SC 618: Analytical and Geometric Dynamics

Final Project - Modelling of a Quadruped using Matlab Simulink

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November 17, 2024

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1 Introduction

1.1 Introduction to the model

The project focuses on creating a flexible spine quadruped model inspired by biological locomotion. Using findings from the referenced papers, the aim is to simulate a planar biped as an intermediate stage and explore realistic gait patterns. The final system will build toward modeling the natural dynamics of a flexible spine quadruped.
All the simulation videos have been uploaded in the drive and the link to the same has been added at the last of the report.

2 Stage 1 - Planar Biped Modeling

2.1 Introduction

In the first stage, the quadruped is simplified into a planar biped model. The model uses a two-dimensional sagittal plane representation, reducing complexity by assuming symmetry between the left and right sides. Each leg is represented as a spring-loaded actuator, mimicking the compliant behavior of real quadrupeds during cyclic leg motion.

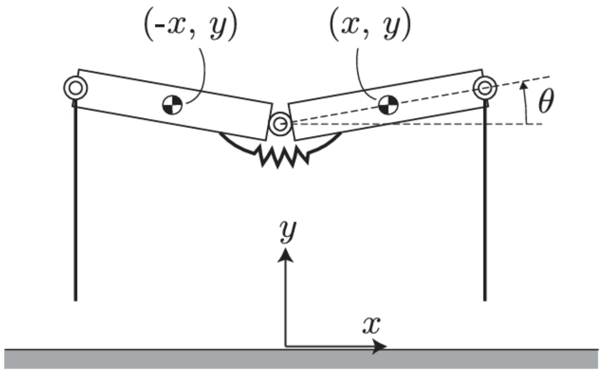

Figure 1: Simplified model by constraint of movement (flexible body model) [1].

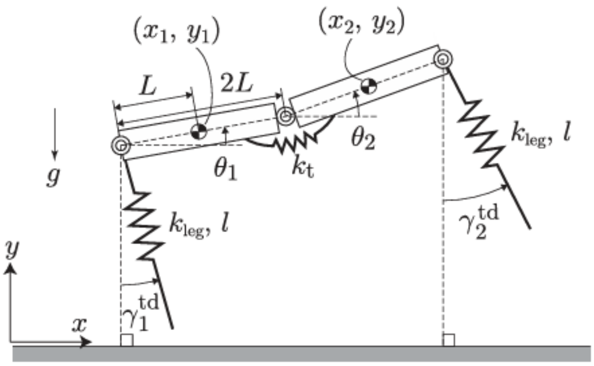

Figure 2: Bounding gait model with a flexible body joint and parameter definition [1]

2.2 Mechanical Components used in Simulink Multibody

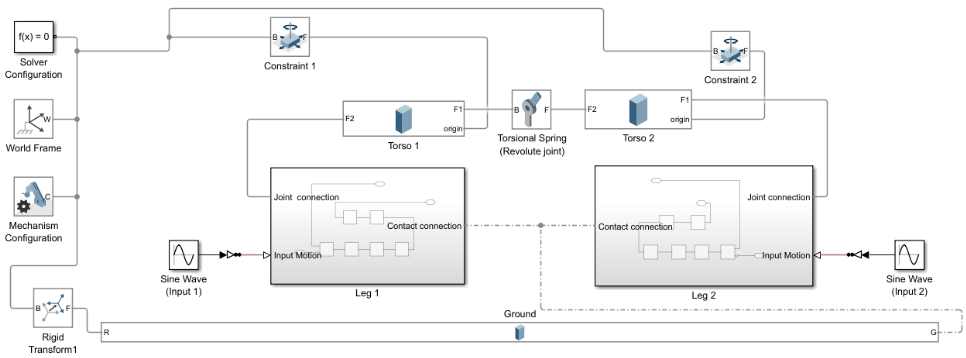

Figure 3: Simscape model of Stage 1

2.2.1 Torso - The upper body

The torso is modeled using two Simulink blocks connected by a rotational joint. The rotational joint has damping to emulate a rotational spring behavior, allowing flexibility and mimicking a spine-like structure. This configuration enables rotational movement between the two blocks, representing the dynamic flexibility of the torso.

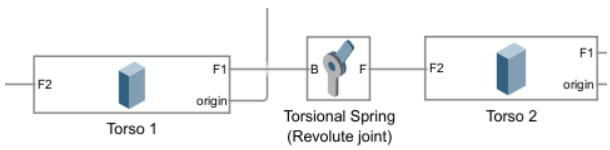

Figure 4: Simscape model of Torso

2.2.2 Legs - The lower body

Legs are represented by two spheres, simplifying the structure while focusing on contact dynamics. Each sphere interacts with the ground using a spatial contact forces block, which accounts for realistic ground interaction. The spheres are indirectly connected to the torso via invisible springs, which emulate compliant leg behavior. A rotational joint is incorporated into the connection, represented as a cylindrical body, allowing rotational motion between the leg and the torso.

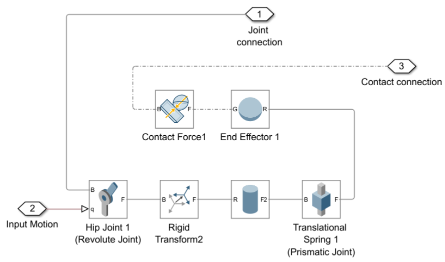

Figure 5: Simscape model of Leg

2.2.3 Interlink Between Torso and Legs

Invisible springs are modeled using prismatic joints connecting the torso and the leg end-effectors. Damping is applied to these prismatic joints to give them a spring-like compliance, simulating natural leg extension and contraction. The connection also includes a rotational joint between the spherical leg and the torso block, allowing additional degrees of freedom for leg motion.

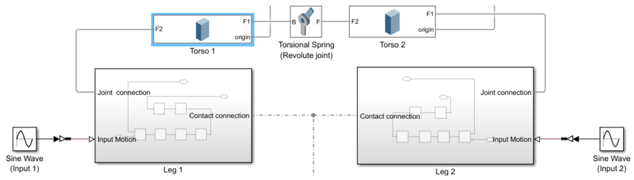

Figure 6: Simscape model of Link

2.2.4 Constraint Addition

Initially, our model experienced instability as it moved out of the plane, leading to it falling due to an unstable equilibrium. This issue was resolved by implementing a planar joint to constrain the biped's motion to the XY plane, allowing only translational motion along the X and Y axes and rotational motion about the Z-axis [2].

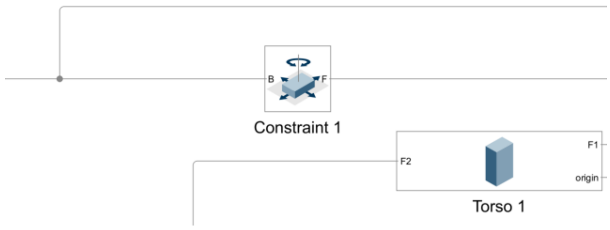

Figure 7: Simulink model of planar joint acting as constraint

2.3 Implementation in Simscape

The model for Stage 1 is implemented in Simulink using various blocks and connections to simulate the dynamics of a planar biped. The implementation is divided into three key sections: torso, legs, and the interlink between them.

2.3.1 Fixed Torso

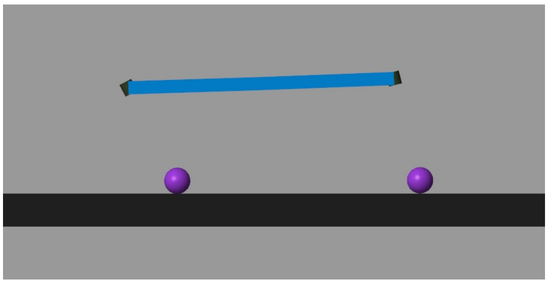

Figure 8: Flexible Torso

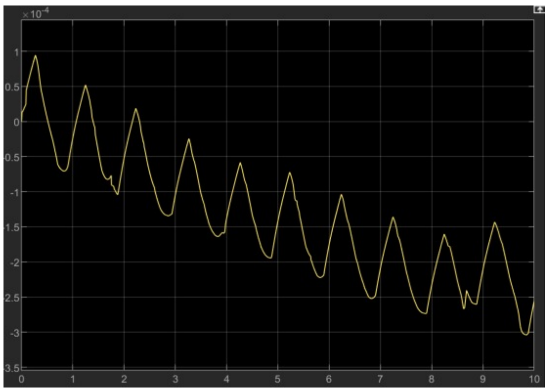

Figure 9: Simplified model by constraint of movement (flexible body model)

2.3.2 Flexible Torso

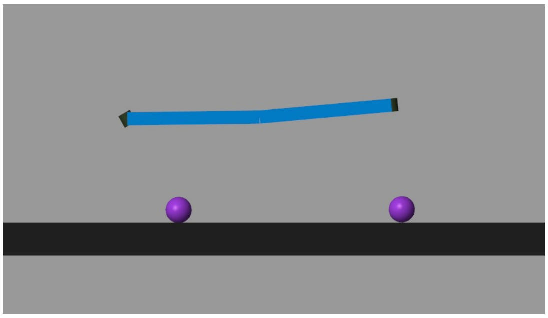

Figure 10: Flexible Torso

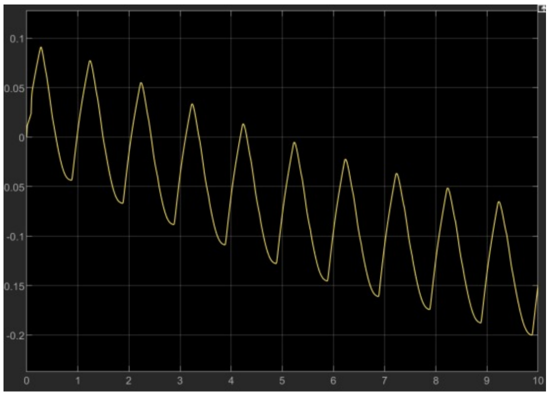

Figure 11: Simplified model by constraint of movement (flexible body model)

3 Stage 2 - Realistic Motion Simulation

3.1 Introduction

Building on the cyclic motion model, Stage 2 introduces realistic dynamics as it focuses on increasing the degree of freedom of the legs in this stage:

- **Asymmetric Phases**: Gait transitions between foreleg stance, hindleg stance, and double-leg flight phases are considered.
- **Interaction with Ground**: Contact dynamics, including touchdown and liftoff conditions, are integrated to simulate realistic leg behavior.
- **Energy Efficiency and Stability**: The model examines energy conservation and ground reaction forces to mimic natural locomotion patterns, referencing experimental findings from cheetah bounding gaits

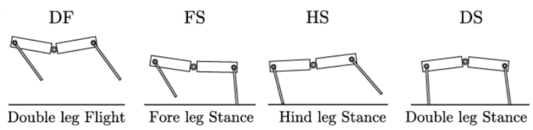

Figure 12: Four phases for the stance condition, DF, HS, FS, and DS [3]

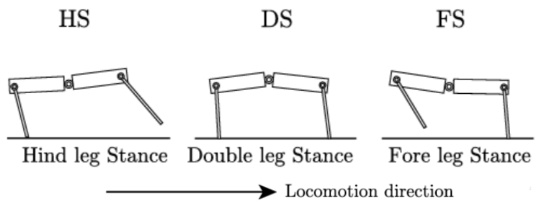

Figure 13: Sequence of phases in bounding gait [3]

3.2 Mechanical Components used in Simulink

In Stage 2, we enhance the planar biped model from Stage 1 by introducing a knee joint to each leg. This allows for greater flexibility and realistic leg motion, especially during the transition phases of the gait cycle.

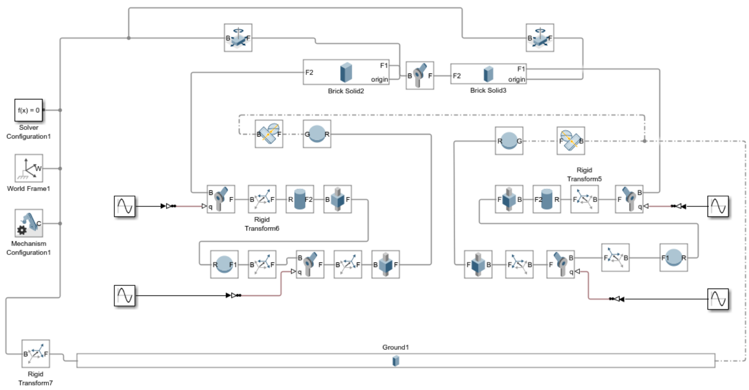

Figure 14: Simscape model of Stage2

3.2.1 Torso - The upper body

The torso remains a flexible structure consisting of two rigid blocks connected by a rotational joint with damping. This joint models a torsional spring, representing the flexibility of the spine. No major changes in the torso design from Stage 1. The torso supports dynamic movements by absorbing and redistributing forces during the gait cycle.

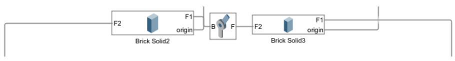

Figure 15: Simscape model of Torso

3.2.2 Legs with knee joints

Each leg is split into two segments connected by a knee joint:
-**Upper Leg (Proximal Segment)**: The upper leg connects directly to the torso via a rotational joint.
-**Lower Leg (Distal Segment)**: The lower leg connects to the upper leg at the knee, adding a second rotational joint.
The knee joint is modeled as a revolute joint with damping and a spring-like compliance to replicate the realistic motion of biological knees, achieved using a torsional spring-damper mechanism to provide resistance and elasticity. Allows flexion and extension of the leg while controlling the extent of the angular displacement.

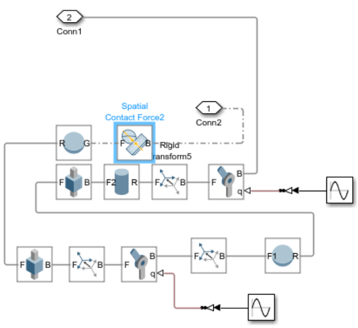

Figure 16: Simscape model of legs

3.3 Implementation in Simscape

In Stage 2, we simulated a 2-dimensional version of a robodog with a flexible spine. The model captures the dynamics of spine flexibility, enhancing the coordination between the front and rear legs for improved movement efficiency.

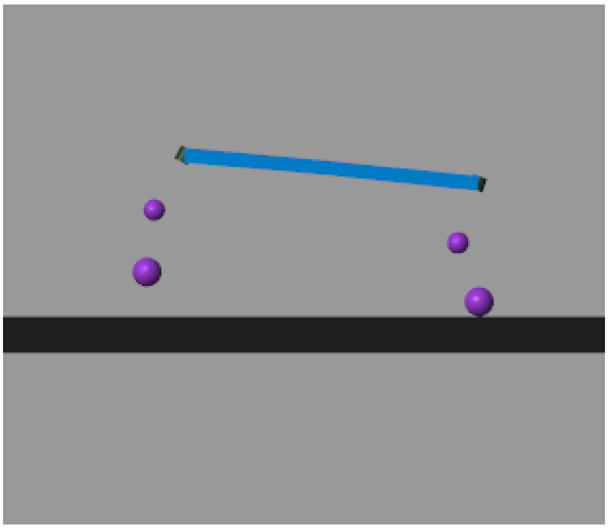

Figure 17: Simulink model of Simscape model of Stage 2

4 Stage 3

4.1 Introduction

In the third stage, a flexible spine is introduced to the quadruped robot, allowing for more realistic and dynamic motion. The spine enhances agility and enables smoother energy transfer between the front and rear legs, simulating the natural movement of real quadrupeds. This design improves coordination and performance, especially in complex environments.

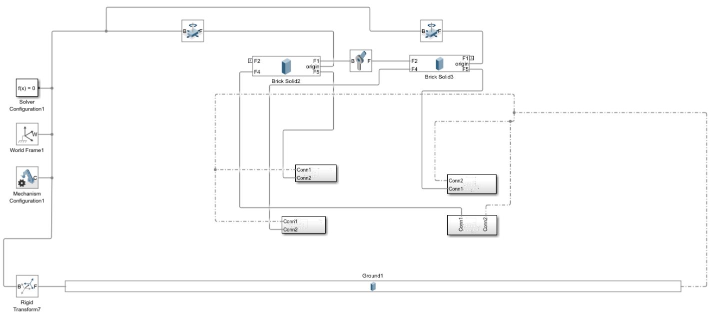

Figure 18: Simscape model of Quadraped

4.1.1 Torso - The upper body

The torso is modeled using two Simulink blocks connected by a rotational joint. The rotational joint has damping to emulate a rotational spring behavior, allowing flexibility and mimicking a spine-like structure. This configuration enables rotational movement between the two blocks, representing the dynamic flexibility of the torso.

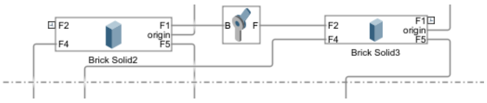

Figure 19: Simscape model of Torso

4.1.2 Interlink Between Torso and Legs

In Stage 3, invisible springs are modeled using prismatic joints with damping to simulate natural leg movement. A rotational joint between the leg and torso adds extra flexibility. Additionally, the alternate legs on opposite sides of the torso are synchronized for coordinated motion.

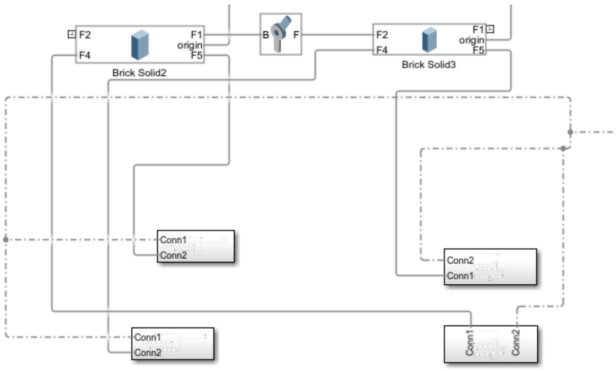

Figure 20: Simscape model of Link

4.1.3 Implementation in Simulink

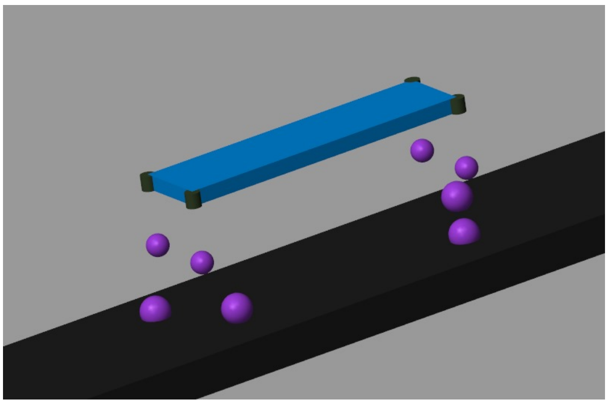

Figure 21: 3D quadaped model

Link to simulation videos -
https://drive.google.com/drive/folders/17x48Jo5s8ooZTVKIbnZfVXkFqiBWsHpG?usp=sharing

References

[1] Tomoya Kamimura, Yuichi Ambe, Shinya Aoi, and Fumitoshi Matsuno. Body flexibility effects on foot loading based on quadruped bounding models. *Artificial Life and Robotics*, 20:270–275, 2015.

[2] Modeling of Walking Robots. https://youtube.com/playlist?list=PLn8PRpmsu08rdL7jwgrQjewdFXxDHbyIV&si=RFyg8I0hK0L6EaqH.

[3] Tomoya Kamimura, Shinya Aoi, Kazuo Tsuchiya, and Fumitoshi Matsuno. Body flexibility effects on foot loading in quadruped bounding based on a simple analytical model. *IEEE Robotics and Automation Letters*, 3(4):2830–2837, 2018.