nandi** due acknowledgements have been made in the text of the thesis to all other material used. This thesis work was done in full compliance with the requirements and constraints of the prescribed curriculum.

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I do hereby recommend that the thesis work prepared under my supervision by **Mr. Manish Sharma** titled **“Energy Efficient Bipedal Robot”** be accepted in the partial fulfillment of the requirements of the degree of Master of Technology in Information Technology for Examination

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Abstract

Bipedal Locomotion is one of the most interesting control problems of current era, increasing demand of deploying them in hostile environments have given wings to the research in the field of legged locomotion. This thesis is focused on studying and modeling of point foot planar bipedal walkers as open link kinematic chains and to make a hardware model of acrobot walker and kneed walker able to walk passively down a slope. Simplified models of acrobot walker and kneed walker are developed and simple energy based linear controller is designed and implemented using partial feedback linearization. The controller developed helps to drive the bipedal in partially passive mode.

Keywords : bipedal locomotion, under actuated control, hybrid dynamics, Acrobot walker,Kneed walker.

Chapter 1

Introduction

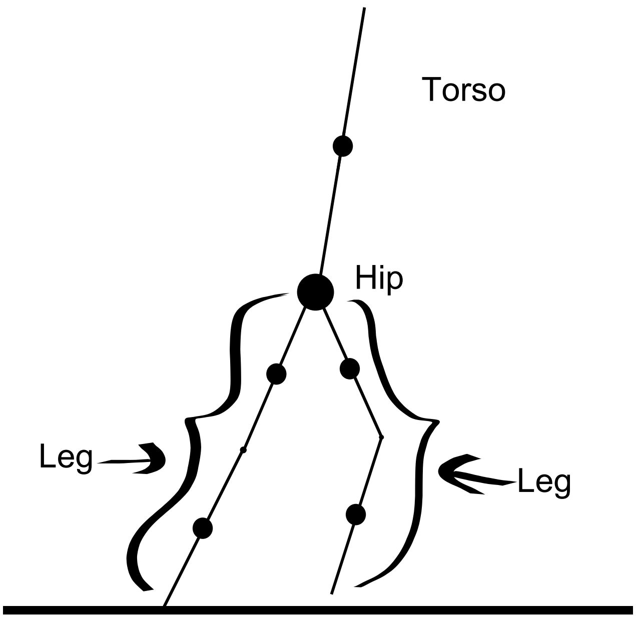


Figure 1.1: A bipedal Robot stick diagram

Legged locomotion is an important problem. From the point of view that it enables us to move around on uneven terrain. In spite of the fact that most of the living organisms who inhabit on lad are legged we as engineers and scientist have not been able to bring some rugged legged platform in everyday use. Bipedal is a smaller subset of the legged robot class of robots and are modeled as an open kinematic chain with 2 end links known as legs. The point at which the two legs join is called hip. Any sub chain coming out of hip apart from the legs is called torso as shown in [1.1]. The reason quoted in [1] is that it is relatively a very complex process from the point of view of dynamics and control. Bipedal walking is normally consists of alternating swing phase and impact phase. And with hip horizontal displacement is monotonically positive/negative. What makes the study and control of bipedal more difficult is the impact with the ground of the swing leg after each step. Normally this alternating dynamics is studied using hybrid dynamics models. Second problem that we face while dealing with the bipedal control is the under-actuated nature of the problem in the swing phase.

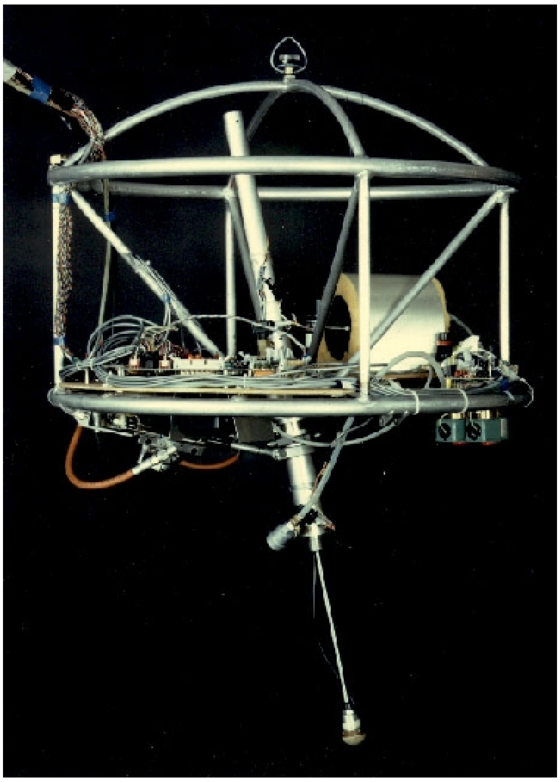


Figure 1.2: Raibert hopper
Source: www.robothalloffame.org [2]

1.1 Analysis of Previous Research

Though their were many attempts to make a legged robot since the start of 1980s, the most noticiable one of all was Raibert et al's monopod hopper [2]. Roboticist Marc Raibert established leg laboratory at CMU in 1980 and later shifted it to MIT in 1986. His idea of making a robot dynamically stable and not statically to make them speedy and more human/animal like. One legged hopper that he developed was ideal for studying dynamic balance and it completely revolutionized the way robots are made to walk. Bipedal Robot locomotion is broadly studied under 3 categories [1].

1. Passive Robots
2. Powered Robots
3. Hybrid Robots

Probably the first well known Passive walker was Wilson Walkie,1938, which was actually a toy [3]. The credit of actually making a passive bipedal walker with knees is given to the pioneering work of Ted McGeer in 1990s [4] who was motivated by mathematical proofs from Tom McMahon at Harward. McGeer Walker was able to walk down a small slope using the potential energy of the model itself which compensates for all the losses at impacts. The results of gaits generated by Ted McGeer kneed walker were strikingly similar to that of humans.And proved that the dynamics of legs are itself capable of walking.

Research on Powered Bipedal started much early than passive walkers. The first noted powered Bipedal is probably WL-5, a 3-dimensional, 11-DOF walker by Kato and Tsuiki, Waseda University, Japan in 1972. This group developed a series of hydraulic powered bipedal with large load carrying capacity but the speed of locomotion for all of them was very low. Some of the noted research test beds in bipedal robots include HOAP series robot by Fujitsu. They released HOAP-1, HOAP-2 and HOAP-3 in 2001,2003 and 2005 respectively. HONDA developed ASIMO(Advanced Step in Innovative MObility) and released it in 2000. Though the robot is not for sale. The ASIMO was a result of 2 decade of work by Honda which also produce Honda E series and Honda P series of humanoid walking robots. ASIMO have over the years gain improved dexterity and is now able to run at a speed of 6 km/hr [5] , climb up the stairs and down the stairs, kick a football and can achieve a range of different tasks.

In the series of Powered humanoid Robots Robonaut-2(R2) is the only name in space robotics, developed by NASA and General Motors which is highly dexterous anthropomorphic robot.Revealed in February 2010, R2 is made with the purpose to take over simple, repetitive and dangerous tasks. R2 is compact, more dexterous and includes a deeper and wider range of sensing than in predecessor R1. Though R2 is only consisting of torso of humanoid robot. Legs are installed on its latest version which will allow it to move and climb on the deck.

The state of Art in the field of bipedal Robots are SCHAFT [8] and ATLAS [7] by SCHAFT Inc. and Boston Dynamics respectively both owned by google now. SCHAFT won (DRC)DARPA Robotics Challenge in 2013 and was definitely much superior than its contender in the event. DRC was aimed at developing robots capable of doing "complex tasks in dangerous, degraded, human-engineered environments"-[9]. Developed by college dropouts from TOKYO University who

Figure 1.3: R2 with legs
Source : http://www.nasa.gov/ [6]

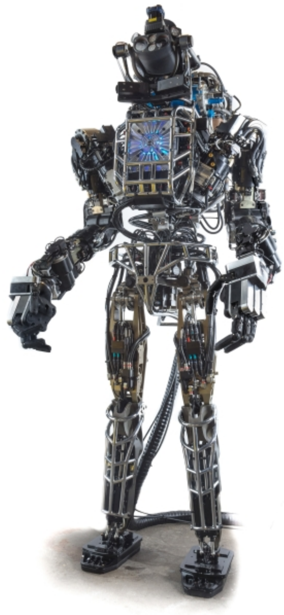


Figure 1.4: ATLAS
Source : http://www.bostondynamics.com/ [7]

worked in JSK lab. SCHAFT had a very robust push recovery capability. ATLAS on the other hand was developed by Boston Dynamics with the funding of DARPA. ATLAS platform was used in the DRC as a platform by many teams to write their algorithm over it. ATLAS has 28 degrees of freedom and have a external power source.

Talking of **Planar Bipedal Robots**, RABBIT is good platform having 5 links. Developed by Greoble, France. A lot of research on this platform was done by Prof. Jessy W. Grizzle et al., The University of Michigan in Ann Arbor from 1999 to 2004. The platform acted as a test bed for many control algorithms implemented and tried by his team. Prof. Grizzle is currently using MABEL platform that he developed with Jonathan Hurst of the Robotics Institute, Carnegie Mellon. Which is a complete 3-D bipedal with capabilities of storing energy in springs while taking steps as we humans do using our tendons [10].

Passive walkers are good to go on inclines and just work without any external energy source by using the gravitational energy to compensate for energy losses during its walk. But they are not usable for practical purpose since they can't walk on plane surfaces. Powered walkers are great in its job and we have seen

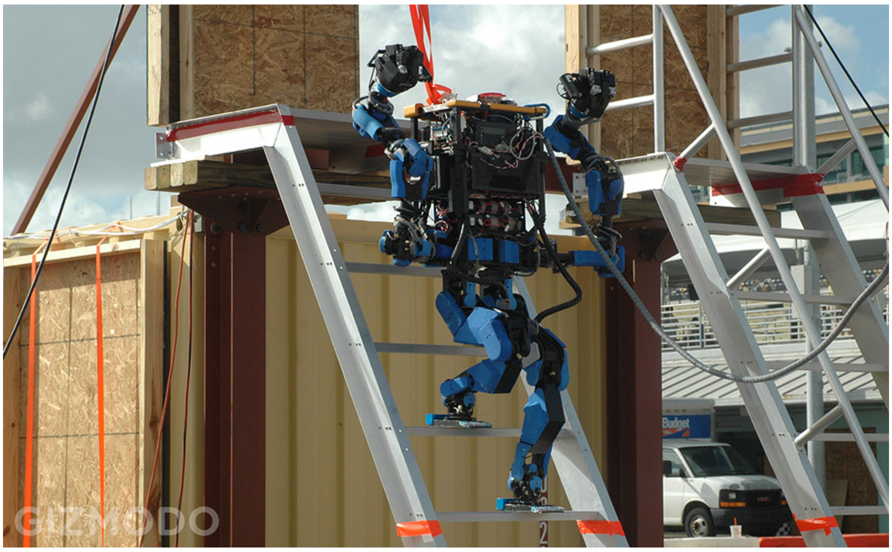


Figure 1.5: SCHAFT

Source : http://spectrum.ieee.org/ [8]

some very good work in the field of powered walkers,but probably the only shortcoming they face is the energy requirement. They have generally very poor energy performance because its internal dynamics is completely killed in the process to drive it the way we want. In this way actuators do enormous amount of work. Firstly, to zero on internal dynamics and Secondly, to overlap the desired dynamics. The whole control is achieved using Feedback linearization or Partial Feedback linearization(**PFL**).

This gave rise to the advent of a 3rd class of bipedal robot, **Partially Passive Bipedal Robot**. The basic idea behind such bipedals is to let the robot move under its internal dynamics most of the time and minimize the use of actuators. The absolute best in this class is **Cornell Ranger**(2001-2012) and **Powered Biped with knees** developed at Cornell University by Prof. Andy Ruina et al. Both of these robots are minimally controlled. Cornell Ranger hold the word record for walking non-stop for 40.5 mile on May 1-2, 2011. The Cost of Transport measured as **COT = Energy/(weight*distance)** for Cornell Ranger was just 0.28 in comparison to ASIMO COT which is about 2. So making an improvement in the performance in terms of energy by a factor of 10 approximately [11]. Another important robot that I particularly find important in this class is Toddler from MIT, developed by Russell L. Tedrake et al. The robot is a single degree of freedom system having curved feet that allow it to avoid foot scuffing. The specialty of the robot is its learning capability. This robot using reinforcement learning strategies to learn the optimal control strategy to walk, and have very good performance which allow it to converge very soon, approximately within 600 steps. Due to its inline learning capability that it does continuously the robot continuously adapt to the new terrains and slopes [12].

1.2 Formulation Of Problem

We have well enough bipedal hardware available, but, we are lacking in the selection and implementation of energy efficient bipedal control algorithms. In my work I have studied simple linear passive dynamic walkers. And tried to implement minimal control algorithms that will use the internal dynamics of the bipedal. Further during my investigation I have made a hardware of passive walker to implement the simulation results in reality.

1.3 Content of Thesis

Chapter 1 is the Introduction of the thesis compromising of a literature survey mainly of the state of art research in bipedal. Chapter 2 and 3 describes the methodology adopted in the thesis.Of which chapter 2 comprises mainly of the description of the process used to find out the mathematical model of planar bipedal models which is basically euler lagrangian method for the derivation of equation of motion in continuous phase of walking and conservation of angular momentum for the impact phase.These schemes are then further used to derive the model of passive bipedal models including Acrobat walker and Kneed/Ballistic walker in chapter. Chapter 3 mainly comprises of the analysis of stability of simple bipedal model and implementation of a simple minimal control algorithm to increase the stability horizon of bipedal walker. Chapter 4 gives a description of the hardware and software made. The final Chapters 6 and 7 sums up all the results generated while the work performed during my thesis work with their possible descriptions and conclusions drawn.

Chapter 2

Physical Modeling of Bipedal

2.1 Overview

Mathematical modeling of bipedal is one of the first step towards making a bipedal. I have implemented only an approximate model of the bipedal with the following assumptions.

2.1.1 Assumptions for model

I have made several simplified assumptions to make the study and derivation of the model tractable for study. The most important of them are enlisted below.

1. Planar dynamics.
2. Point mass.
3. Friction less.
4. Point feet.
5. Instantaneous impact.

2.2 Forward Kinematics of the Planar Bipedal

Forward Kinematics is the process of find out the coordinates of any general point on the robot if the robot configuration is known. Generally the robot configuration is known in the joint coordinates and the points of the general point on the robot is computed in Cartesian space.

My thesis explicitly focuses on planar bipedal robot thus the z position of any of the point on the manipulator is zero. The robot configuration that I have selected is referred to as extended configuration coordinates.

Consisting of $q_e = (x_0, y_0, q1_{abs}, q2_{rel}, q3_{rel} ......, qn_{rel})$. Where all the relative angles are measured in anti-clockwise direction.

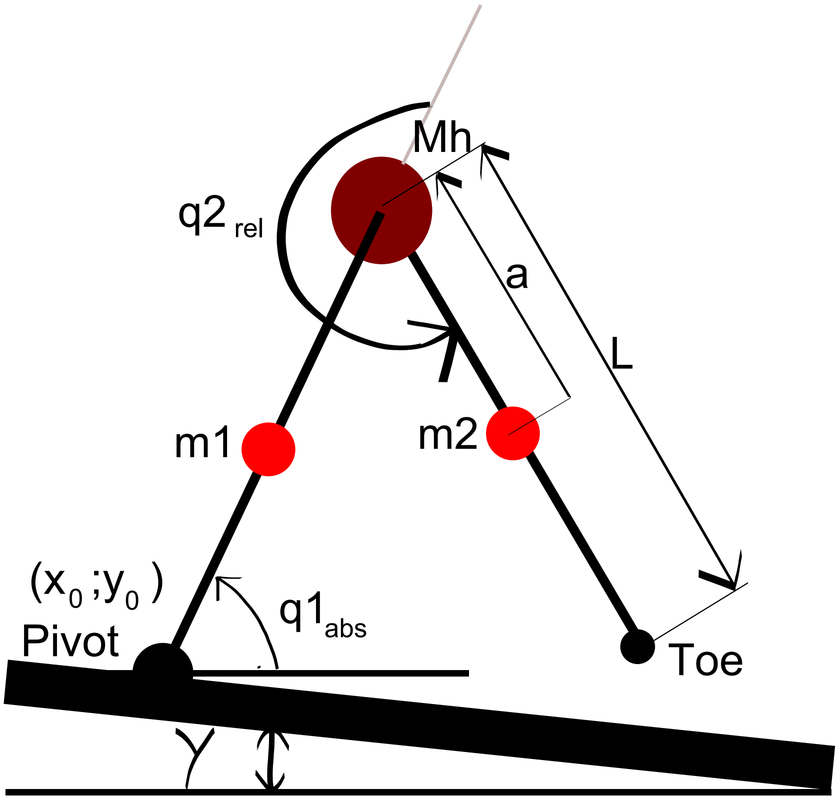


Figure 2.1: Acrobat walker Coordinate frame

Also I am assuming point mass model for the simplicity so only requirement of my forward kinematic model will be to derive the position of those point where the mass is assumed to be lumped. figure reffig:acrobot] depicts all the assumed angles and configuration of the Acrobot Walker.

The points of interest are $P_{pivot}, P_{m1}, P_{mH}, P_{m2}, P_{toe}$

$$P_{pivot} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \tag{2.1}$$

$$P_{m1} = P_{pivot} + R(q1_{abs}) \times \begin{bmatrix} L-a \\ 0 \end{bmatrix} \tag{2.2}$$

where, $R(\theta)$ is the rotation matrix given by

$$R(\theta) = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix}$$

$$P_{mH} = P_{pivot} + R(q1_{abs}) \times \begin{bmatrix} L \\ 0 \end{bmatrix} \tag{2.3}$$

$$P_{m2} = P_{mH} + R(q1_{abs} + q2_{rel}) \times \begin{bmatrix} a \\ 0 \end{bmatrix} \tag{2.4}$$

$$P_{toe} = P_{m2} + R(q1_{abs} + q2_{rel}) \times \begin{bmatrix} L \\ 0 \end{bmatrix} \tag{2.5}$$

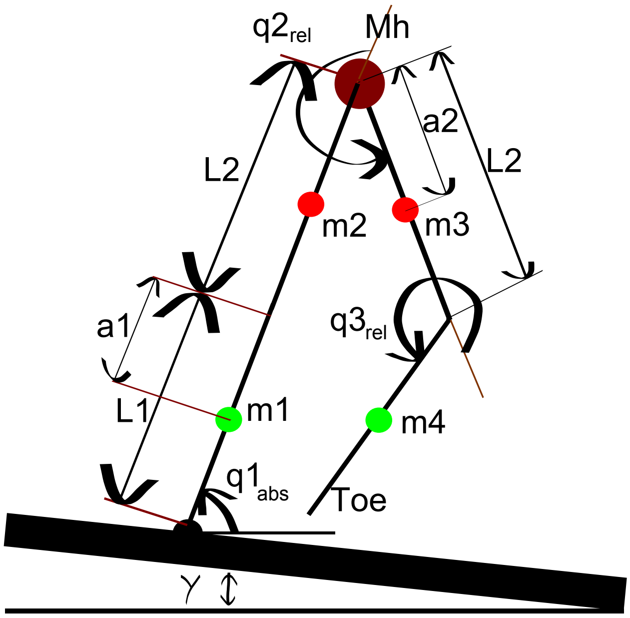


Figure 2.2: Ballistic walker Coordinate frame

In the similar fashion the forward kinematics of the Ballistic walker can be arrived. The point of importance in the ballistic walker are :

$P_{pivot}, P_{m1}, P_{m2}, P_{mH}, P_{m3}, P_{m4}, P_{toe}$ as depicted in fig [2.2].

$$P_{pivot} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \tag{2.6}$$

$$P_{m1} = P_{pivot} + R(q1_{abs}) \times \begin{bmatrix} L - a \\ 0 \end{bmatrix} \tag{2.7}$$

$$P_{m2} = P_{pivot} + R(q1_{abs}) \times \begin{bmatrix} L1 + L2 - a2 \\ 0 \end{bmatrix} \tag{2.8}$$

$$P_{mH} = P_{pivot} + R(q1_{abs}) \times \begin{bmatrix} L1 + L2 \\ 0 \end{bmatrix} \tag{2.9}$$

$$P_{m3} = P_{mH} + R(q1_{abs} + q2_{rel}) \times \begin{bmatrix} a \\ 0 \end{bmatrix} \tag{2.10}$$

$$P_{knee} = P_{mH} + R(q1_{abs} + q2_{rel}) \times \begin{bmatrix} L2 \\ 0 \end{bmatrix} \tag{2.11}$$

$$P_{m4} = P_{knee} + R(q1_{abs} + q2_{rel} + q3_{rel}) \times \begin{bmatrix} a1 \\ 0 \end{bmatrix} \tag{2.12}$$

$$P_{toe} = P_{knee} + R(q1_{abs} + q2_{rel} + q3_{rel}) \times \begin{bmatrix} L1 \\ 0 \end{bmatrix} \tag{2.13}$$

2.3 Forward Dynamics of the Robot

Forward Dynamics is the mathematical modeling describing the evolution of the system coordinates (positions and velocities) given the applied forces and torques.

$$\ddot{q} = D(q)^{-1}(-C(q, \dot{q})\dot{q} - G(q) + \Gamma) \tag{2.14}$$

2.3.1 Different phases of model

Bipedal or any walking robot can be thought of as having 2 different phases.

1. Swing phase.
2. Impact phase.

Swing phase can be thought of as a planar open kinematic chain pivoted to the ground at a point. With no possible actuation between the ground and the link pivoted to it. So the system is under-actuated.

While the impact model is modeled by thinking the robot to the a free open kinematic chain and impact happening as an instantaneous force at the end of swing leg.

The generalized coordinates will be denoted by $(q; \dot{q})$ for the extended coordinate(impact phase) system we required since it will have 2 more degrees of freedom so the generalized configuration variable in that case will be denoted by $q_i = (q; P0_h; P0_v)$ where $(P0_h; P0_v)$ are the coordinates of any fixed point on the n-link manipulator in the inertial frame.

2.3.2 Swing Phase

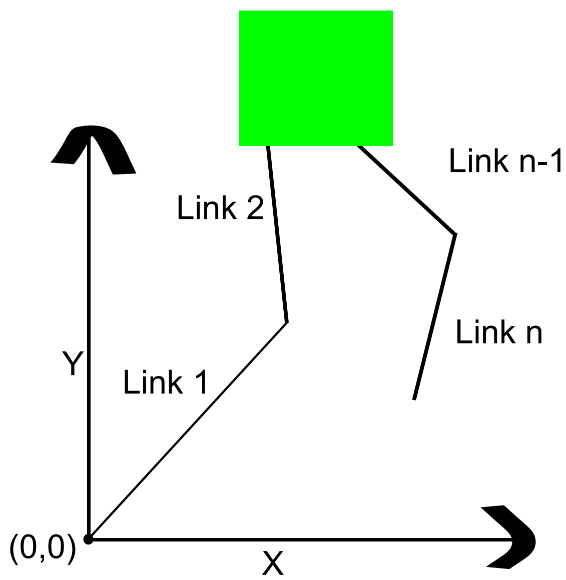


Figure 2.3: n-link open kinematic chain pivoted at a point

In swing phase the planar bipedal is modeled as n-link open kinematic chain pivoted at a point.

I have preferred to use body coordinates for defining the generalized configuration. So the generalform of the generalized configuration vector will be $(\theta_1^{abs}; \theta_2^{rel}; \theta_3^{rel}; ....; \theta_n^{rel})$ where all the relative angles are taken counter-clock wise.

The dynamic model is derived using Lagrange method, which include the following sequence of steps :

1. Compute the Kinetic Energy(KE) and Potential energy(PE) of each link in terms of the generalized coordinates and sum them up to get the overall KE and PE of the system.

2. Compute Lagrangian which is defined as

   $$L(q, \dot{q}) = K(q, \dot{q}) - V(q) \tag{2.15}$$

   where K and V are the Kinetic Energy and the Potential Energy respectively.

3. Lagrange equation is

   $$\frac{d}{dt}(\frac{\partial L}{\partial \dot{q}}) = \Gamma \tag{2.16}$$

4. Now if the KE is quadratic, then the results in the [2.16] can be reduced to the following form

   $$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \Gamma \tag{2.17}$$

5. D, C, G and Γ are the mass matrix, centrifugal matrix, gravitation matrix and generalized torques respectively.

6. Gravity matrix will be derived as

   $$G(q) = \frac{\partial V(q)}{\partial q}, \tag{2.18}$$

7. Centrifugal matrix is derived as

   $$C(q, \dot{q})\dot{q} = (\frac{\partial}{\partial q}(D(q)\dot{q}))\dot{q} - \frac{1}{2}(\frac{\partial}{\partial q}(D(q)\dot{q}))'\dot{q} \tag{2.19}$$

   $$C_{kj} = \sum_{i=1}^{N} \frac{1}{2}(\frac{\partial D_{kj}}{\partial q_i} + \frac{\partial D_{ki}}{\partial q_j} - \frac{\partial D_{ij}}{\partial q_k}), \tag{2.20}$$

   $1 \leq k, j \leq N$, where N is the length of the generalized configuration vector. above equation is directly used from [1]

8. Generalized force vector in the swing phase is just torque acting between the joints which is calculated as

   $$\Gamma_j = (\frac{\partial \theta_j^{rel}}{\partial q})'\tau \tag{2.21}$$

   where τ is the torques applied between the joints.

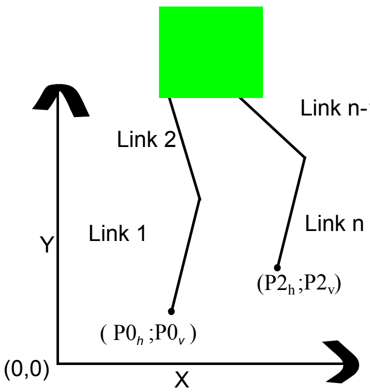


Figure 2.4: n-link open free kinematic chain

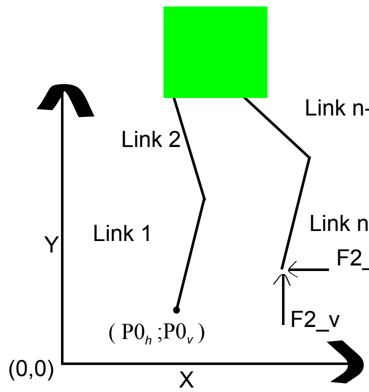


Figure 2.5: n-link open free kinematic chain with the impact vectors acting due to instantaneous impact

2.3.3 Impact Phase

Impact phase model have a couple of assumptions involved that may look like an oversimplification, the assumptions are the :

1. Instantaneous Impact,

2. Perfectly inelastic Collision with the surface,

3. At the time of the impact the previous stance leg leaves the ground as soon as the impact happens without any interaction with the ground.

Apart from that the model is again assumed to be an open kinematic chain but this time not pivoted to the ground. Thus this model have 2 more variables in the configuration space $P0 = (P0_h; P0_v)$. I will denote the extended configuration space as $q_i = (q; P_h; P_v)$ throughout my thesis for the impact phase. Subscript i for impact.

Again in this case we can apply the method of Lagrange to get the dynamical equation in the form

$$D_i(q_i^+)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + G_i(q_i) = B_i(q_i)u + \delta F_{ext} \tag{2.22}$$

since we have assumed instantaneous impact we can further simplify the model by integrating over δ time to get

$$D_i(q_i^+)\dot{q}_i^+ - D_i(q_i^-)\dot{q}_i^- = F_{ext} \tag{2.23}$$

where $q_i^+ = q_i^-$, angular positions just before the impact and after the impact are same. Their will just be an instantaneous change in the velocity due to impact. The velocity before the impact is assumed to be known here since we already have derived the swing phase model. So we will take the final joint velocities before the impact condition is arrived as $w = \dot{q}_i^-$ for the computation of the velocities after the impact $w = \dot{q}_i^+$ we will follow the following steps :

1. The impact can be thought of as a force acting at a point on the bipedal. In this case the point of impact is supposed to be the end point of the last link(the link which is going to impact on the ground). Suppose that force is $F = (F_T; F_N)$ which is acting at the point $P2 = (P2_h; P2_v)$. as depicted in figure [2.4] and figure [2.5]

   Then from [1, Appendix B.4]

   $$\Gamma_i = (\frac{\partial p_i}{\partial q})' F \tag{2.24}$$

   are the generalized forces acting at impact

2. Also we have the configuration space as

   $$q_i = [q; f(q)] \tag{2.25}$$

   Since we can find $(P2_h; P2_v)$ depicted in figure as a function of q and model parameters. Now using virtual work

   $$F_{ext} = E_2(q_i^-)F_2 \tag{2.26}$$

   where $E_2(q_i) = \frac{\partial}{\partial q_i} P_2(q_i)$ and $F_2 = (F_2^T; F_2^N)$ is force acting at the end due to impact. also,

   $$\dot{q}_i^- = [I; (\frac{\partial}{\partial q} f(q^-))]\dot{q}^- \tag{2.27}$$

   Since we have assumed perfectly inelastic collision with the ground

   $$E_2(q_i^-)\dot{q}_i^+ = 0 \tag{2.28}$$

3. Equations [2.28] and [2.23] can be combined in matrix form as

   $$\begin{bmatrix} D_i(q_i^-) & -E_2(q_i^-)' \\ E_2(q_i^-) & 0_{2\times 2} \end{bmatrix} \times \begin{bmatrix} \dot{q}_i^+ \\ F_2 \end{bmatrix} = \begin{bmatrix} D_i(q_i^-)\dot{q}_i^- \\ 0_{2\times 1} \end{bmatrix} \tag{2.29}$$

The above equation can be solved for $\dot{q}_e^+$ and F_2 $F2$ and F_2 are used interchangeably by me at many places.

4. this general case was for impact with ground. For knee impact in case of kneed walker I have equated angular momentum before and after the impact about each consecutive parent joint as [13]

2.3.4 Hybrid Dynamics

Once we have the swing phase model and the impact phase model we can combine all of them using Hybrid Dynamics model. Hybrid Dynamics model is used to join separate models and may have continuous as well as discrete developments. The general form is easily thought of as if the system will show one particular dynamics until a switching condition is met, which will bring the system to some other set of states which will show some different dynamics.

Bipedal as such has 2 types of dynamics :

1. Continuous dynamics
2. Discrete dynamics

Continuous dynamics is constituting the swing phase and Discrete dynamics is observed in the form of impact. To jump from continuous dynamics to the discrete dynamics normally some specific events happen which embarks the jump from one dynamics to another. One thing that should be taken care of while using hybrid dynamics model that though hybrid dynamics have provisions for discrete jump in velocities(with respect to bipedal robot) it don't allow any discrete jump in position coordinates. Any jump observed in configuration coordinates in the phase plot is only due to the update of the reference point after the impact.

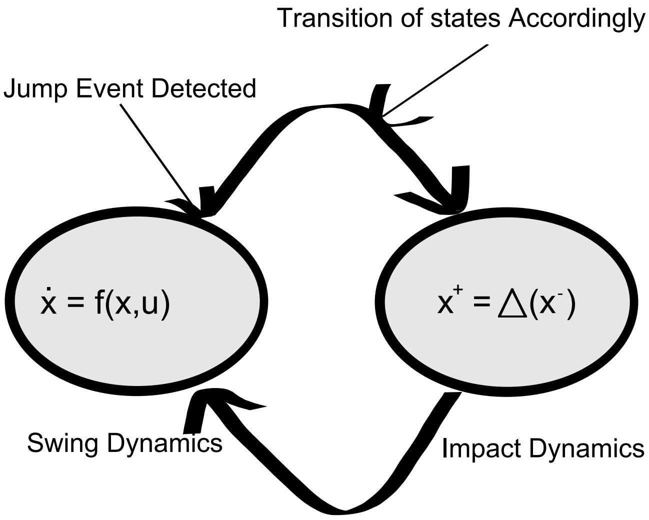


Figure 2.6: Hybrid dynamic model of Acrobot Walker

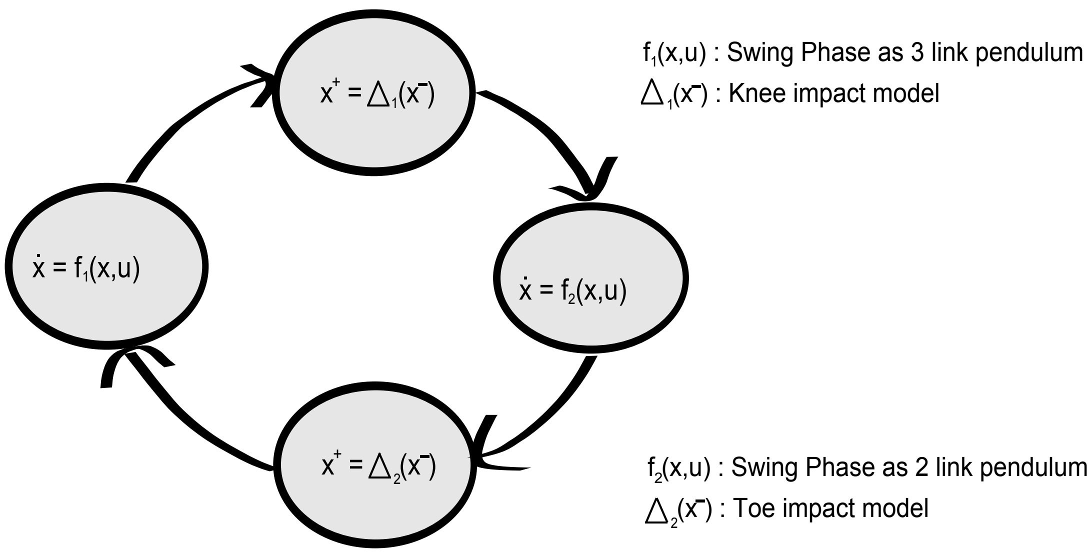


Figure 2.7: Hybrid dynamic model of kneed Walker

Chapter 3

Bipedal Stability analysis and Control

Probably the main reason over the choice of Wheeled Robots over legged robots is the ease of stability analysis and control. Bipedal robots are inherently unstable and have relatively very small stability margin while performing any task. Point foot model of walking is statically unstable.

3.1 Stability Analysis

Since bipedal is a nonlinear dynamic system of hybrid nature. The rich classical techniques which involve frequency domain techniques as Laplace transform, Z transform and Eigenvalue value methods can not be applied as such. So the stability of Nonlinear systems is normally dealt with entirely different set of tool that involves Poincare section, Piece wise linearization about the point of interest or numerical methods that allow present day computers to get the solutions numerically rather than analytically.

3.1.1 Method of Poincare

In this technique a section is cut in the phase plot that brings down the dimension by 1. The section is called Poincare section. Poincare map P is a mapping from U to the Poincare section S

$$P : U \to S \tag{3.1}$$

such that $P : U \to P(U)$ should be a diffeomorphism.

Assume having a state vector of dimension n. Then the phase plot will be a curve in n dimension. After selecting a poincare section. The points will be points will be marked where the phase plot is crossing this section. From the relative positioning of points between adjacent points $x(n)$ and $x(n+1)$ we can extract useful information about the stability of the system. Problems that we face while using this method is in finding a proper poincare section. For lower dimensions upto 3 it is easy to visualize, but for higher dimensions the task of finding poincare section can be very arduous.

3.1.2 Method of Piecewise linearization about equilibrium/fixed points

This method involves first searching of fixed points or equilibrium points. Fixed point is a point for a system $\frac{d\vec{x}}{dt} = f(t, \vec{x})$ at which $\frac{d\vec{x}}{dt} = 0$ for all t.

The piecewise linearization is performed at the equilibrium point using Jacobian matrix, and then the Eigenvalues computed at each equilibrium point tells about the stability of that particular equilibrium point. Once all the eigenvalues and eigenvectors are computed we can qualitatively determine the behavior of the system for initial values, if they are close to these equilibrium points. Negative eigenvalues means a stable nodes while positive leads to unstable nodes. If a few eigenvalues are positive and a few are negative then the node is saddle point. Eigenvalue 0 leads to a special case.

3.2 Control Methods

3.2.1 Fully Actuated Vs Under Actuated

Bipedal Robots are different from the manipulators because of the underactuation that we face in legged robots, specially point foot models. We can not provide actuation between the ground and the leg connected to it in classical sense, or, rather say we can not directly provide a torque between them. Though we can achieve this to some extent in models with feet. This very fact do not allow us to apply Feedback linearization technique to control the bipedal.

3.2.2 Under Actuated Control

Such underactuated systems can still be controlled to some extent in the same fashion using Partial Feedback linearization(PFL). The technique is used by Spong to make a double pendulum go upside down in his classical work [14], [15] and [16]. PFL allow us to linearize a limited number of degrees of freedom atleast. Spong in his work developed a simple controller based on the idea to pump the energy in each swing to bring the pendulum to the holonomic orbit and then switching the controller with a LQR controller when the pendulum reaches the near upside down state.

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} \ddot{q_1} \\ \ddot{q_2} \end{bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} \dot{q_1} \\ \dot{q_2} \end{bmatrix} + \begin{bmatrix} \ddot{G_{11}} \\ \ddot{G_{12}} \end{bmatrix} = \begin{bmatrix} \tau \\ 0 \end{bmatrix} \tag{3.2}$$

As explained in [17] and [18]collocated linearization give us the form

$$\ddot{q_1} = v \tag{3.3}$$

The above matrix is sum of 2 equations :

$$M_{11}\ddot{q1} + M_{12}\ddot{q2} + C_{11}\dot{q_1} + C_{12}\dot{q_2} + G_{11} = \tau \tag{3.4}$$

$$M_{21}\ddot{q1} + M_{22}\ddot{q2} + C_{21}\dot{q_1} + C_{22}\dot{q_2} + G_{21} = 0 \tag{3.5}$$

The [3.5] can be represented in form

$$\ddot{q2} = -M_{22}^{-1}(M_{21}\ddot{q1} + C_{21}\dot{q_1} + C_{22}\dot{q_2} + G_{21}) \tag{3.6}$$

Place it in [3.4] to get

$$M_{11}\ddot{q1} + M_{12}(-M_{22}^{-1}(M_{21}\ddot{q1} + C_{21}\dot{q_1} + C_{22}\dot{q_2} + G_{21})) + C_{11}\dot{q_1} + C_{12}\dot{q_2} + G_{11} = \tau \tag{3.7}$$

$$(M_{11} - M_{12}M_{22}^{-1}M_{21})\ddot{q1} + M_{12}(-M_{22}^{-1}(C_{21}\dot{q_1} + C_{22}\dot{q_2} + G_{21})) + C_{11}\dot{q_1} + C_{12}\dot{q_2} + G_{11} = \tau \tag{3.8}$$

Putting the value of τ as

$$\tau = (M_{11} - M_{12}M_{22}^{-1}M_{21})v + M_{12}(-M_{22}^{-1}(C_{21}\dot{q_1} + C_{22}\dot{q_2} + G_{21})) + C_{11}\dot{q_1} + C_{12}\dot{q_2} + G_{11} \tag{3.9}$$

to get the PFL form [3.3]. In the acrobot case $\ddot{q_1}$ is $\ddot{q^2_{rel}}$, or the relative angular acceleration of the swing leg with respect to the stance leg.

The control scheme implemented take stride length which increase with the hip velocity and decreases with the decrease of hip velocity while trying to drive the system passively most of the time, ie $\tau = 0$.

The detailed description of the control is as below :

1. Set a desired velocity $V_{desired}$ instantaneously after the impact.

2. Calculate error as $e = V_{actual} - V_{desired}$

3. Provide a square pulse of duty cycle .5 after the impact with amplitude proportional to error and time period constant(constant time period is chosen by manual tuning and help in decreasing the amount to parameters that we need to control)

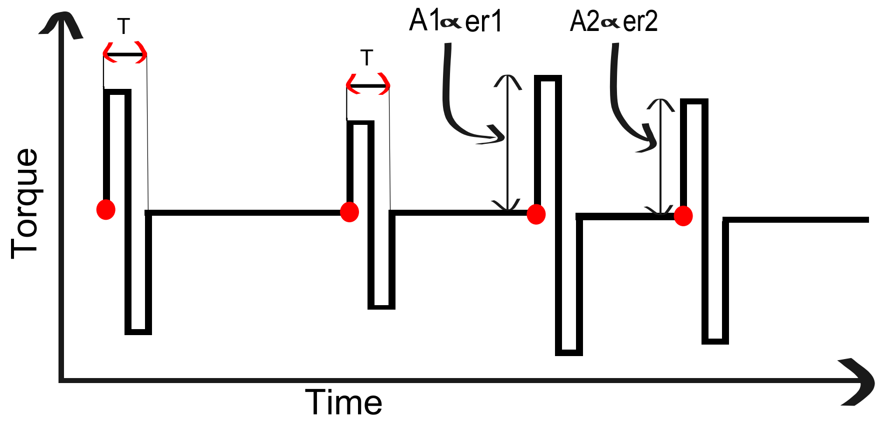


Figure 3.1: General Torque Profile
A torque pulse is generated after every impact

An equally simple controller is developed in this thesis on the basis of simple idea that **take larger steps if you have large velocity or when you are descending down a larger slope and take smaller steps vice versa**. The idea is implemented with the help of collocated PFL(in which the system is partially linearized) for the dimensions which are actuated.

A detailed stability analysis of the control method presented in the thesis is not yet performed. But the results are verified in the simulation and showing considerably improved performance for a constant slope if controller is tuned properly and starts from suitable initial states. But is failing for the case of uneven terrain.

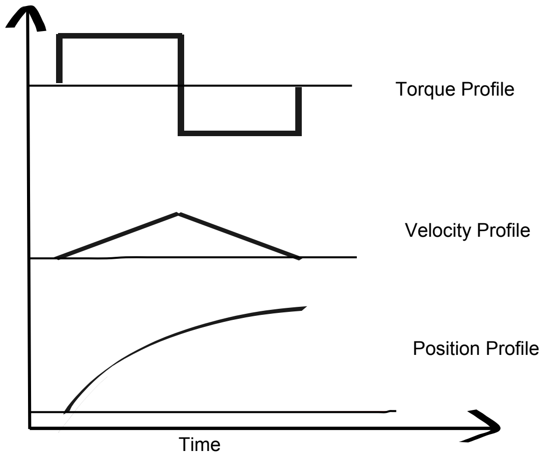


Figure 3.2: Velocity and position profile for the square pulse of torque

Chapter 4

Hardware and Software Description

4.1 Software Description

Simulations are written using matlab for both the acrobot walker and the kneed walker. All the ODEs of the system are derived with the help of computer program that minimized a lot of overhead and reduces the chance of manual error to minimal.

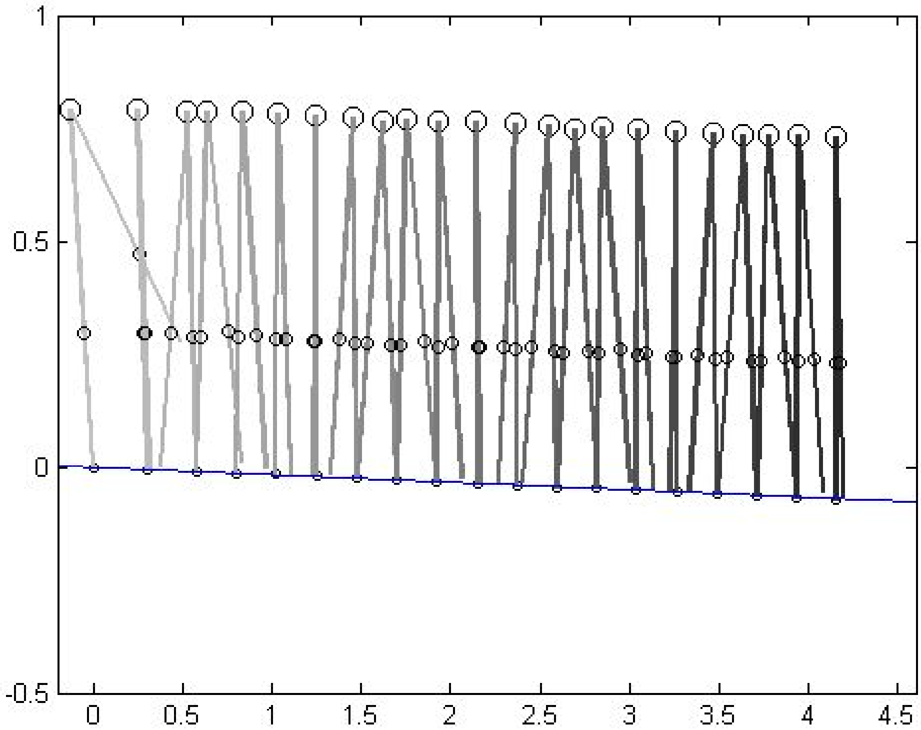


Figure 4.1: Acrobot temporal Plot

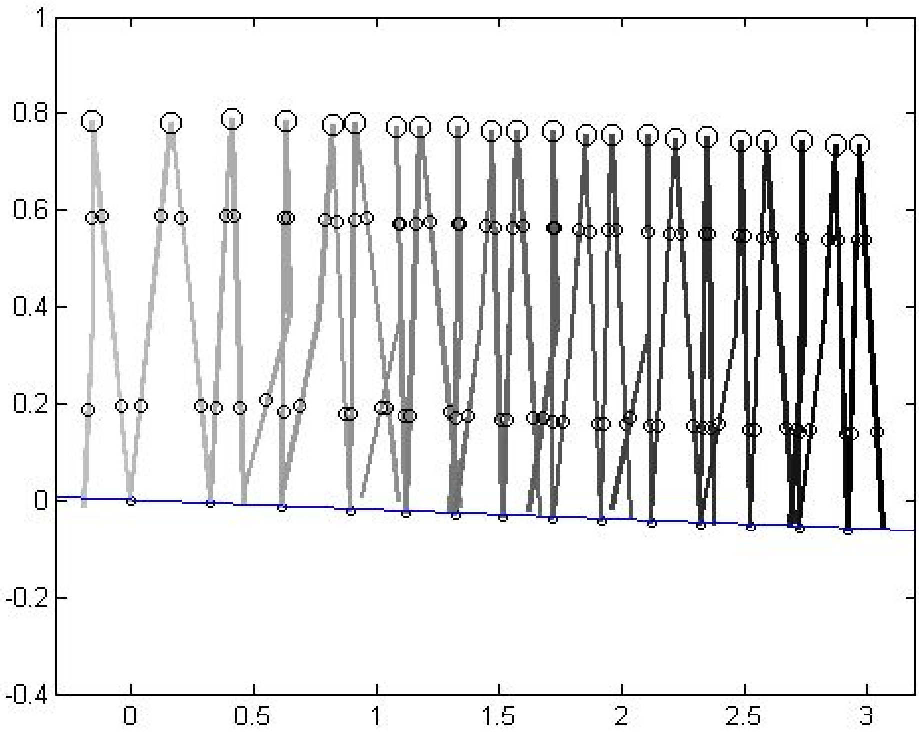


Figure 4.2: Kneed walker temporal Plot

4.2 Hardware Description

A $0.82m$ long planar kneed walker was designed and manufactured. The inner two legs were locked directly using long screws and the outer legs were locked using an outer ring.

For the knee locking mechanics we tried putting electromagnets that were switched off and on using micro controller. The time of switching on and off were decided by each consecutive step/impact. We installed an accelerometer on the hip that was detecting impacts.

Since the body was made entirely of aluminium frame. Iron L sections were bonded on the shank to use the electromagnets for locking purpose.This idea failed because of insufficient force generated by the electromagnets and also due to failure of the accelerometer in detecting the toe impacts properly.

Not only that the internally dynamics of the bipedal were changed entirely due to heavy electromagnets. We tried to make it walk but the walker was not able to walk more than a couple of steps.

This lead us to lock the knee and remove the electromagnets to make the bipedal walk as an acrobot. Our acrobot walker was quite stably walking for more than 5-6 steps many of the time.

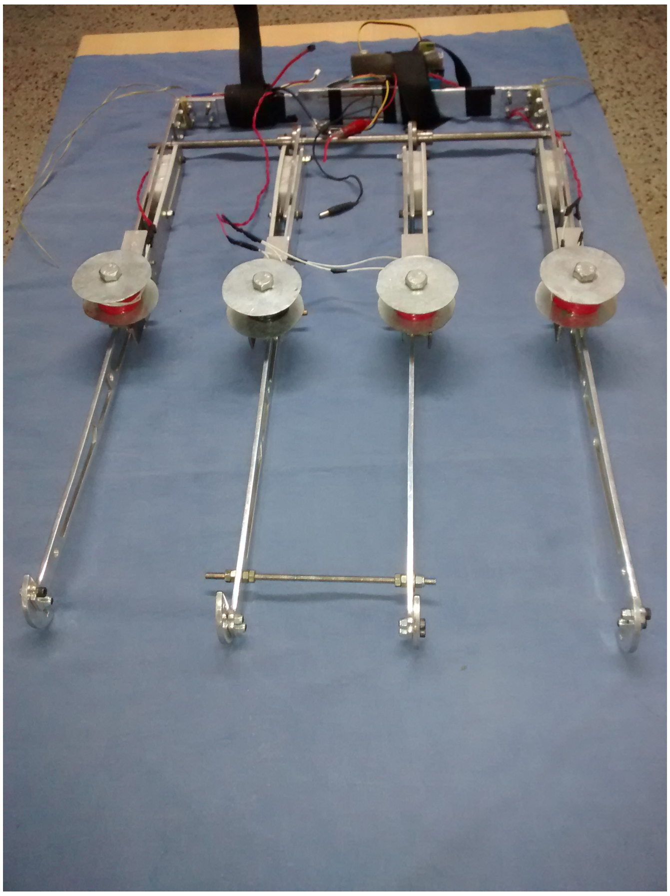


Figure 4.3: Full kneed walker image

Figure 4.4: Knee Lock configuration and electromagnets (a)

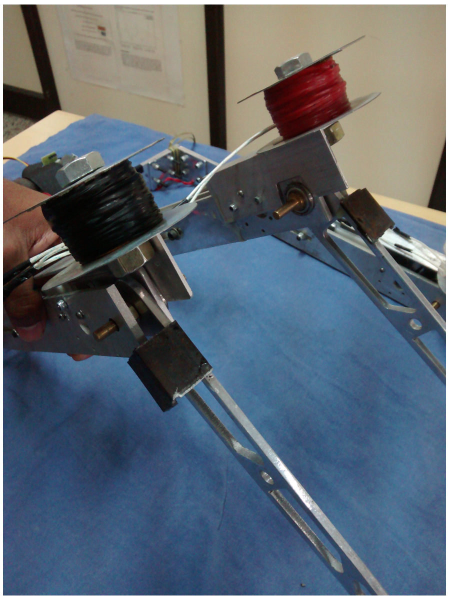


Figure 4.5: Knee Lock configuration and electromagnets (b)

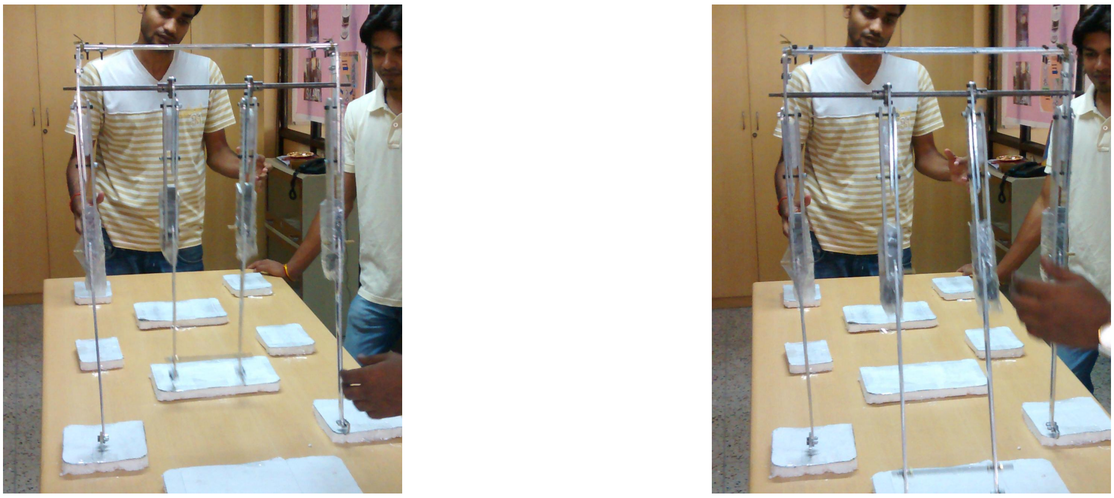


Figure 4.6: Acrobot walker walking on slope

Chapter 5

Results

Simulation result comprises of different phase plots and stride lengths and other indexes of performance that I am getting by changing the parameters of my model, or by switching on and off my controller.

5.1 Simulation Result

5.1.1 Acrobot Walker

Simulation Output of Acrobot Walker on slope of 0.03 radian

parameter	value
L_1, L_2	1
a_1, a_2	0.5
m_1, m_2	2
m_H	4
Slope γ	0.03^c
g	9.81

Table 5.1: Model Parameters Acrobot Walker at 0.03^c without control

State vector	value
q_1	1.7708^c
$\dot{q_1}$	$-1.00^c/s$
q_2	2.7416^c
$\dot{q_2}$	$0.6000^c/s$

Table 5.2: Initial Condition Acrobot walker at 0.03^c without control

Passive walking at 0.03^c generates nice converging limit cycles for each link. Plots of total energy showing step decrements in Inertial frame and convergence in body frame. Stride length and Joint velocities are showing periodic behavior after initial few seconds which is the time for the system to reach it stable limit cycle.Horizontal hip velocity is always negative showing the continuous forwarding behavior of the acrobot walker, with the velocity at the time of impact lying at nearly $1.1ms^{-1}$. Horizontal hip position is showing a maxima between adjacent 2 impacts, where impacts are the points where the curve achieving its minima.

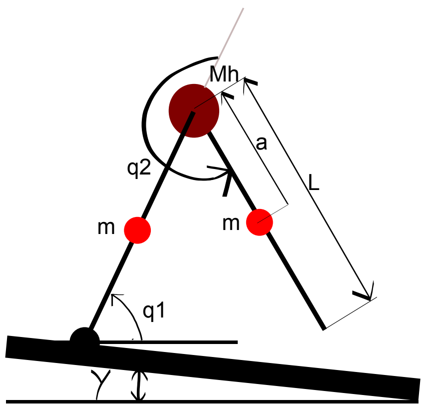


Figure 5.1: Acrobot walker parameters

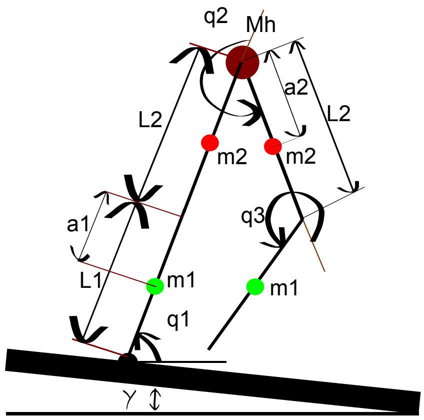


Figure 5.2: Kneed walker parameters

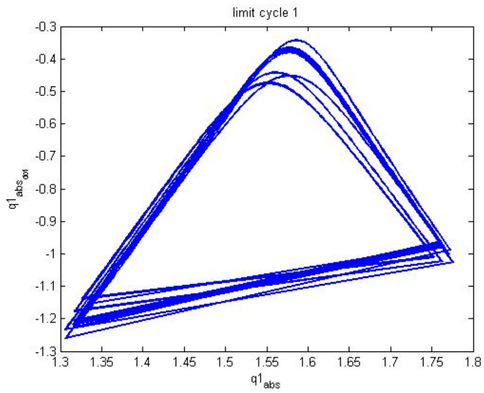


Figure 5.3: Limit cycle Link 1 at 0.03 radian

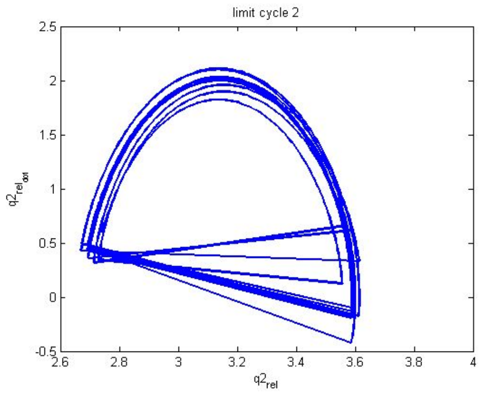


Figure 5.4: Limit cycle link 2 at 0.03 radian

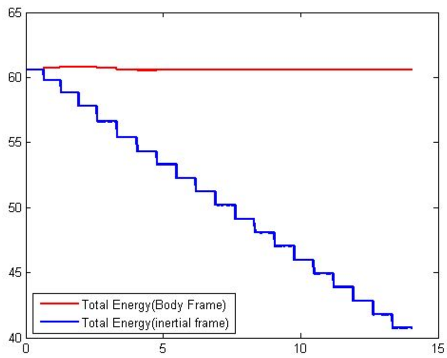


Figure 5.5: Total Energy of Acrobot at 0.03 radian

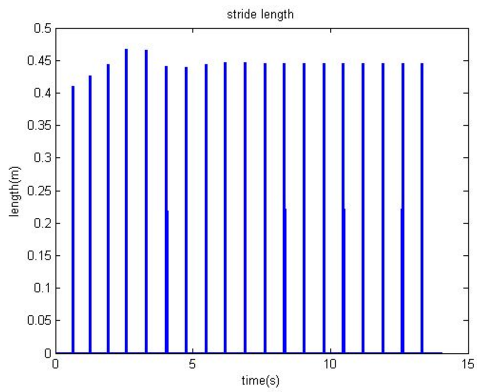


Figure 5.6: Stride length at 0.03 radian

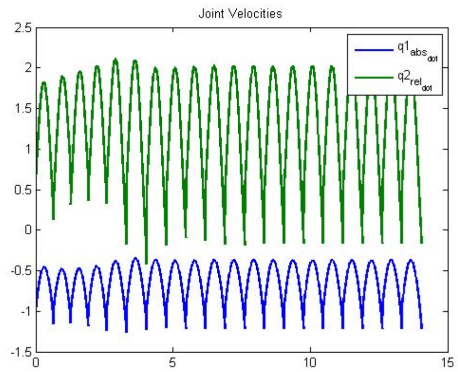


Figure 5.7: Joint Velocities(radians/sec) at 0.03 radian

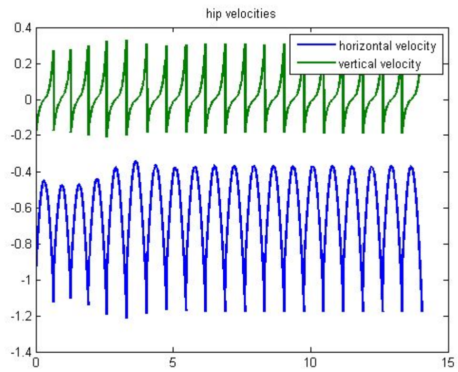


Figure 5.8: hip velocities (m/s) at 0.03 radian

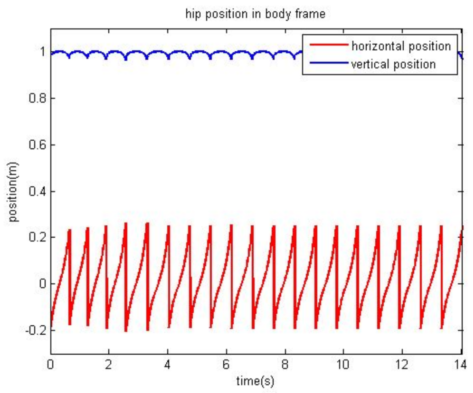


Figure 5.9: hip position in body frame at 0.03 radian

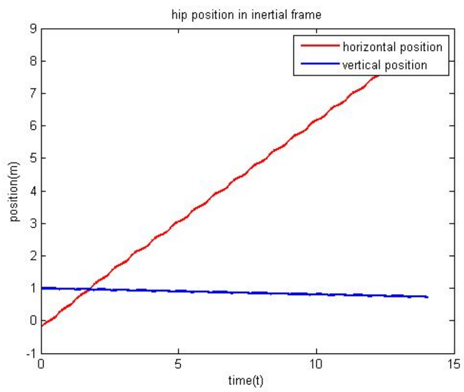


Figure 5.10: hip position in inertial frame at 0.03 radian

parameter	value
L_1, L_2	1
a_1, a_2	0.5
m_1, m_2	2
m_H	4
Slope γ	0.03^c
g	9.81

Table 5.3: Model Parameters Acrobot Walker at 0.03^c with control

State vector	value
q_1	1.6708^c
$\dot{q}_1$	$-1.00^c/s$
q_2	2.7416^c
$\dot{q}_2$	$0.6000^c/s$
k_p	50

Table 5.4: Initial Condition Acrobot walker at 0.03^c with control

Simulation Output of Acrobot Walker on slope of 0.03 radian with control

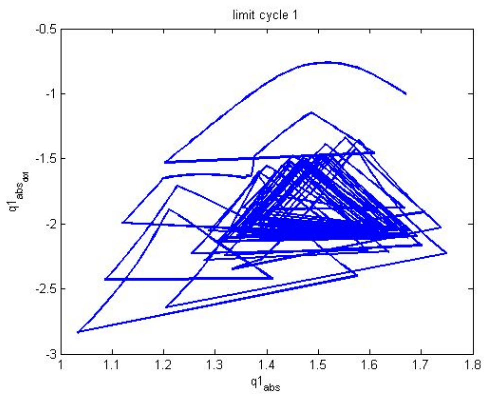


Figure 5.11: Limit cycle link 1 at 0.03 radian with control

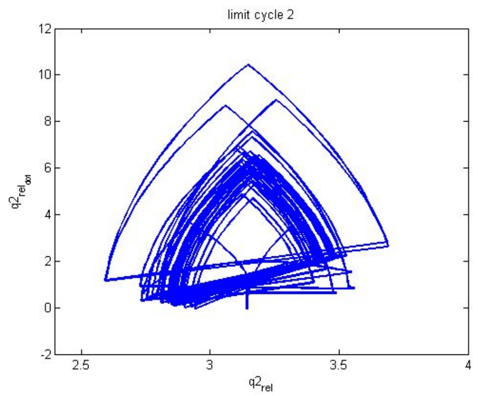


Figure 5.12: Limit cycle link 2 at 0.03 radian with control

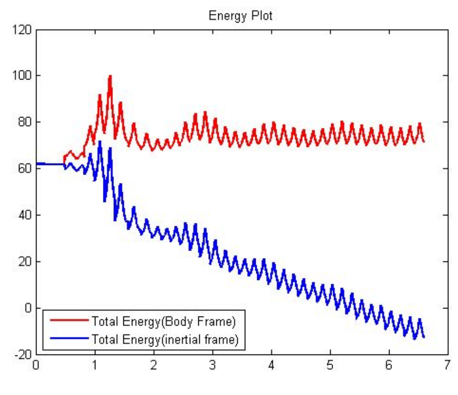


Figure 5.13: Total Energy of Acrobot at 0.03 radian with control

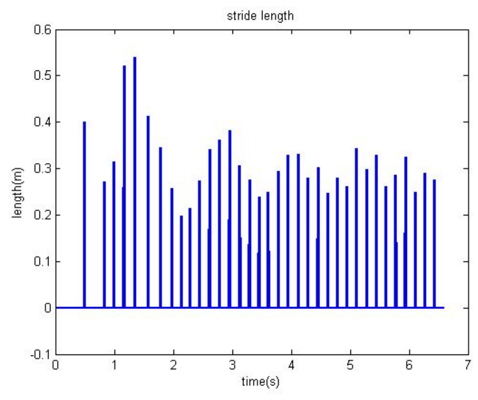


Figure 5.14: Stride length at 0.03 radian with control

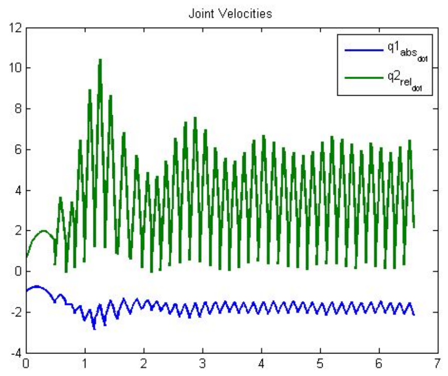


Figure 5.15: Joint Velocities(radians/sec) at 0.03 radian with control

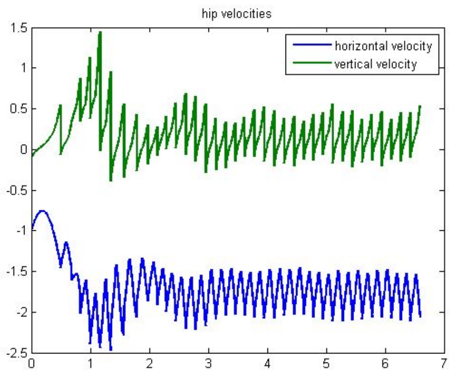


Figure 5.16: hip velocities (m/s) at 0.03 radian with control

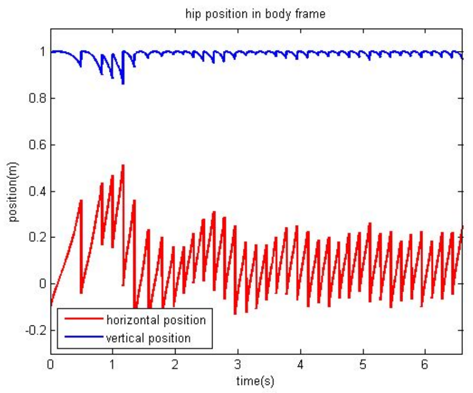


Figure 5.17: hip position in body frame at 0.03 radian with control

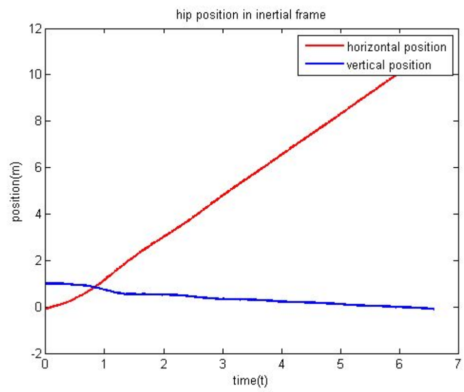


Figure 5.18: hip position in inertial frame at 0.03 radian with control

Plots are with Kp = 50, and time period of square pulse equal to 0.2 seconds .Limit cycles are not as clean as the passive case. But the acrobot is still stable. Energy plot is showing that energy is lost at each impact but some energy is pumped after each impact. The time between each impact very low, and is not allowing even to the square pulse to complete.

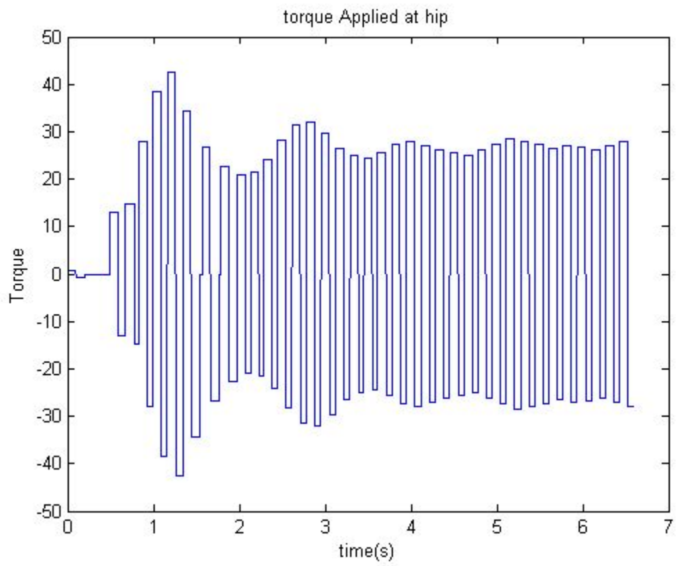


Figure 5.19: Torque Profile at 0.03 radian slope

Simulation Output of Acrobot Walker on slope of 0.04 radian

For the given initial condition the model is not able to walk passively and is falling down after a couple of steps. Limit cycle is showing extreme deviations. Falling at 0.04^c does not mean that the robot can not walk passively at 0.04^c. After changing its initial conditions it is very much possible for it to walk down passively.

parameter	value
L_1, L_2	1
a_1, a_2	0.5
m_1, m_2	2
m_H	4
Slope γ	0.04^c
g	9.81

Table 5.5: Model Parameters Acrobot Walker at 0.04^c without control

State vector	value
q_1	1.7708^c
$\dot{q}_1$	$-1.00^c/s$
q_2	2.7416^c
$\dot{q}_2$	$0.6000^c/s$

Table 5.6: Initial Condition Acrobot walker at 0.04^c without control

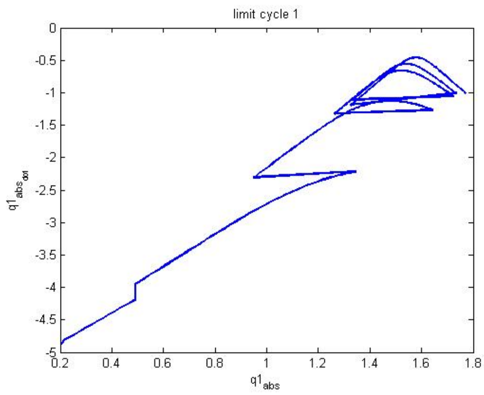


Figure 5.20: Limit cycle Link 1 at 0.04 radian

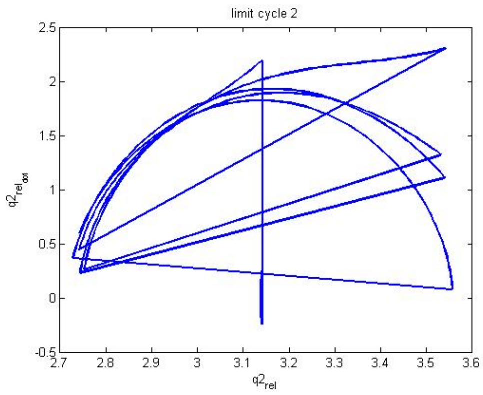


Figure 5.21: Limit cycle Link 2 at 0.04 radian

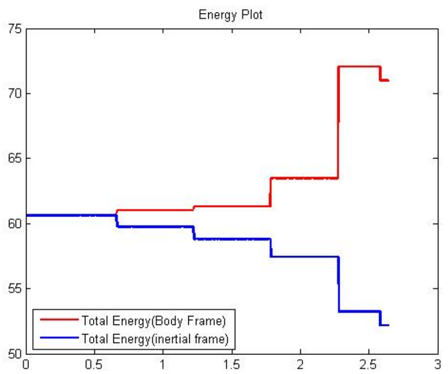


Figure 5.22: Total Energy of Acrobot at 0.04 radian

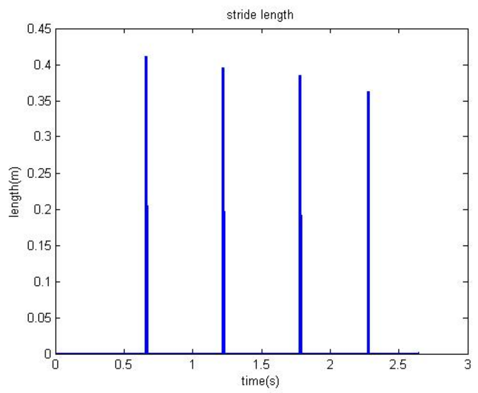


Figure 5.23: Stride length at 0.04 radian

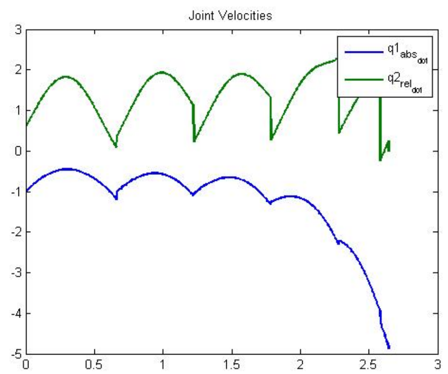


Figure 5.24: Joint Velocities(radians/sec) at 0.04 radian

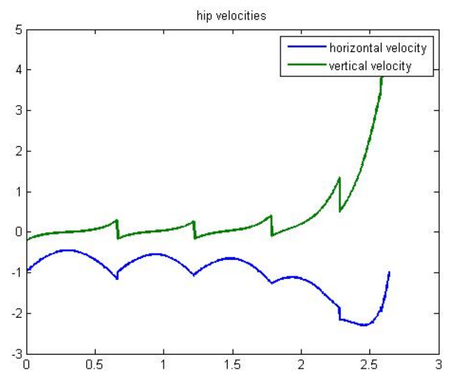


Figure 5.25: hip velocities (m/s) at 0.04 radian

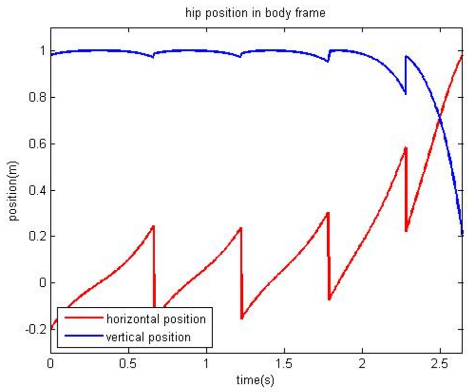


Figure 5.26: hip position in body frame at 0.04 radian

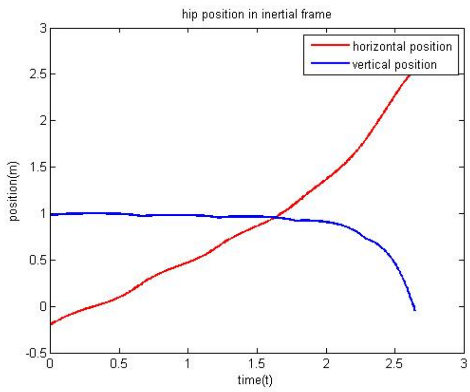


Figure 5.27: hip position in inertial frame at 0.04 radian

Simulation Output of Acrobot Walker on slope of 0.04 radian with control

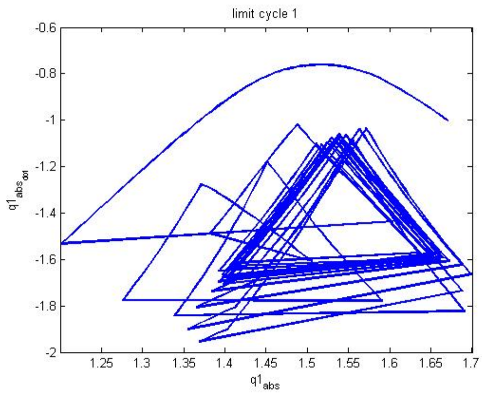
Acrobot is able to walk with the provided initial condition with the control of $Kp = 75$ and time period of square pulse $T = 0.2$ seconds. These values are able to keep the robot walk stably. Though the values like stride length, joint velocities are not exactly showing a periodic behavior. There is an extra point that is not differentiable in the swing phase. This point is representing the point where the square torque pulse is ending. At slope 0.04^c also the torque profile is active all the time. And the impacts are happening almost at time after the square pulse is ending.

parameter	value
L_1, L_2	1
a_1, a_2	0.5
m_1, m_2	2
m_H	4
Slope γ	0.04^c
g	9.81

Table 5.7: Model Parameters Acrobot Walker at 0.04^c with control

State vector	value
q_1	1.6708^c
$\dot{q}_1$	$-1.00^c/s$
q_2	2.7416^c
$\dot{q}_2$	$0.6000^c/s$
k_p	75

Table 5.8: Initial Condition Acrobot walker at 0.04^c with control



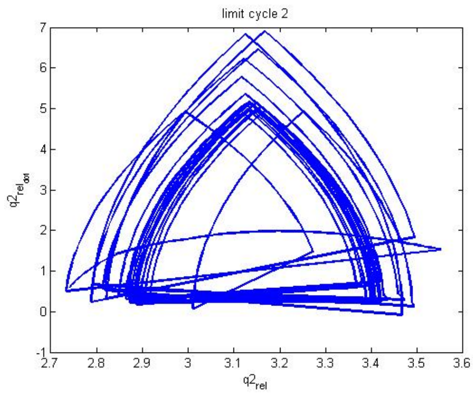
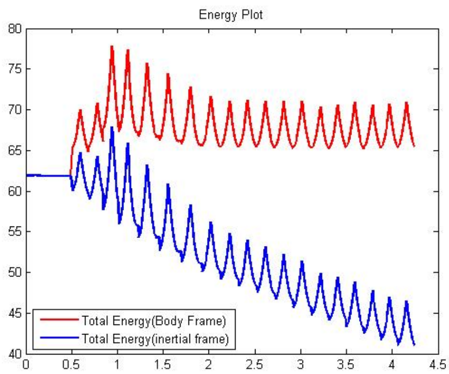


Figure 5.28: Limit cycle Link 1 at 0.04 radian with control

Figure 5.29: Limit cycle Link 2 at 0.04 radian with control



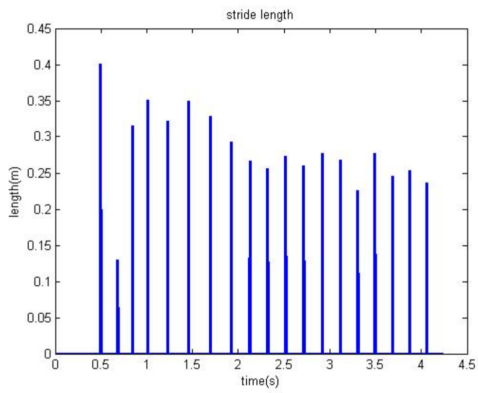
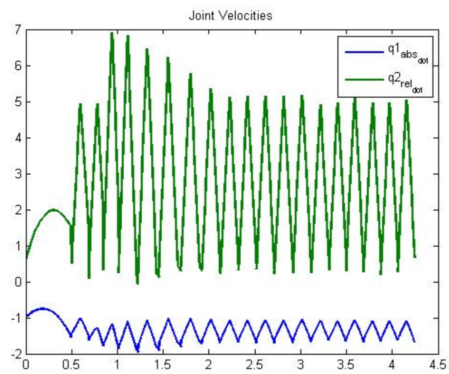


Figure 5.30: Total Energy of Acrobot at 0.04 radian with control

Figure 5.31: Stride length at 0.04 radian with control



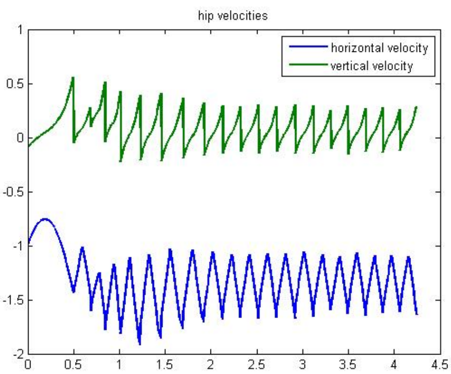


Figure 5.32: Joint Velocities(radians/sec) at 0.04 radian with control

Figure 5.33: hip velocities (m/s) at 0.04 radian with control

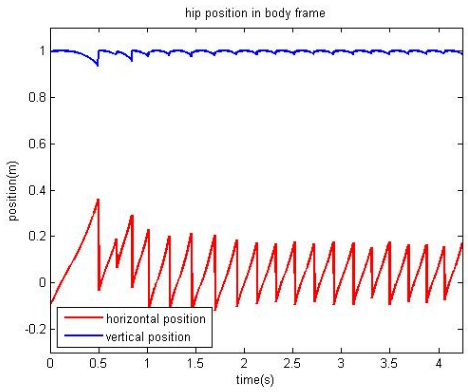


Figure 5.34: hip position in body frame at 0.04 radian with control

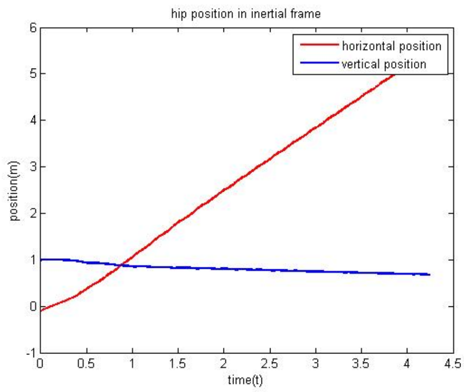


Figure 5.35: hip position in inertial frame at 0.04 radian with control

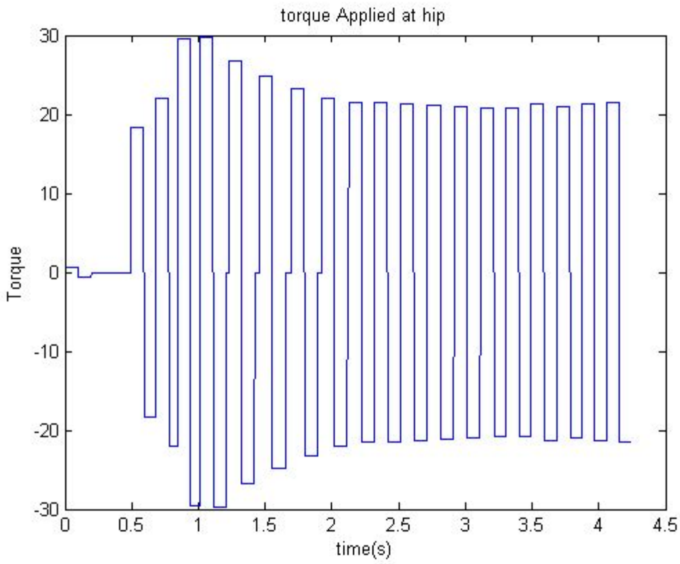


Figure 5.36: Torque Profile at 0.04 radian slope

Simulation Output of Acrobot Walker on slope of 0.2 radian

The controller is able to walk even at 0.2^c which is very high angle for a passive walker to walk. The Kp value is 100 and $V_{desired} = -1$. Square pulse of time period 0.2 seconds is generated after the impact and the controller is off almost all the time and thus is depicting how we can control in a partially passive fashion.

parameter	value
L_1, L_2	1
a_1, a_2	0.5
m_1, m_2	2
m_H	4
Slope γ	0.2^c
g	9.81

Table 5.9: Model Parameters Acrobot Walker at 0.2^c with control

State vector	value
q_1	1.6708^c
$\dot{q}_1$	$-1.00^c/s$
q_2	2.7416^c
$\dot{q}_2$	$0.6000^c/s$
k_p	100

Table 5.10: Initial Condition Acrobot walker at 0.2^c with control

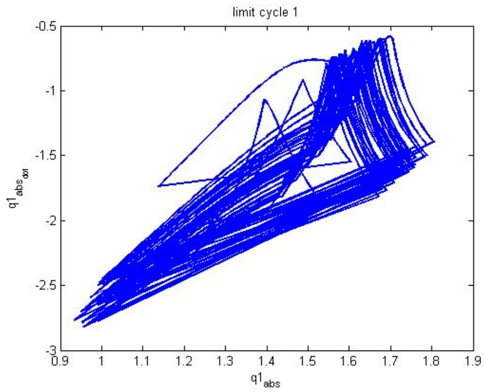


Figure 5.37: Limit cycle Link 1 at 0.2 radian with control

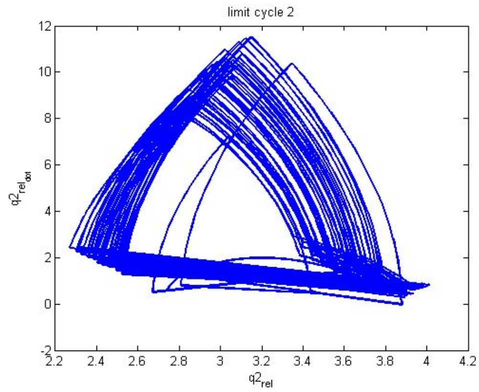


Figure 5.38: Limit cycle Link 2 at 0.2 radian with control

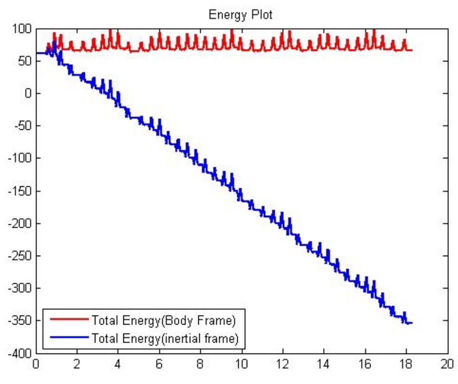


Figure 5.39: Total Energy of Acrobot at 0.2 radian with control

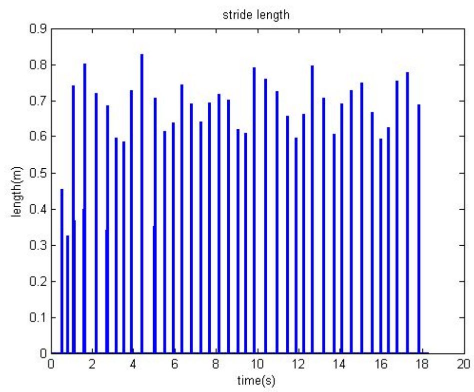


Figure 5.40: Stride length at 0.2 radian with control

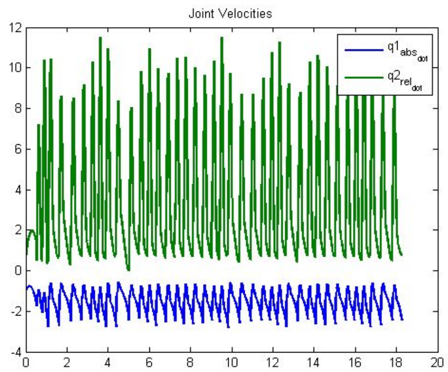


Figure 5.41: Joint Velocities(radians/sec) at 0.2 radian with control

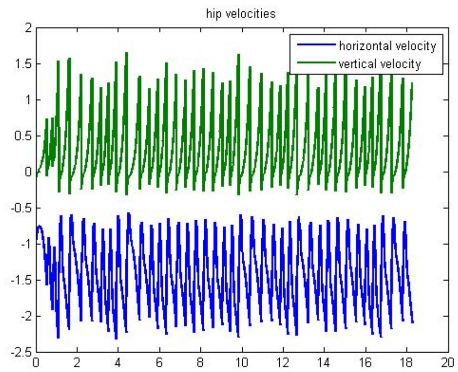


Figure 5.42: hip velocity at 0.2 radian with control

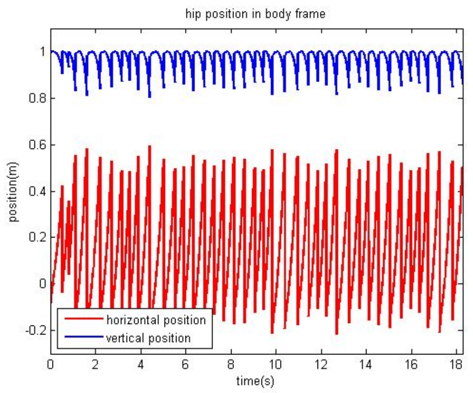


Figure 5.43: hip position in body frame at 0.2 radian with control

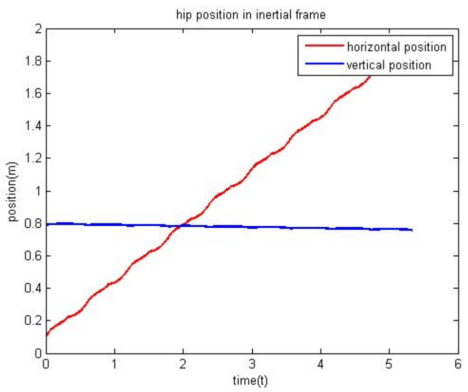


Figure 5.44: hip position in inertial frame at 0.2 radian with control

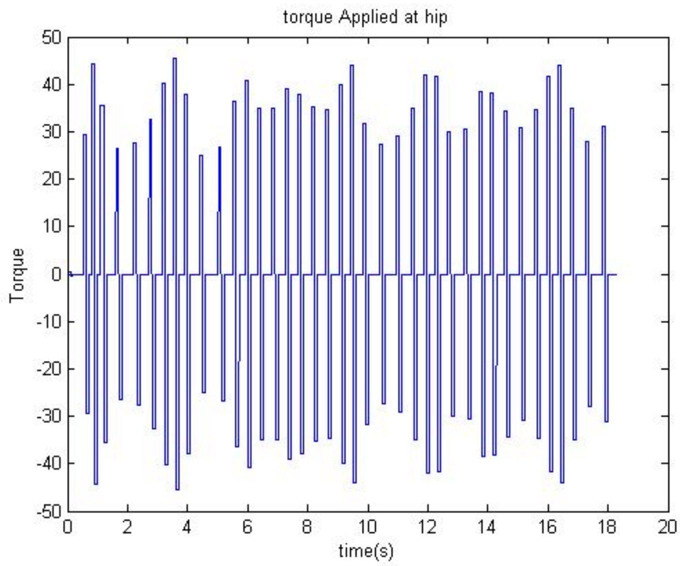


Figure 5.45: Torque Profile at 0.2 radian slope

5.1.2 Kneed walker

Simulation Output of Kneed Walker on slope of 0.02 radian

Kneed walker have many advantages over the acrobot walker. Acrobot walker face foot scuffing because both the legs are of same length so the swing foot touches the ground while swinging forward which is not the case with the kneed walker. Even the movements of hip are much smoother showing more efficient walking because of smaller impacts. The problem with kneed walker is that they have very small stability margin.

parameter	value
L_1, L_2	0.4
a_1, a_2	0.2
m_1, m_4	0.5
m_2, m_3	1.5
m_H	0.5
Slope γ	0.02^c
g	9.81

Table 5.11: Model Parameters Kneed Walker at 0.02^c with control

State vector	value
q_1	1.4431^c
$\dot{q}_1$	$-0.7712^c/s$
q_2	3.3985^c
$\dot{q}_2$	$0.1397^c/s$
q_2	0
$\dot{q}_2$	0

Table 5.12: Initial Condition Kneed walker at 0.2^c with control

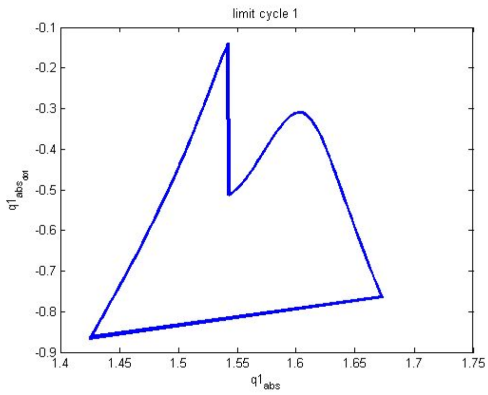


Figure 5.46: Limit cycle Link 1 of kneed walker at 0.02 radian

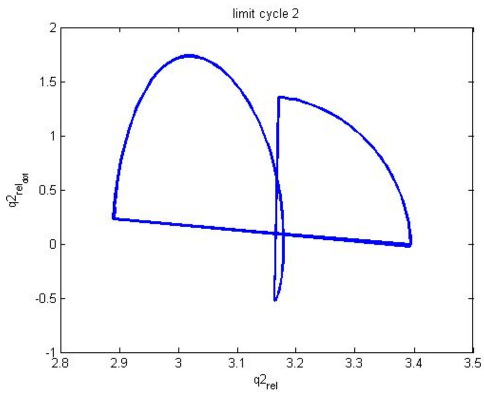


Figure 5.47: Limit cycle Link 2 of kneed walker at 0.02 radian

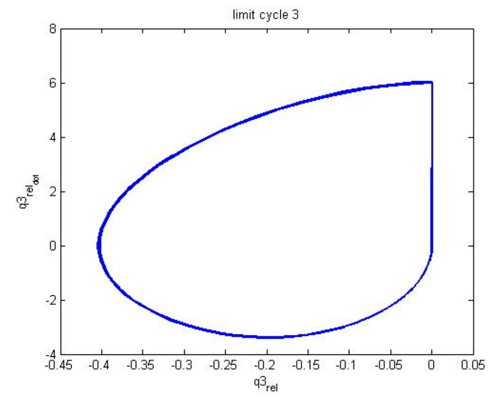


Figure 5.48: Limit cycle Link 3 of kneed walker at 0.02 radian

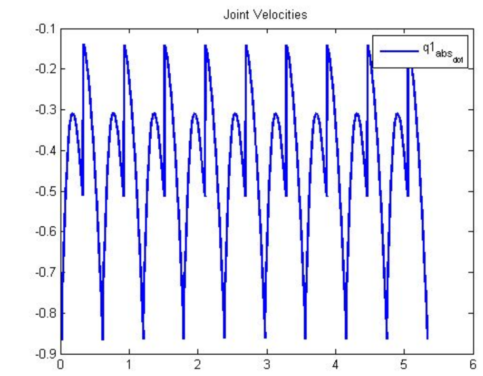


Figure 5.49: Joint velocity link 1 of kneed walker at 0.02 radian

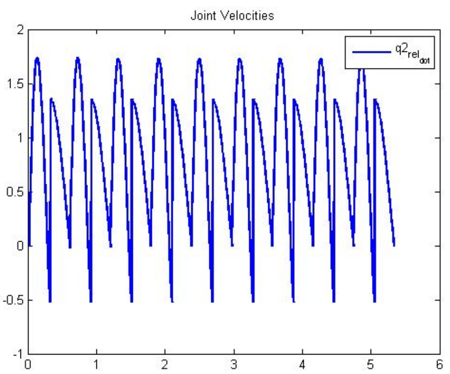


Figure 5.50: Joint velocity link 2 of kneed walker at 0.02 radian

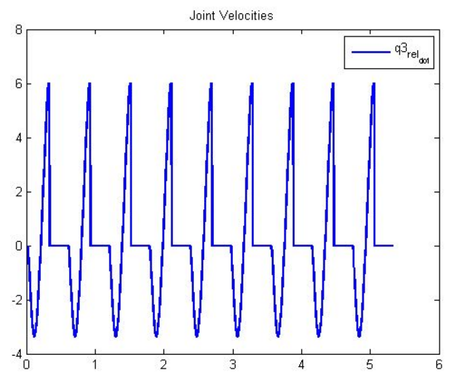
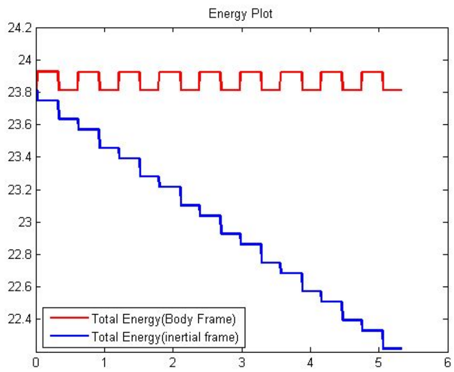


Figure 5.51: Joint velocity link 3 of kneed walker at 0.02 radian



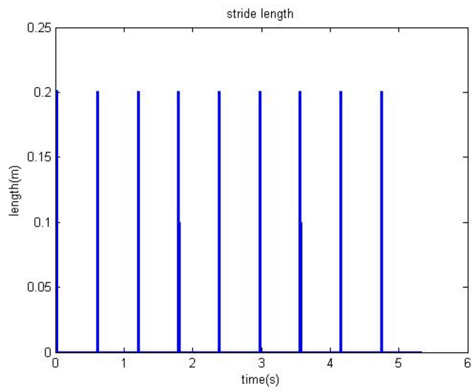
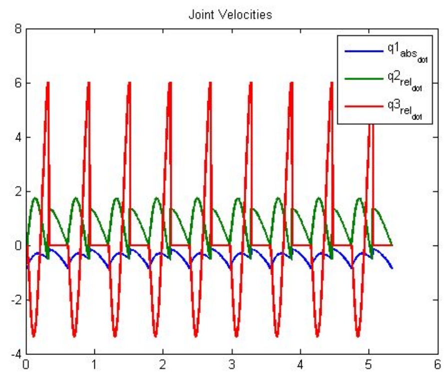


Figure 5.52: Total Energy of kneed walker at 0.02 radian

Figure 5.53: Stride length of kneed walker at 0.02 radian



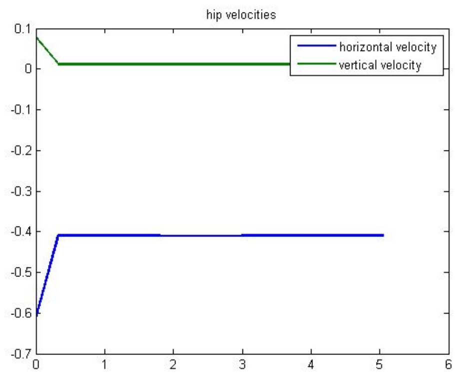
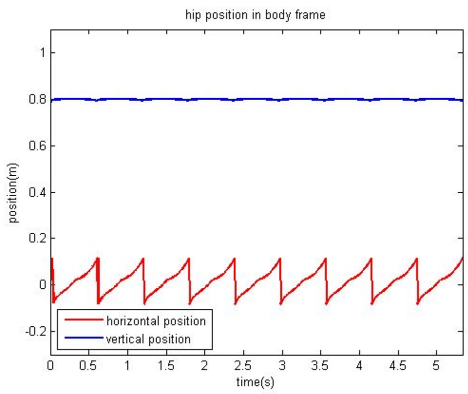


Figure 5.54: Joint Velocities(radians/sec) at 0.02 radian

Figure 5.55: hip velocity at 0.02 radian



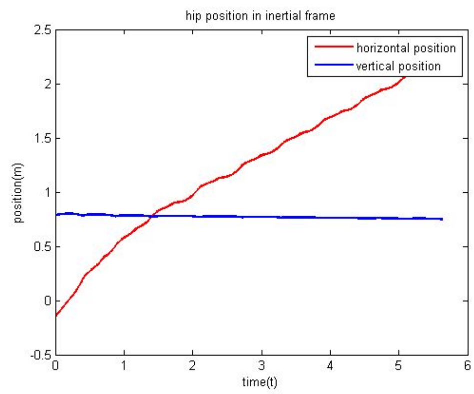


Figure 5.56: hip position of kneed walker in body frame at 0.02 body

Figure 5.57: hip position of kneed walker in inertial frame at 0.02 radian

Chapter 6

Conclusions and Future work

6.1 Conclusion

I started my thesis trying to develop a passive kneed walker and then was forced to reduce the model of my hardware to simple acrobot due to the structural complexities that I faced in developing kneed walker. One of the reasons that my model was failing while working as a kneed walker was improper knee locking while in swing phase after the knee impact.

While my acrobot walker and kneed walker simulations are performing nicely, but, the limitation imposed due to some hard constraints including point foot, lumped mass and instantaneous impact assumptions disallow the model to be directly applied in the real word scenario. Nevertheless constraints such as point foot, lumped mass, instantaneous impact and reduction of model to 3 link from 4 while walking, helped me to make a mathematically tractable model of kneed walker, and, acted as a good point to start studying the behavior of a general n-link bipedal.

In the control section for the acrobot walker I have tried to develop a model based controller using Partial Feedback linearization principle. The controller is working on the simplest principle that I could have thought. That is **take larger steps if you have large velocity**. The controller took some of my time to tune manually but is performing decently and is able to increase the range of angles of slopes (γ) for which a acrobot can walk down given a constant initial condition. Extension of such rule based controller to larger degrees of freedom system is quite an extensive task and may require a lot of mathematical number crunching for applying.

6.2 Future Work

I think the future work for extending this thesis can be classified in 3 sections. Firstly, a more efficient hardware can always be made. Since my model was a

planar passive one. There is always a possibility to extend it to a full 3D version and adding actuation to make it more real in the sense of applicability. But before taking this extra degree of freedom I will suggest to make a planar model with spring mass damper in legs and actuation facility to make it a partially active robust model that can walk on a plane surface or even up the slope. Spring mass dampers are required to make a rugged mechanical model that will allow the bipedal to take many more steps/impacts before damaging .If a mechanism can be added that can allow partially passive actuation then it will be a great extension.

Secondly, trying to develop more realistic simulation models of bipedal, specially the one which have torso, and feet because such models give a lot of freedom in terms of actions that can be performed to increase the stability margin.

Finally, work on the stability analysis of the models and real time control of the actual bipedal can be performed. More efficient control algorithm can be developed that minimizes the energy losses at impact. And even partially passive drives can be performed that may lead to extremely efficient gaits.

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