Multibody Control and Simulation

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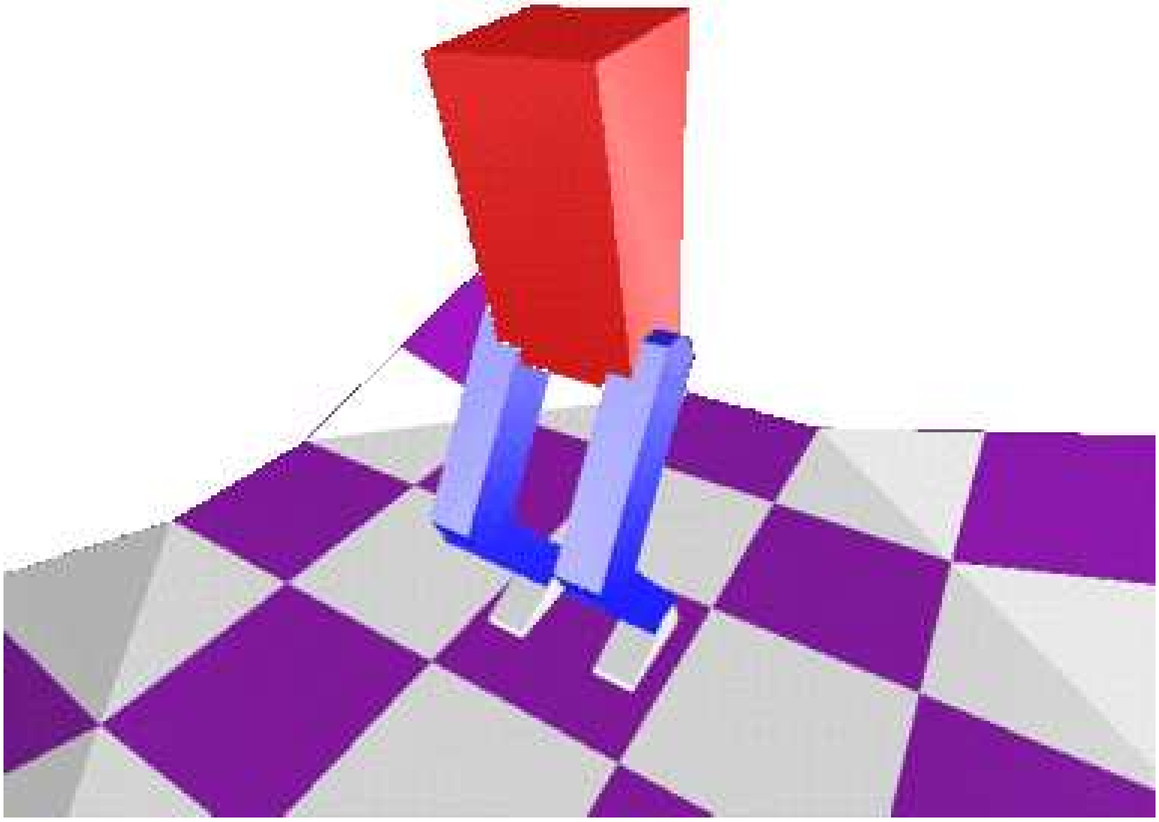

March 22, 1996

Introduction

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3. Research Plan
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   (b) Description of Balancing Controller
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Multibody Control Challenges

- Complex Nonlinear Dynamic Equations
- Many Degrees of Freedom
- Need to Coordinate Force and Motion
- Difficult to Transform Desired Behavior into Controller Design
- Difficult to Tune Joint Gains
- Difficult to Handle Contact with Environment
- Interactive Simulation Speeds are Difficult to Achieve

Our Approach to Multibody Control

- Use Recursive Dynamics to Simulate the System and to Create the Model for the Controller
- Use Recursion to Calculate Force and Kinematic Transformations
- Form Errors in the Space Important to the Desired Behavior
- Use Model-Based Controllers
- Use a Multibody Simulator Designed to Handle Contact Models (Impulse)
- Honest Models of Contact and Dynamics

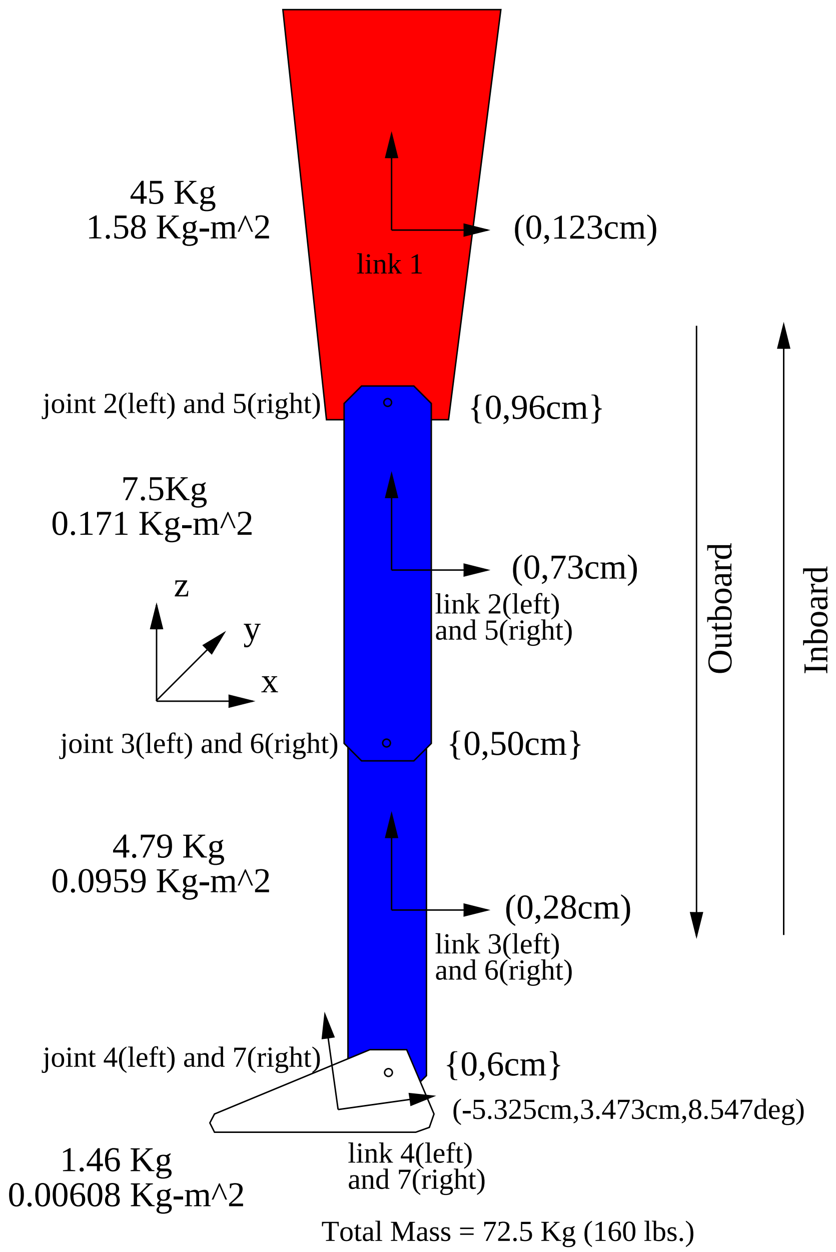
Research Plan

1. Balancing Planar Biped $\surd$
2. Balancing 3D Biped
3. Taking Steps
4. Walking
5. Adapting to Loads
6. Running
7. Jumping
8. Changing Direction

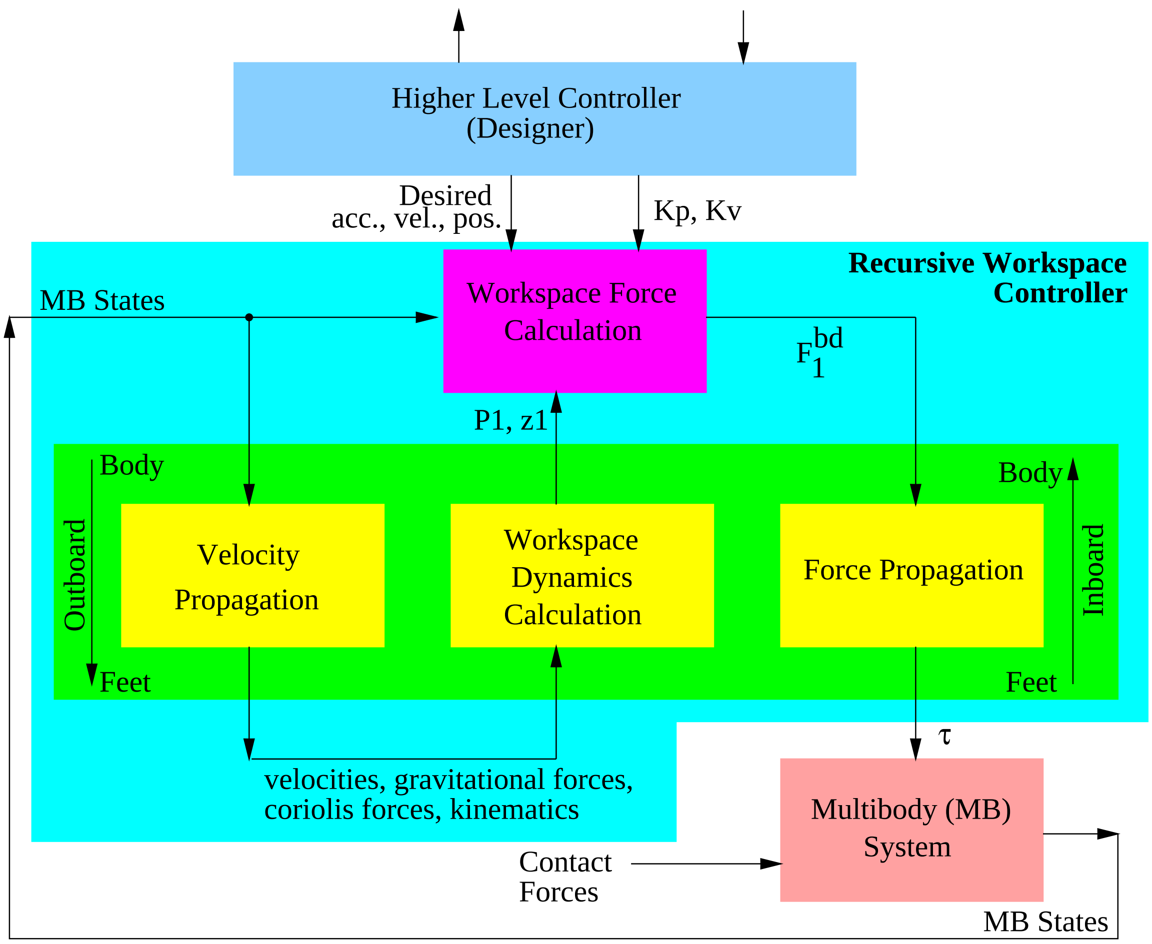
Planar Biped Example

- Description of Model
- Description of Balancing Controller
- Video
- Simulation Results

Description of Model



Balancing Controller



Controller Initialization

Given V_1^b, $g_{0,1}$, θ, $\dot{\theta}$

Initialize Variables

$$a_1^b = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$b_1^b = -g_{1,0} \begin{bmatrix} 0 \\ -m_1 g \\ 0 \end{bmatrix} + \begin{bmatrix} +m_1 \dot{\theta}_1 V_{1,z}^b \\ -m_1 \dot{\theta}_1 V_{1,x}^b \\ 0 \end{bmatrix}$$

Velocity Propagation

```
For i = (min joint index) to (max joint index)
```

$$
\begin{aligned}
g_{i.o,0} &= g_{i.o,i.i}(\theta_i) g_{i.i,0} \\
A^{i.o}_{i.i} &= \mathrm{Ad}_{g_{i.o,i.i}(\theta_i)} \\
V^b_{i.o} &= A^{i.o}_{i.i} V^b_{i.i} + H_{i.o}\dot{\theta}_i \\
a^b_i &= \dot{A}^{i.o}_{i.i} V^b_{i.i} \\
b^b_{i.o} &= -g_{i.o,0} \begin{bmatrix} 0 \\ -m_{i.o} g \\ 0 \end{bmatrix} + \begin{bmatrix} +m_{i.o}\dot{\theta}_{i.i} V^b_{i.o,z} \\ -m_{i.o}\dot{\theta}_{i.i} V^b_{i.o,x} \\ 0 \end{bmatrix}
\end{aligned}
$$

```
end loop
```

Workspace Dynamics Calculation

```
For j = (min link index) to (max link index)
```

$$z_j = b_j^b$$

$$P_j = M_j = \begin{bmatrix} m_j & 0 & 0 \\ 0 & m_j & 0 \\ 0 & 0 & \mathbb{I}_j \end{bmatrix}$$

```
end loop
Apply fixed base approximation
```

$$M_7 = M_4 = 10^6 M_1$$

$$b_7 = b_4 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

```
For i = (max joint index) to (min joint index)
```

$$\begin{aligned} D_{i.o} &= H_{i.o}^T P_{i.o} H_{i.o} \\ K_{i.o} &= H_{i.o}(D_{i.o})^{-1} H_{i.o}^T \\ L_{i.i}^{i.o} &= [I - K_{i.o} P_{i.o}] A_{i.i}^{i.o} \\ P_{i.i} &= P_{i.i} + (L_{i.i}^{i.o})^T P_{i.o} A_{i.i}^{i.o} \\ z_{i.i} &= z_{i.i} + (L_{i.i}^{i.o})^T (z_{i.o} + P_{i.o} a_i) \end{aligned}$$

```
end loop
```

Workspace Force Calculation

Given x_1^d, z_1^d, θ_1^d, V_1^{bd}, and $\dot{V}_1^{bd}$

$$
\begin{aligned}
e &= \begin{bmatrix} R_{1,0} \begin{bmatrix} x_1 - x_1^d \\ z_1 - z_1^d \end{bmatrix} \\ \theta_1 - \theta_1^d \end{bmatrix} \\
\dot{e} &= V_1^b - V_1^{bd} \\
F_1^{bd} &= P_1(\dot{V}_1^{bd} - K_v \dot{e} - K_p e) + z_1.
\end{aligned}
$$

Force Propagation

```
Divide desired force to each leg
```

$$F^{bd}_{2.i} = F^{bd}_{5.i} = \frac{F^{bd}_1}{2}$$

```
For i = (min joint index) to (max joint index)
```

$$F^{bd}_{i.o} = -(A^{i.i}_{i.o})^T F^{bd}_{i.i}$$

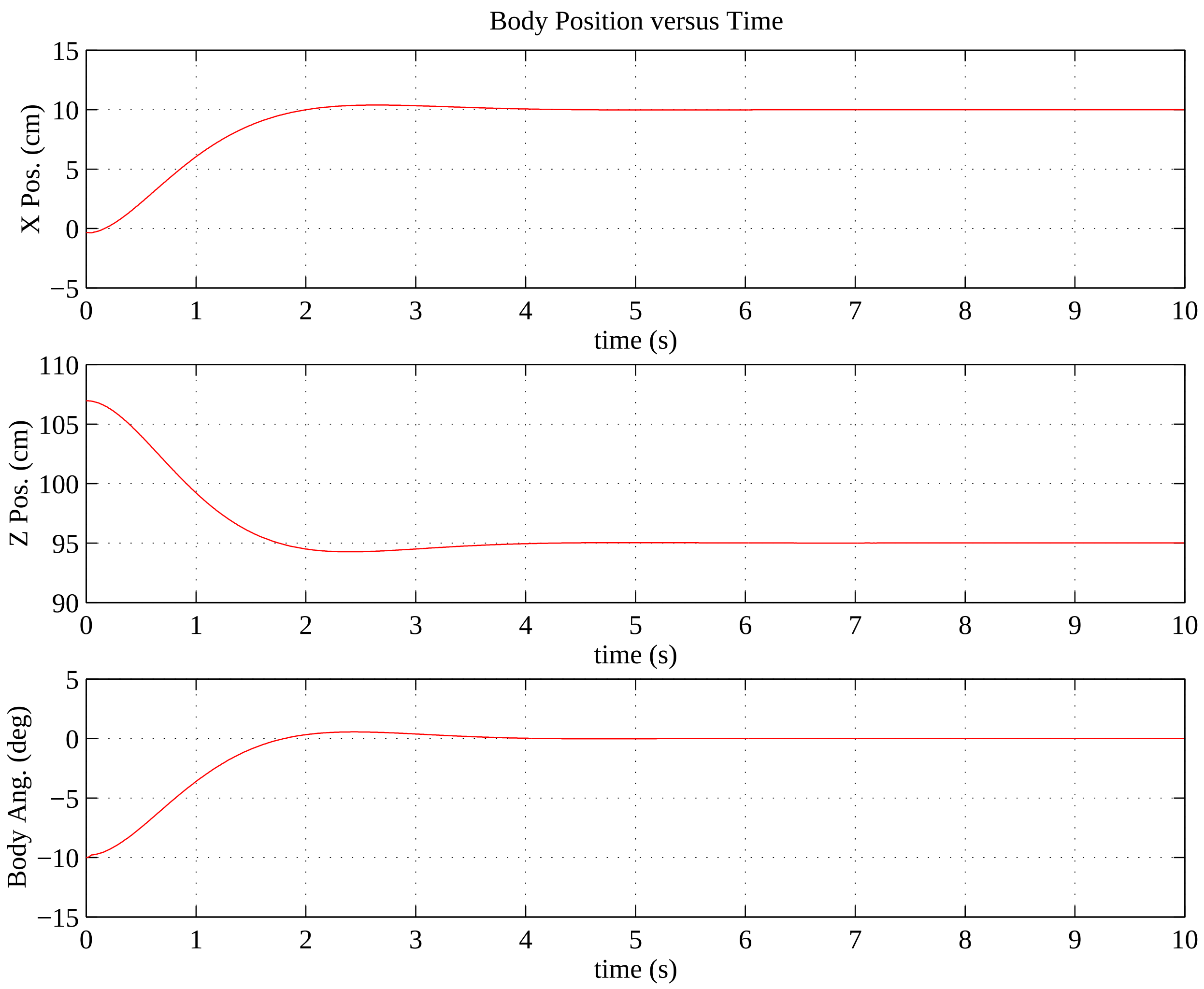
$$\tau_i = H^T_{i.o} F^{bd}_{i.o}$$

```
 if link i.o is a not a leaf
```

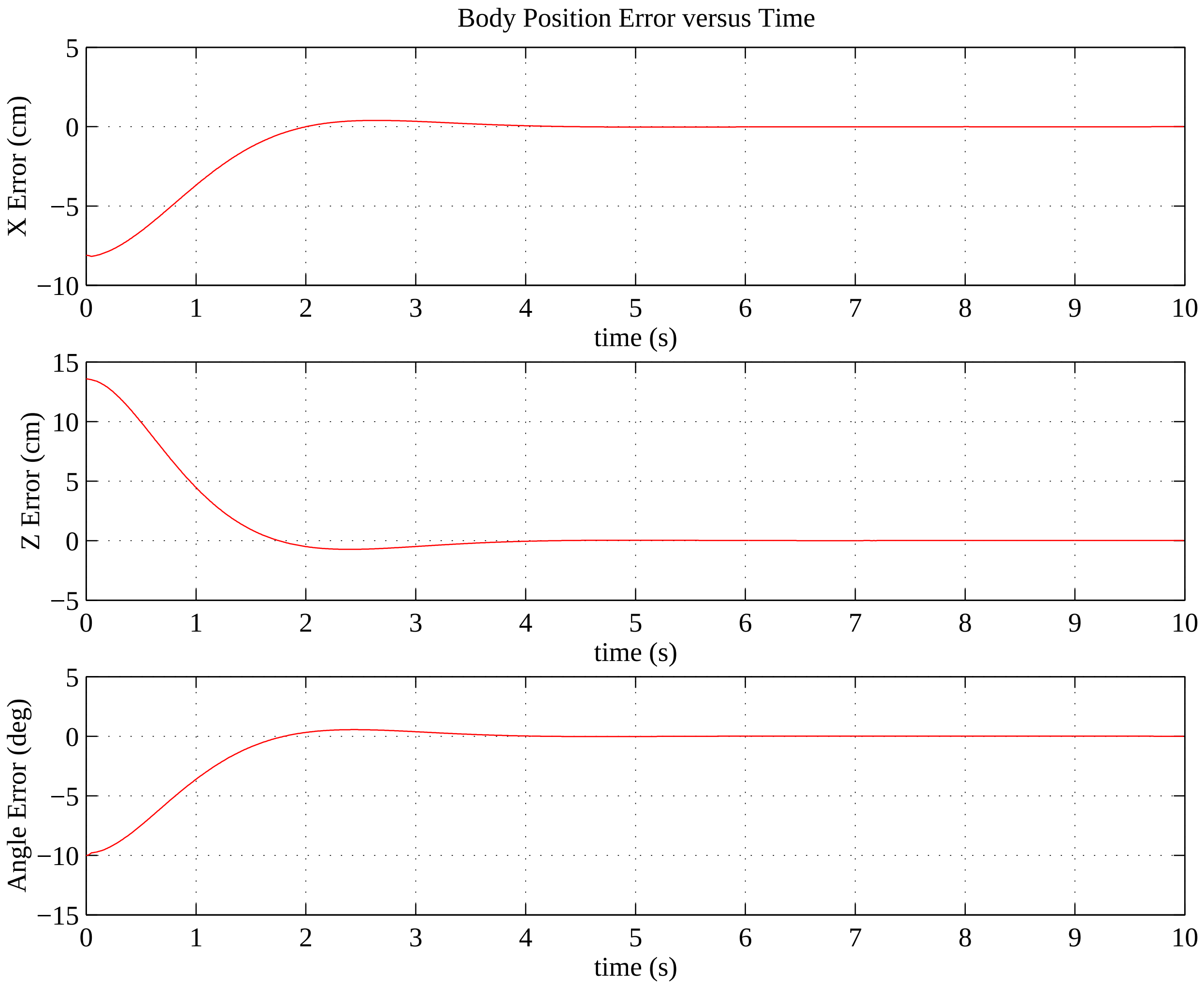
$$F^{bd}_{(i+1).i} = -F^{bd}_{i.o}$$

```
 endif
end loop
```

Simulation Results



Simulation Results



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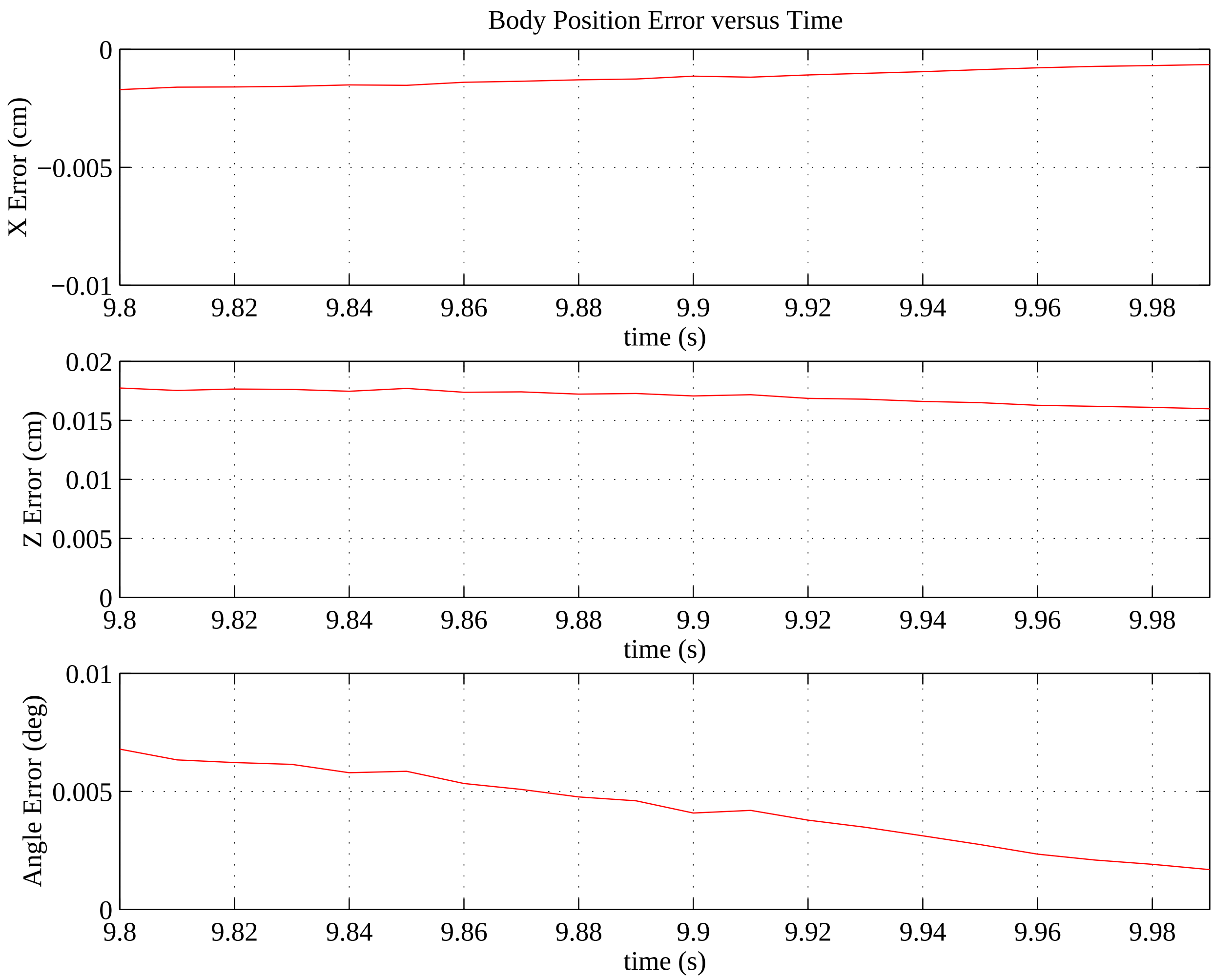

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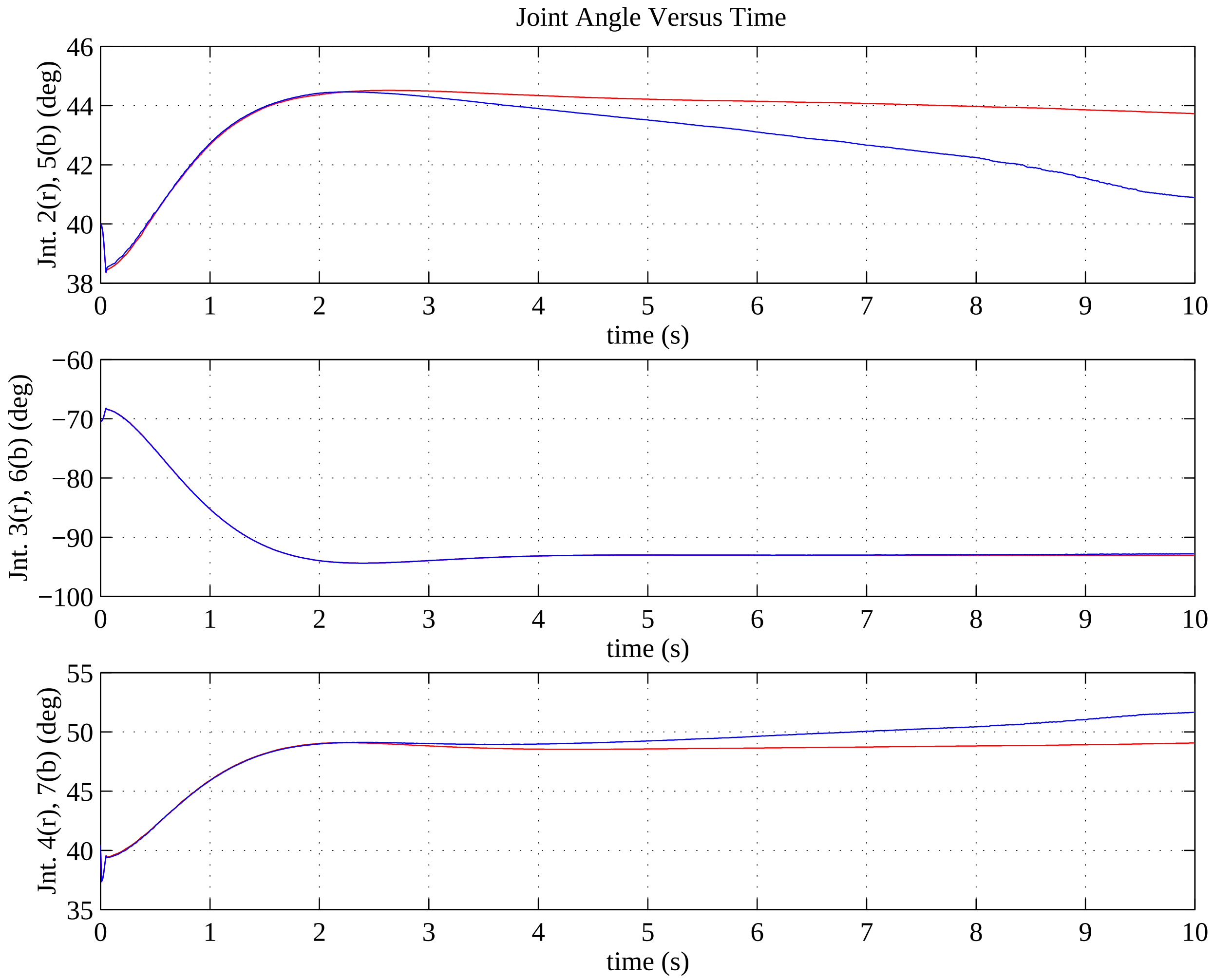

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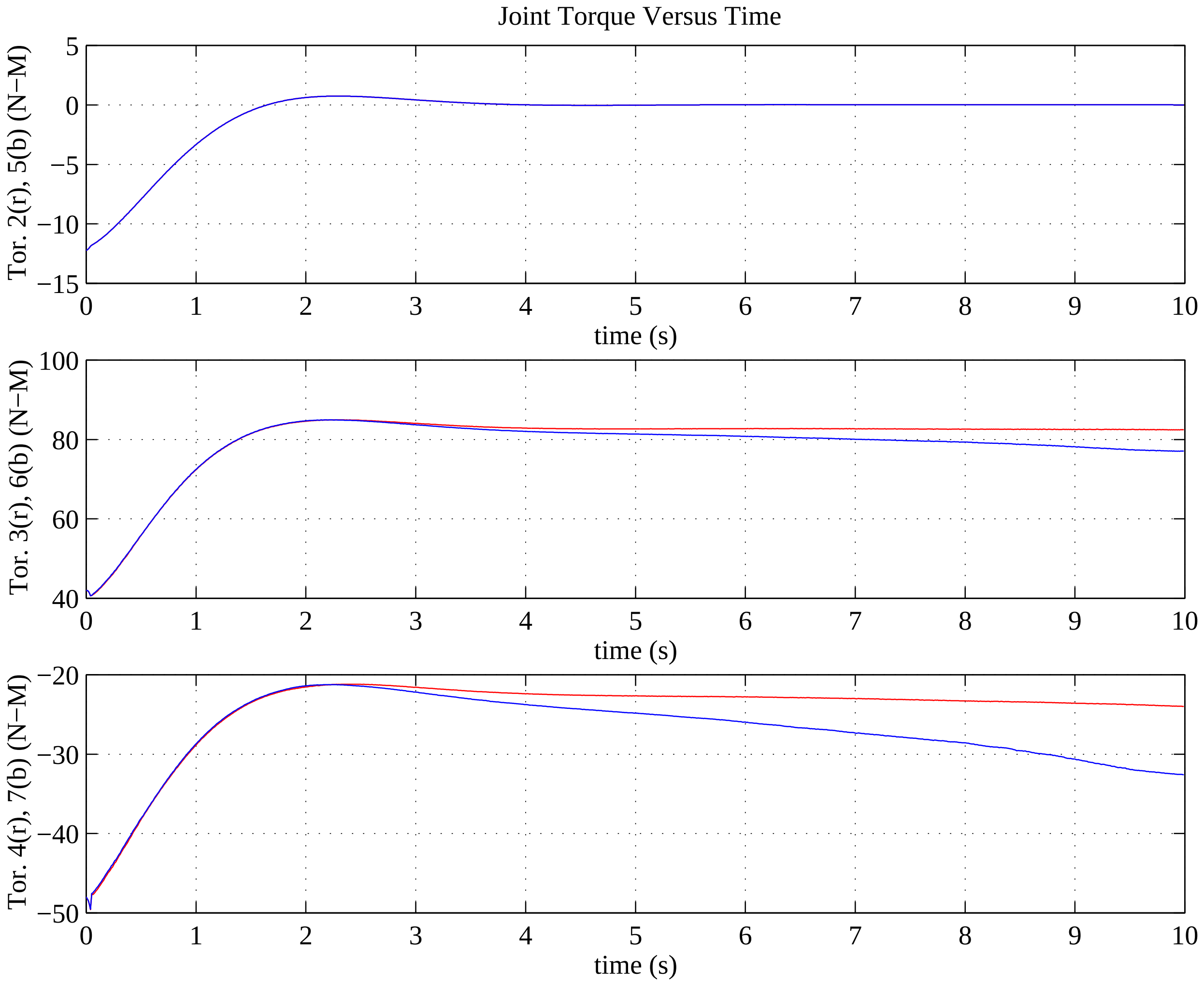

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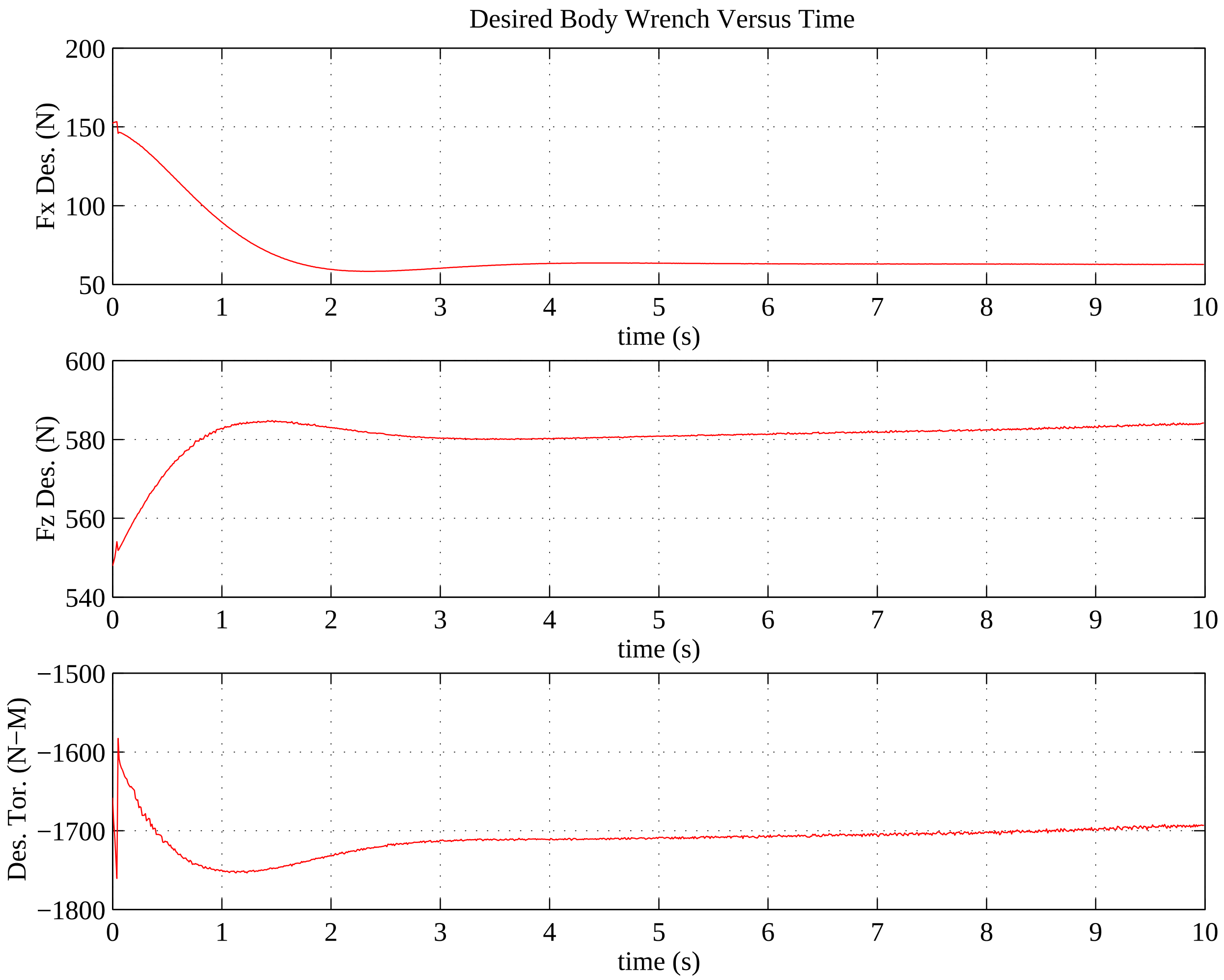

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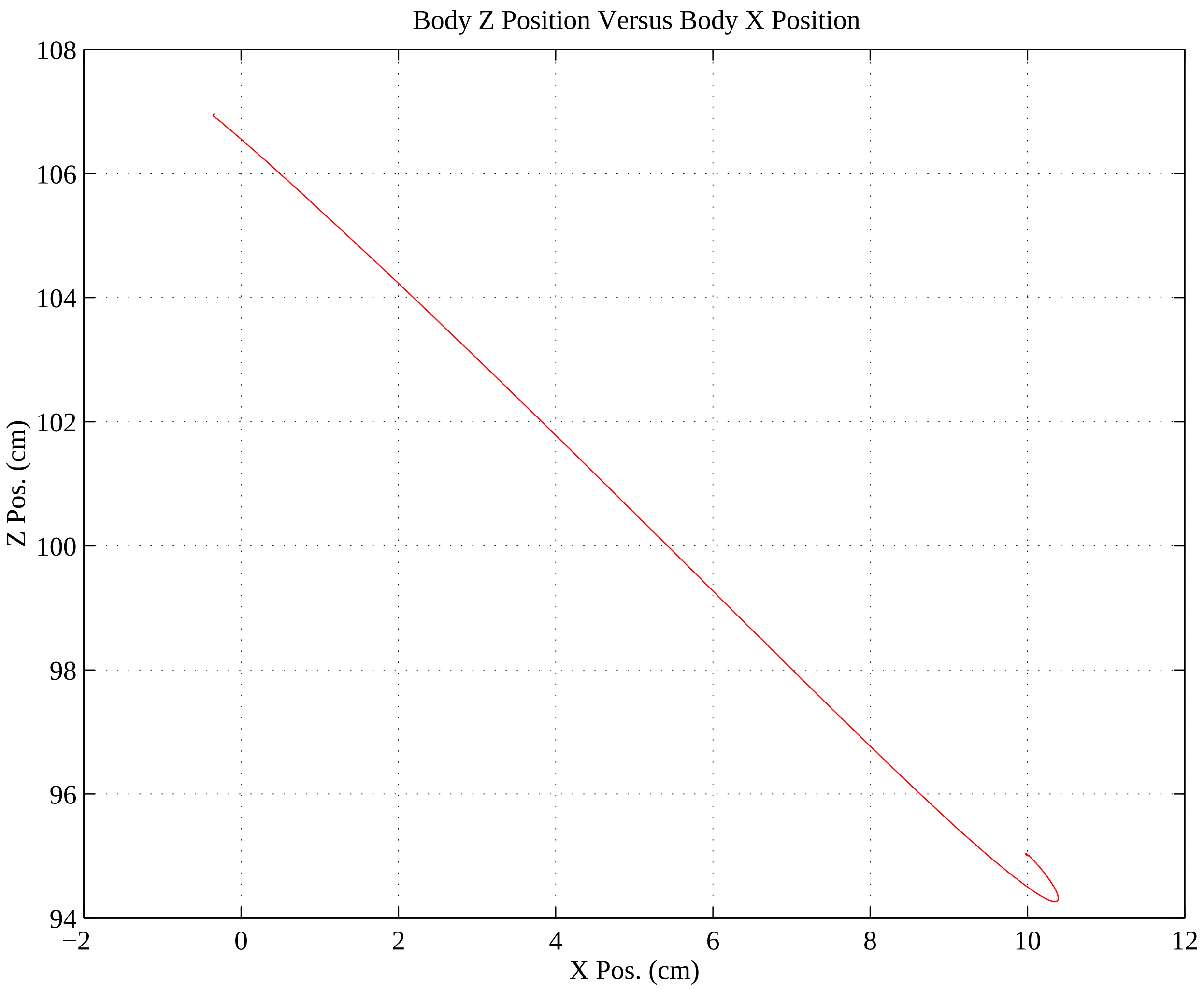

Conclusions

- Controller is Intuitive and Easy to Tune
- Never Calculate Explicit Equations for Kinematics and Dynamics
- Errors are Calculated in the Body
- Visualization Important for Controller Development
- Simulation Speed is Currently too Slow (100-200 Times Real-Time)
- Experienced Slipping Feet

Future Work

- Improve Simulation Speed to Achieve Real-Time Simulation
- Improve Collision Response for Planar Continuous Contact
- Choose Gains to More Closely Match Human Responses
- Create 3D Model and Implement Balancing Controller
- Implement Higher Level Controllers to Take Steps and Walk
- Design Controllers to Adapt to External Loads, Run, Jump, and Change Direction