Design of a compliant spine for the Locomorph quadruped robot

Semester Project

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Nature analysis

Cheetah spine bending during running
(Cheetahs on the Edge, Director’s Cut – National Geographic)

Two main reasons:

**Spine bending:** Increase stride length

**Compliance:** Flexible system = Shock absorption, Efficient use of energy
Goal

- Construction of an actuated and compliant spine for Locomorph robot
- Comparison of results: rigid spine/actuated spine (Speed variation, Energy consumption)

Cheetah bendable and compliant spine

+ Locomorph robot

Desired spine properties:
- Torque control
- Spring and actuation in serie
- Lightweight
- Configurable = compliance variation (“Morphosis”)

Robot specifications:
- Max frequency: 2Hz
- Max amplitude: 30°
Designs introduction

Design 1:
DC motor, timing belt, leaf-spring

Design 2:
DC motor, crank-slider, spring
Design 1: Bending mechanism

Primary actuator:
- DC motor
- Timing-belt

Secondary actuator:
- Leaf-spring (belt tension)
  “Morphosis system” = Changing leaf-spring length to change the effective bending for the same force.
Design 2: DC motor, crank-slider, spring

- Fix liaison
- Pivot liaison

- Encoder (torque control)
- Rigidity variation
- Pivot liaison

Ball bearing
Linear ball bearing

Top view
Side view
Zoom on slider (top view)
Design 2: Working principle
Design 2: Changing movement amplitude

Principle:
Sliding the attach point on the crank-slider = changing amplitude of leg movement
## Designs comparison

<table>
<thead>
<tr>
<th>Design 1: Timing belt + Leaf-spring</th>
<th>Design 2: Crank-slider + Linear springs</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Not continuous rotation</td>
<td>+ Continuous rotation</td>
</tr>
<tr>
<td>- Open loop</td>
<td>+ Close loop</td>
</tr>
<tr>
<td>+ Timing-belt for adapting gear ratio</td>
<td></td>
</tr>
<tr>
<td>- Requires timing belt loading mechanism</td>
<td></td>
</tr>
<tr>
<td>+ More flexible control of amplitude (timing belt)</td>
<td>- Changing amplitude require changing crank-slider geometry</td>
</tr>
<tr>
<td></td>
<td>- Torque of crank-slider changes depending on it’s extension</td>
</tr>
</tbody>
</table>

**Chosen mechanism:** Design 2 (Crank-slider + linear springs)
Design 2: Dimensioning

Boundary conditions:
- Spine length: ratio 2/3 (leg length/spine length), as in the cheetah
- Unavailable space next to the floor

Optimal actuator placement:
- Crank-slider attachment point close as possible to the leg structure
- Crank-slider force applied perpendicularly to the structure
- Actuator in the center: optimal weight distribution

![Diagram showing actuator placement and boundary conditions with dimensions and angles marked.]
Main components:
• Bending axis / ball-bearing
• Crank-slider mechanism
• Motor/ gearbox
Bending axis / ball bearing

Ball bearing:

a)  b)  c)

Bending axis:
- Steel Ø6mm

Flexion calculus: $P = 36N$ (mass of front legs)

$$f = \frac{Pl^3}{3EI} = 2.8\text{mm}$$

with

$$I_x = \frac{Pi \cdot d^4}{64}$$

$\Rightarrow$ Maximum flexion: 2.8mm
$\Rightarrow$ Need of stiffening structure
Crank-slider mechanism

Maximum torque on rotation axis:
• \( M = 7.4 \text{ Nm} \)

Changing amplitude: changing first segment length => slider
Motor / gearbox

Motor: Maxon EC-4pole 22
- Nominal torque: 64.9mNm
- Nominal speed: 15’600rpm

Planet. Gearbox: Maxon GP 32 C, 1-6 Nm, 111:1
- Reduction factor: \( I_{\text{reduction}} = 111 \)
- Max bending freq.: \( \frac{15'600}{111} = 140 \text{rpm} = 2.33Hz \)

\[
M_{\text{motor}} = \frac{M_{\text{crankslider}}}{I_{\text{reduction}}} = \frac{7.4}{111} = 66mNm
\]

Ideal case

Planet. Gearbox: Maxon GP 32 C, 1-6 Nm, 132:1
- Desired bending frequency: \( 2Hz = 120 \text{rpm} \)
- Needed reduction factor: \( I_{\text{reduction}} = \frac{15'600}{120} = 130 \)

\[
M_{\text{motor}} = \frac{M_{\text{crankslider}}}{I_{\text{reduction}}} = \frac{7.4}{130} = 57mNm
\]
Weight analysis

Weight: **1.24kg**
- Motorization: 223g
- Crank-slider: 149g (possible weight improvement)
- Structure: 868g (possible weight improvement)

=> Weight improvement: **60-120g** (5-10%)

Center of gravity: **2.4cm** (from center)
- Solution: slide the structure
Deformation analysis

Help of Massimo

a) Deformation scale: 1

b) Deformation scale: 44.1406

Applied force: 40N (leg weight 3.6kg + 10% margin)

=> Maximum deformation = 1.01mm
Stress analysis

Applied force: 40N (leg weight 3.6kg + 10% margin)

=> Maximum stress location = stiffening plate
## Goals summary

<table>
<thead>
<tr>
<th>Goals</th>
<th>Status</th>
<th>Solution / Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuated bendable spine</td>
<td>✓</td>
<td>DC motor + crank-slider</td>
</tr>
<tr>
<td>Possibility to change movement amplitude</td>
<td>✓</td>
<td>Slider</td>
</tr>
<tr>
<td>Possibility to change elastic behavior of the spine</td>
<td>✓</td>
<td>Clamping rings</td>
</tr>
<tr>
<td>Bending frequency</td>
<td>✓</td>
<td>1.85Hz</td>
</tr>
<tr>
<td>Bending amplitude</td>
<td>✓</td>
<td>30°</td>
</tr>
<tr>
<td>Possibly of torque controlled mechanism</td>
<td>✓</td>
<td>1 encoder on axis motor + 1 encoder on bending axis</td>
</tr>
<tr>
<td>Lightweight</td>
<td>✓</td>
<td>1.2kg, max improvement 5-10%</td>
</tr>
<tr>
<td>Build the mechanism</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Test and compare performances</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 1 - Design 1: Working principle

a) Motor rotation

b) 

c) Energy storage phase = leaf-spring bending

d) 

e) Energy release phase
Appendix 2 - Design 2: Working principle

a) Rotation phase - energy released

b) Energy storage phase

motor rotation

shortening


c) Rotation phase - energy released

d) Rotation phase

shortening

elongation


e) Rotation phase

f) Energy storage phase

shortening

elongation
Appendix 3 - Design 2: Changing stiffness mechanism

Options:
- 2 motors + worm-slider
- Clamping ring

Changing spring length = changing stiffness
Structure stiffening

Stiffening:
• Goal: Create a volume structure
• Carbon fiber plates (grid pattern=less weight)
• Fixation: POM parts screwed
Ball spline / linear springs

Ball-spline:
- **Pink**: fixation to the axis
- **Steel axis**: Ø8mm

Linear spring:
- **DIMENTIONNING**
- **DRAWING OF SPRING MOVEMENT**