Experiments on Planar Biped

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Abstract

Many of the unique abilities that robots possess come from their mobility. Legged robots have an advantage over wheeled robots on rough terrains; legged robots use the available footholds, which are often isolated or hidden by obstacles. This paper outlines a simulation based study of planar biped system that runs. Springy telescopic legs, a simple body and actuated hip-type joints are incorporated in the biped model. The control strategy suggested by Raibert (1984) [1] is incorporated in this paper. The control is decomposed into a vertical bouncing part, a forward speed part and a body attitude part. The control strategy has been implemented and validated through dynamic simulations in V-REP simulator.

Keywords: Planar Biped, Legged Robots, Running, Computer Simulation

1. Introduction

Both running and walking are a form of legged locomotion; unlike walking, running has a flight phase which plays important role in obtaining high speeds. Our running robot uses just one leg for support at a time, as do humans. The control algorithm for this one-foot gait mode of running has same essential features as one legged running system [1]. Legged robots have to balance actively like an inverted pendulum when their foot is in contact with the ground. In 1951 Claude Shannon used automatic control to build a cart-pendulum that can balance itself. This became precursor to later work on legged locomotion that used inverted pendulum models for legs to achieve active balance. To study running in its simplest form a planar running machine with just one leg was built at MIT [1]. Their machine had a body and a leg that was springy and could telescope to change length. For this machine there are two phases during a cycle. One phase called stance, the leg supports the weight of the body and foot stays in fixed location on the ground. In this phase the machine tips like an inverted pendulum but here there is no chance to mode the foot directly. In order to change the foot position the machine has to jump and this phase is called flight; the leg gets unloaded and is free to move. They have come up with a simple control strategy which is decomposed into three parts, first, control hopping height, second, forward speed, and third, body attitude. They could achieve a top running speed of 1.2 m/s [2]. Later they built biped robot making use of the same control algorithms as that used for one-legged robot and were able to achieve top running speeds of 4.3 m/s (Raibert et al. [3]).

In this paper a CAD model of planar biped was built and using the control algorithms of the one-legged robot [1] we achieved a top running speed of 2.5 m/s. Control algorithms were implemented and simulations were run in Virtual Robot Experimentation Platform (V-REP).

The following section-2 describes the model of biped that is used in this paper. Section-3 provides the control algorithm which is essentially same as the control used for one-legged hopper [1]. Section-4 provides the results obtained from the experiments that were conducted using Virtual Robot Experimentation Platform (V-REP) and ODE (Open Dynamics Engine) physics engine.

2. The Model

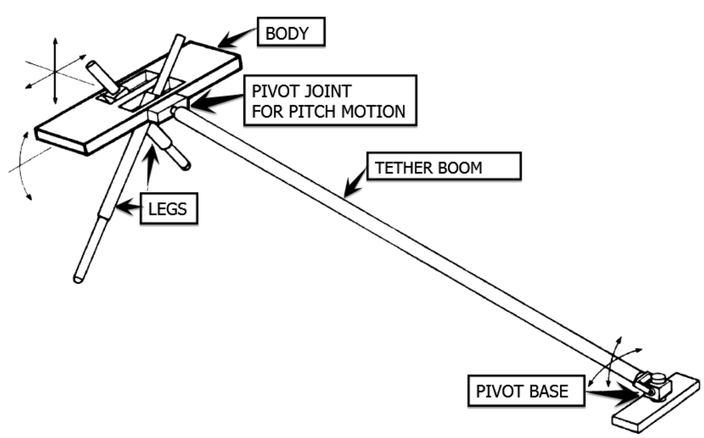
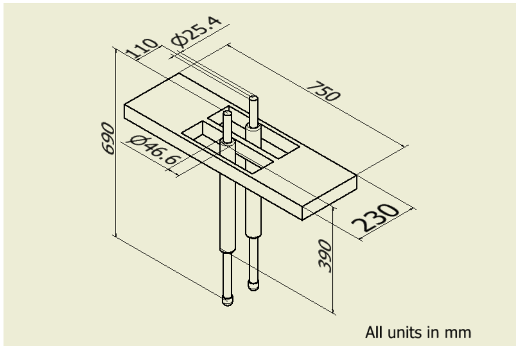
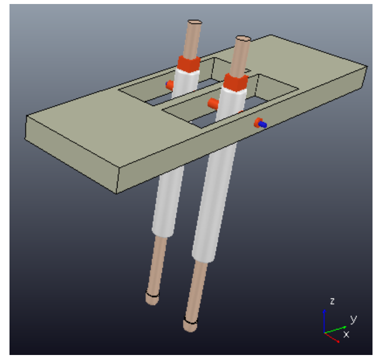


Figure 1: Planar biped constrained by a tether mechanism



(a) Robot Dimensions



(b) V-REP Model

Figure 2: Planar Biped Model

Figure-1 shows the robot that was modelled to study running. The basic components of this legged system are a pair of legs and a body. The planar biped has two telescoping legs connected to the body by pivot joints that form hips. Each hip has a hydraulic actuator that positions the leg fore and aft. An actuator within each leg changes the leg length, and an air spring makes the leg springy in the axial direction. The motion of the running machine is restricted to a plane. The tether mechanism shown in the Figure-1 constraints the biped to move with only three degrees of freedom; horizontal, vertical and rotation about pitch axis. The robot moves on the surface of a large sphere centered at the pivot center. This mechanism permits the robot to travel on a circular path with a radius of 5m. The dimensions of the planar biped used for the running experiments in Section-4 are shown in Figure-2a.

Each of the two legs is made up of a piston cylinder assembly with padded foot attached to the lower end of piston. The foot is narrow, about 25 mm diameter, can be approximated as a support point. The coefficient of friction between foot and the ground is 1.0, so the foot does not slip much. In the V-REP simulation, piston and cylinder are connected by a prismatic joint. The leg is made springy by using a PD control for the prismatic joint (PD parameters are chosen based on the spring stiffness). To propel the body upward and forward a constant thrust force is applied by the prismatic joint in the leg. Legs of the biped articulate with respect to the body about the hip and are actuated by revolute joints. A control torque τ is generated by revolute joint at the hip using a close loop PD control. Same feedback loop is used during stance and flight with different kp and kv values.

3. Control Strategy

The goal of the biped control system is to produce dynamically stable running behaviour. The operator specifies the forward speed and hopping height, and the control system adjusts the running behaviour to follow the commands. The control system relies on a three-part decomposition of the problem. One part regulates the amplitude of the machine's bouncing motion, another stabilizes the forward running speed, and the third maintains the body in a level attitude.

3.1. Activity Cycle

The hopping motion has to establish a regular cycle of activity within which the three-part control can take place. A leg changes its point of support all at once and for this unloading of leg is necessary. In a legged system there must be periods of support when the leg bears the weight and other periods when the leg is unloaded and foot is free to move. For the biped robot these periods occur exactly once during each step. For each leg these periods occur exactly once every two steps; active leg alternates every step (Active leg is the leg which is going to bear the weight during a step). The cycle of activities are illustrated in Figure-3 and the event that trigger a particular state for the biped along with the list of actions that need to be executed is tabulated in Table-1.

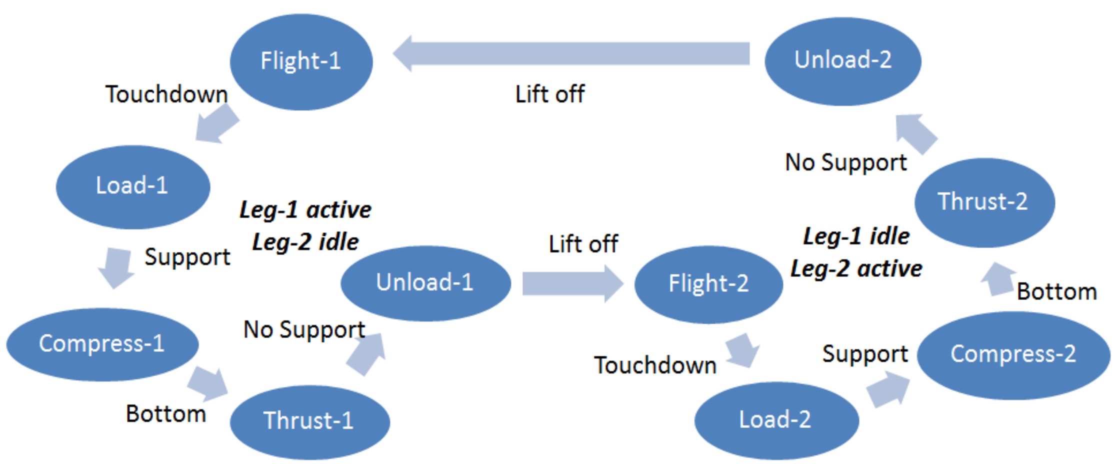


Figure 3: Activity Cycle

State	Trigger Event	Actions
Flight	Active leg leaves ground (lift off)	Interchange active and idle legs Stretch active leg for landing Shorten the idle leg Adjust active hip angle for foot placement Mirror active hip angle with idle hip Control body attitude with idle hip
Loading	Active leg touches ground (touchdown)	Active hip is set free
Compression	Leg spring shortens (support)	Control body attitude with active hip Mirror active hip angle with idle hip
Thrust	Leg spring starts to lengthen (bottom)	Apply thrust from active leg Control body attitude with active hip Continue mirroring angles
Unloading	Active leg stretches to full length (no support)	Active hip is set free Shorten the active leg Continue mirroring angles

Table 1: Actions required based on the machine state

3.2. Vertical Control

The hopping behaviour is a spring mass oscillation which is determined mainly by the springiness of the leg, mass of the body and gravity. Just like a bouncing ball, every time it collides with the ground some part of the energy is lost and with the remaining energy it bounces up. This makes the amplitude of hopping to decay with time. To maintain desired amplitude thrust force is applied by the legs during each hop. With this the machine is set into a steady state oscillation where the energy lost in collision is exactly compensated by the thrust provided during each hop. Steady state amplitude increases with increasing thrust force. This thrust force is delivered during every stance phase (when foot is in contact with the ground). We have chosen a fixed value of thrust which is giving an acceptable hopping height, there by flight duration.

Thrust is applied just after the leg fully compresses, that is when the leg start to increase its length during stance. During repeated hopping, each stance interval has duration:

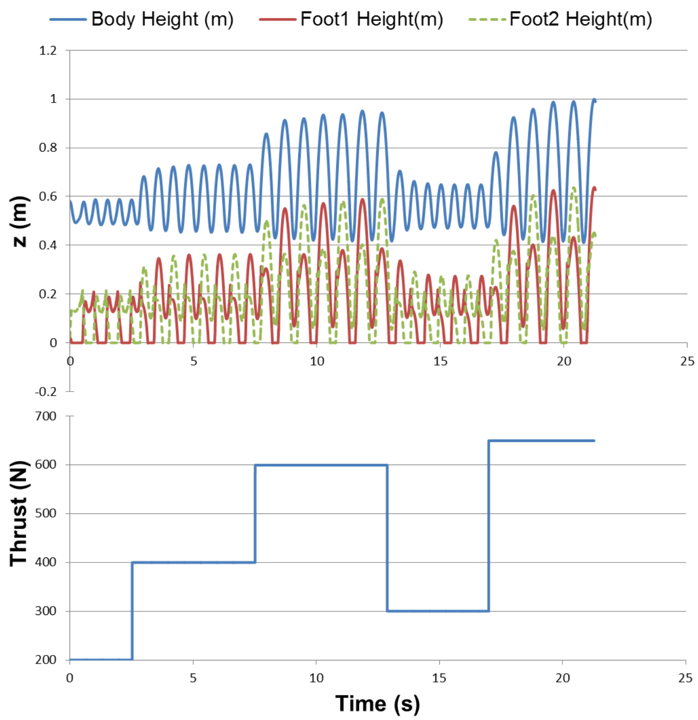
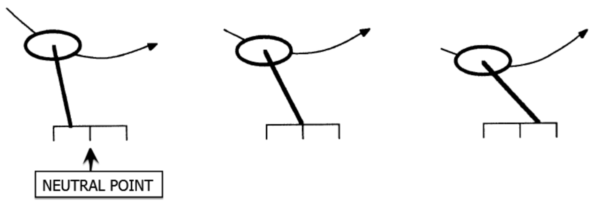


Figure 4: Thrust force is varied according to the lower graph while the robot hops in place. Vertical positions of body and both foot are shown in the top graph.

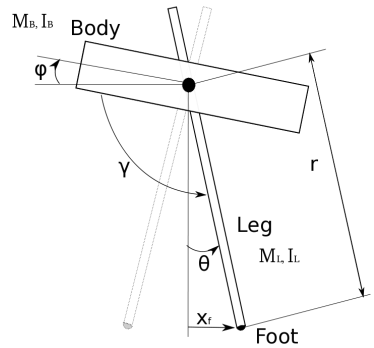
$$T_{st} = \frac{\pi}{\omega} = \pi\sqrt{\frac{M_B + M_L}{K_L}}$$

3.3. Control Forward Running Speed

The previous section discussed the vertical hopping motion of biped and its control. In order to travel form place to place, the robot has to actively balance and control the forward speed. Foot placement has a powerful effect on the tipping motion. Gravity generated torque is proportional to the horizontal position of foot with respect to the center of gravity. In biped running, each leg extends forward during flight so that the foot first touches the ground some distance in front of the body. During stance the leg sweeps backwards with respect to the body. The foot then leaves the ground some distance behind the body and the other foot extends forward. There is symmetry in this motion about the point half way through stance, when the leg



(a) Foot placement relative to neutral point



(b) Planar Biped

Figure 5

is directly under the center of gravity. This foot position for which stance phase is symmetric is called neutral point. In such a symmetrical motion, tipping moments average to zero throughout stance. Any amount of deviation from this symmetric motion results in non-zero horizontal acceleration. Placing the foot after the neutral point results in deceleration as the robot spends more time tipping backwards than in tipping forward and placing the foot behind the neutral point results in a net forward acceleration.

To regulate the forward speed, the control system must calculate a forward position of foot based on current and desired horizontal velocity. To place the foot at the neutral point, i.e the center of CG-print (during stance), leg is extended forward so that the foot lands at the neutral point.

$$x_{f0} = \frac{\dot{x}T_{st}}{2}$$

To accelerate the machine to a desired speed proportional control is used.

$$x_{f\Delta} = k_{\dot{x}}(\dot{x} - \dot{x}_d)$$

Algorithm for foot placement

$$x_f = \frac{(\dot{x}T_{st})}{2} + k_{\dot{x}}(\dot{x} - \dot{x}_d)$$

Corresponding hip angle is

$$\gamma_d = \phi - sin^{-1}\left(\frac{(\dot{x}T_{st})}{2r} + \frac{k_{\dot{x}}(\dot{x} - \dot{x_d})}{r}\right)$$

3.4. Control Body Attitude

The control system maintains a level attitude of the body by exerting torques about the hip during the stance phase. Any deviation from upright attitude of the body is corrected by exerting torques during stance phase. Angular momentum is conserved during flight; the stance phase provides an opportunity to change the angular momentum of the whole system. Friction between foot and the ground provides external torque required to change the angular momentum of the system. To servo the body to a desired attitude, this control torque is applied:

$$\tau = -k_p(\phi - \phi_d) - k_v(\dot{\phi})$$

Mirror the angle of active hip with idle hip to have zero net torque on the body. This mirroring helps to reduce oscillations of the body. During flight phase body attitude can be controlled to some extent by the idle hip. In addition to attitude control during stance phase, both mirroring and flight phase attitude control using idle leg are also implemented for the experiments conducted in the V-REP simulator.

4. Running Experiments

To test the workability of the three-part control strategy and the dynamic balance of the planar biped machine; first a solid model of the biped is created in Autodesk Inventor and the obtained mesh data is exported to V-REP in STL (Stereo Lithography) CAD format, then all the dynamic parameters like mass, inertia, motor limits etc. are given to the simulator. A general PID control is implemented for each motor and the control parameters are fed to the motors by a main program. All simulation parameters can be found in Appendix TableA.2. Simulation time step is taken as 1ms, although motor control program runs 10 times during each time step to stabilize dynamic simulations. The three-part control and activity cycle are monitored by the main program. And the data thus generated is recorded and presented here.

4.1. Speed Control

In the first experiment the biped runs forward with the desired velocity specified by the operator by adjusting a slider type user interface (UI) during a simulation run. The results of the experiment are plotted in Figure-6 . The simulation is run over a 25 seconds interval and stair-case of desired forward speed values is specified. The biped initially hops in place and then gradually increasing its velocity to 2.0 m/s and the decreasing to zero. More forward acceleration can be achieved by adjusting the velocity error gain, $k_{\dot{x}}$.

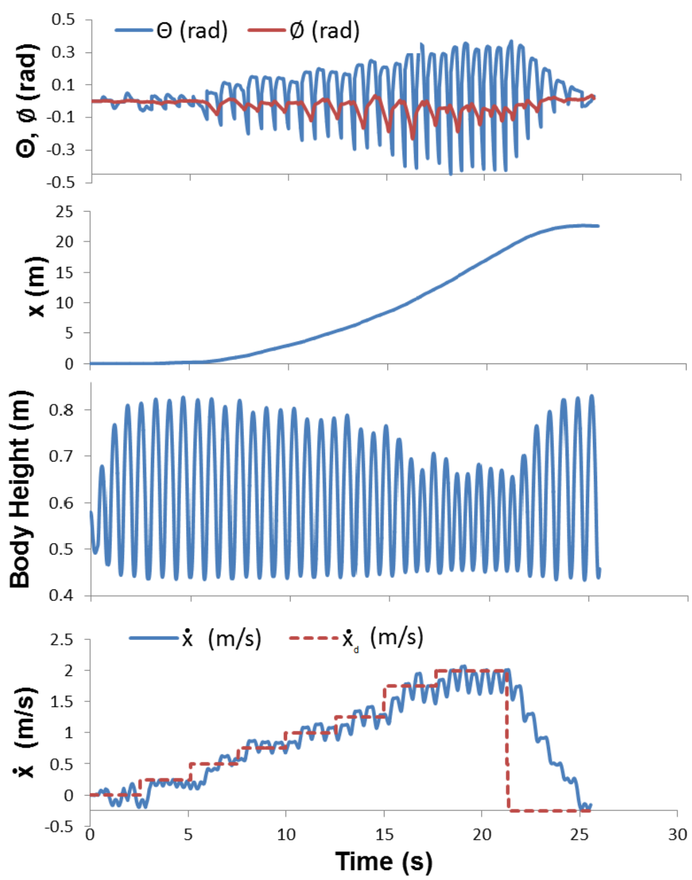


Figure 6: Desired forward speed is varied in steps (dashed line, bottom graph). Forward Velocity achieved by the robot is shown in blue line(bottom graph). Body pitch angle Θ, leg angle ϕ, position of the robot z and vertical position of body are also shown.

During running, oscillations of the body are observed and the body attitude is corrected during stance phase by the torques applied by active hip and during flight phase by the torques applied by idle hip. Hopping height is also affected by the running speed, though a fixed thrust force is applied during every stance, mainly because of the angle of leg at touchdown.

4.2. Position Control

Position control was introduced in the three-part control by calculating desired forward speeds based on position errors. And a maximum velocity cap is introduced to limit the forward speed.

$$\dot{x}_d = min[k(x - x_d), \dot{x}_{max}]$$

Target position is set by the main program from predefined sequence of positions. The results obtained are plotted in Figure-7 . The biped was able to reach the specified location within an error of 0.25 m.

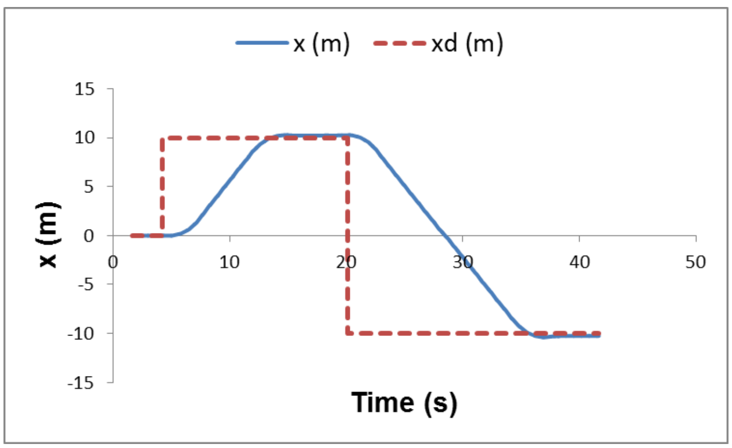


Figure 7: Position control with k=0.8 and max speed = 1.5 m/s. Initially biped hops in place and then at t=4s desired position is set to 10m and after t=20s desired position was reset to -10m.

5. Conclusion

The model of biped used in this paper consists of body, two actuated hip joints and a pair of legs. Legs are springy with non-zero mass and their lengths can be controlled using position actuators. Control of running biped can be decomposed into height control, forward speed control and body attitude control. Two virtual experiments were conducted to demonstrate velocity and position control of the biped while maintaining dynamic balance. The results presented in this paper are obtained from computer simulations of a biped robot built and simulated in Virtual Robot Experimentation Platform (V-REP), using Open Dynamics Engine (ODE) for physics.

References

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Appendix A.

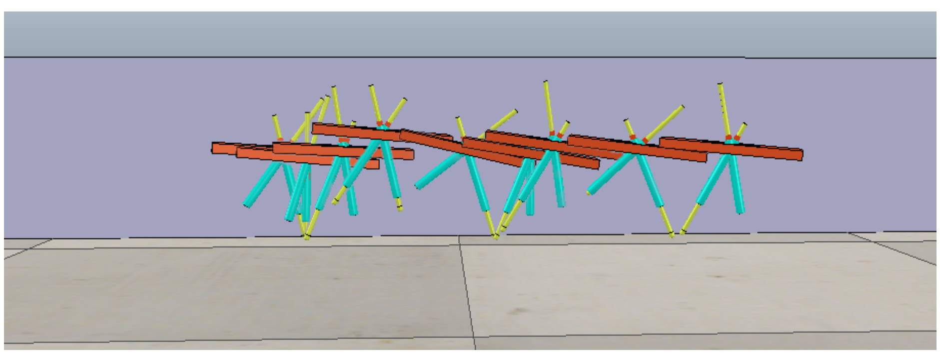

Figure A.8: Two steps of planar biped. During the first step left leg is active and during the next step right leg is active. The idle leg shortens during flight. The blue wall behind the biped is 1m high and grid on the floor has 2m spacing.

Parameter	**Value**
Total Mass	14.56 kg
Body	
Mass	11.54 kg
Moment of Inertia	0.42 Kg-m^2
Leg	
Total mass	1.51 kg
Moment of Inertia	0.18 kg-m^2
Piston mass	0.29 kg
Foot and Ground	
Coefficient of friction	1
Coefficient of restitution	0
Boom radius	5 m
Hip Actuator	
sweep	±40 deg
Max Torque	50 N.m
Flight	
k_p	67 N.m/rad
k_d	4.26 N.m/(rad/s)
Stance	
k_p	100 N.m/rad
k_d	20 N.m/(rad/s)
Leg Actuator	
stroke	0.2 m
Max Force	1100 N
Compress	
k_p	3000 N/m
k_d	175 N/(m/s)
Thrust	
Force	500 N
Simulation Parameters	
Time step	1 ms
Simulation passes per frame	20
Graph data buffer size	30000

Table A.2: Physical and Simulation Parameters of the planar biped