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Optimizing energy consumption for legged robot by adapting equilibrium position and stiffness of a parallel torsion spring

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1 Introduction

This work addresses the energy inefficiency of legged robots. Locomotion still result in excessive energy consumption due to researchers have explored elastic elements, static heat loss and high motor loads. While many compliance mechanisms lack adaptability to varying conditions.

We propose a novel adaptive compliance system using a **torsion spring** integrated into a robotic leg's knee joint (see Fig. 1). This system dynamically adjusts the equilibrium position to reduce motor torque and enhance energy efficiency.

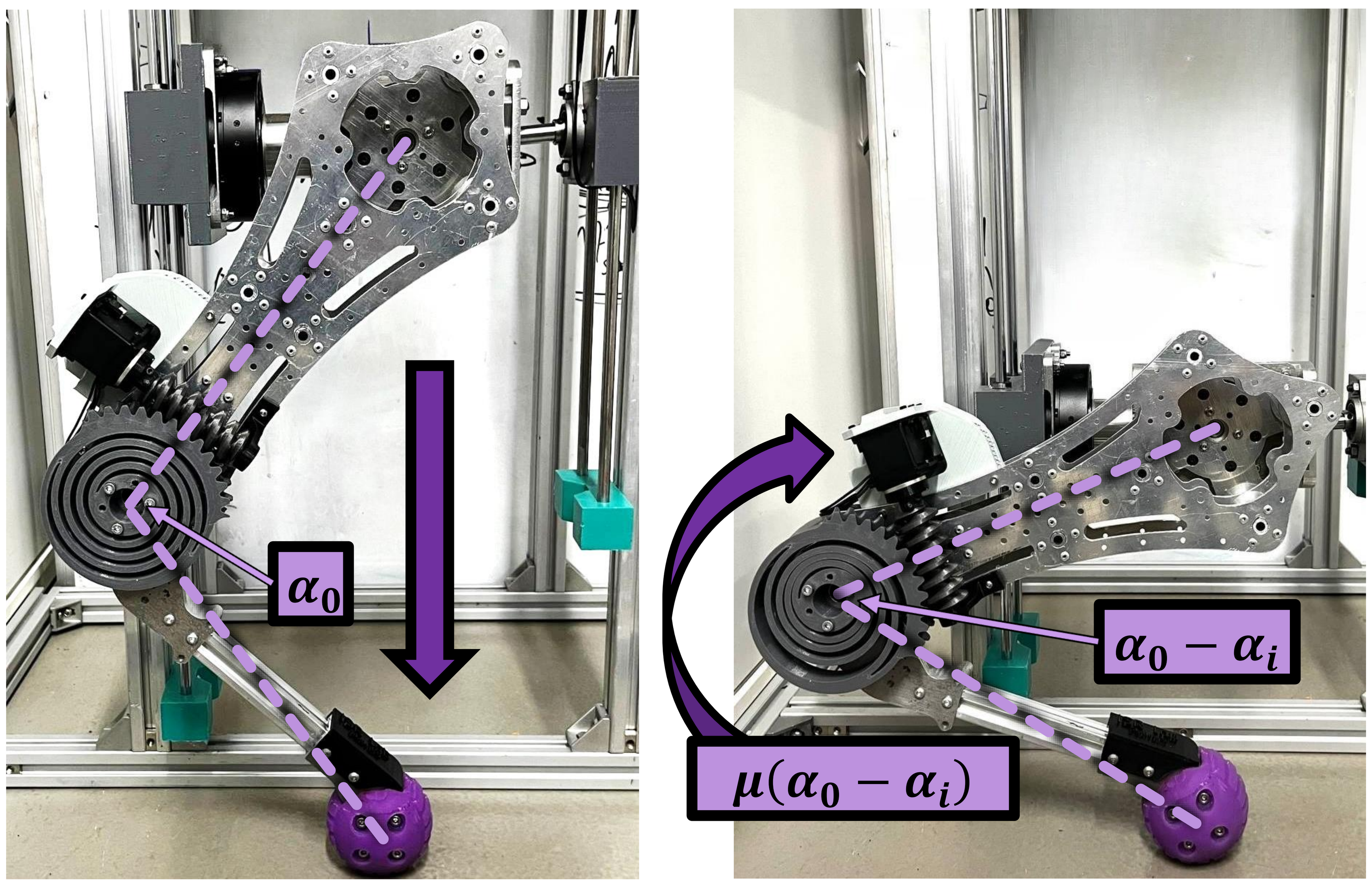

Fig. 1 – Principle of Torque Compensation of Parallel Torsion Spring

2 Method

At each step i, the actuator exerts a torque τ_i, and the knee joint has an angle α_i. Total energy consumption over the cycle is:

$$E = K \sum_{i=1}^{n} \tau_i^2 \cdot \Delta t$$

Where K is the motor-specific constant, Δt is the time step and n is the number of steps.

The **spring** applies a compensatory torque $\mu(\alpha_i - \alpha_0)$, where μ is the stiffness and α_0 is the equilibrium position. With the spring, the energy consumption becomes:

$$E = K \sum_{i=1}^{n} \left(\tau_i - \mu(\alpha_0 - \alpha_i)\right)^2 \cdot \Delta t \qquad \frac{\partial E}{\partial \alpha_0} = 0 \xrightarrow{\text{yields}} \alpha_0^*$$

3 Results

The experiments demonstrate that incorporating an adaptive torsion spring mechanism significantly reduces energy consumption during cyclic movements. By optimizing stiffness μ^* and equilibrium position α_0^* using a closed-form solution, the proposed approach showed a decrease in actuator torque under various conditions (e.g., mass, oscillation frequency, and amplitude).

Key findings include:

• The ratio of energy consumption with the optimal spring to the baseline without the spring ranged from 0.15% to 3.9%, depending on test parameters.

• Even in conditions with increased load or frequency, the spring reduced torque demands, thereby extending component longevity and improving system efficiency.

The results are summarized in Table 1 and Figure 2, illustrating the reduction in motor torque and energy consumption across multiple scenarios.

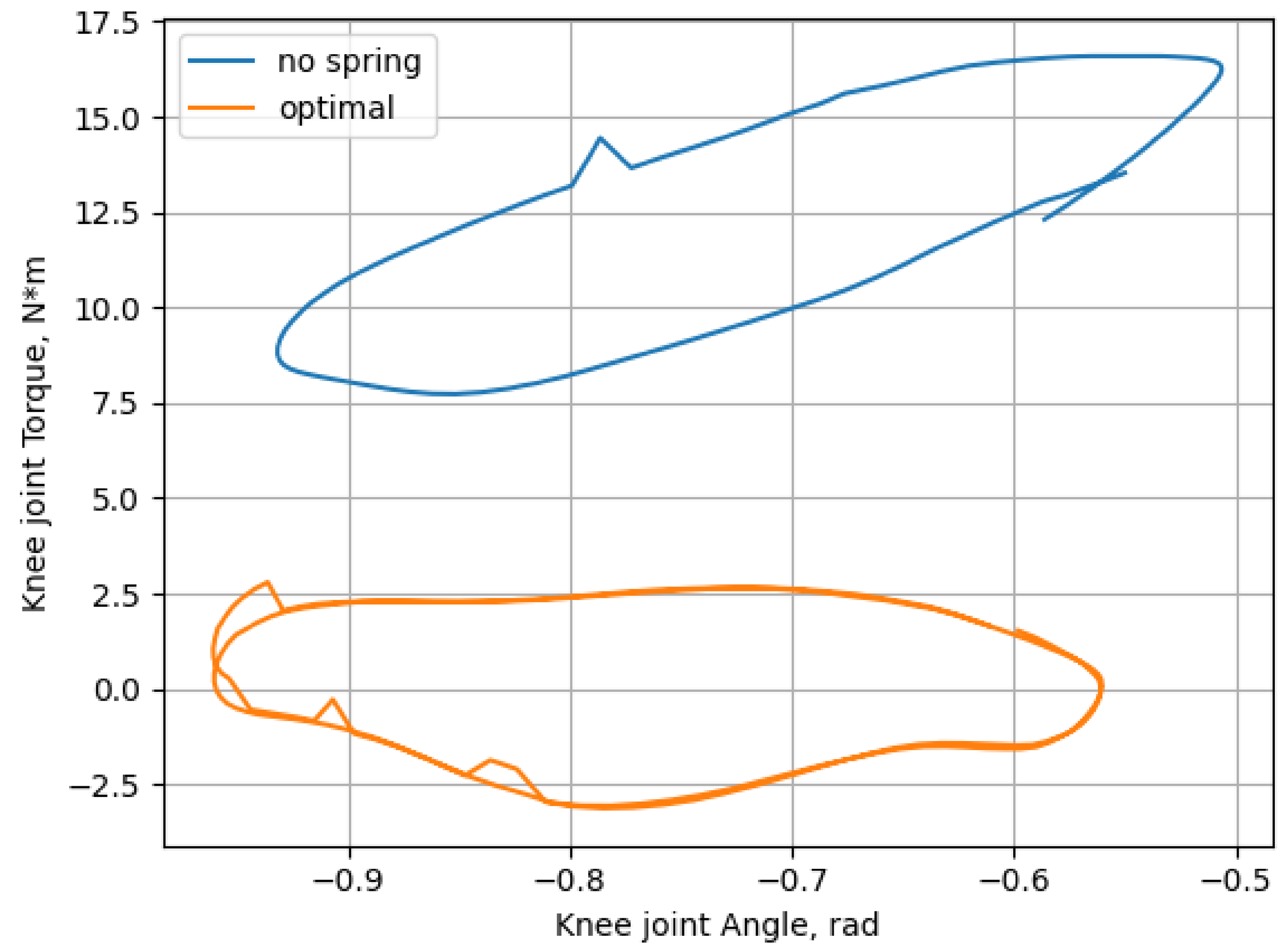

Fig. 2 – Comparison of knee motor torques during a single cyclic motion without and with a spring

The negative torque values on the trajectory graph are explained by the motor working against the spring.

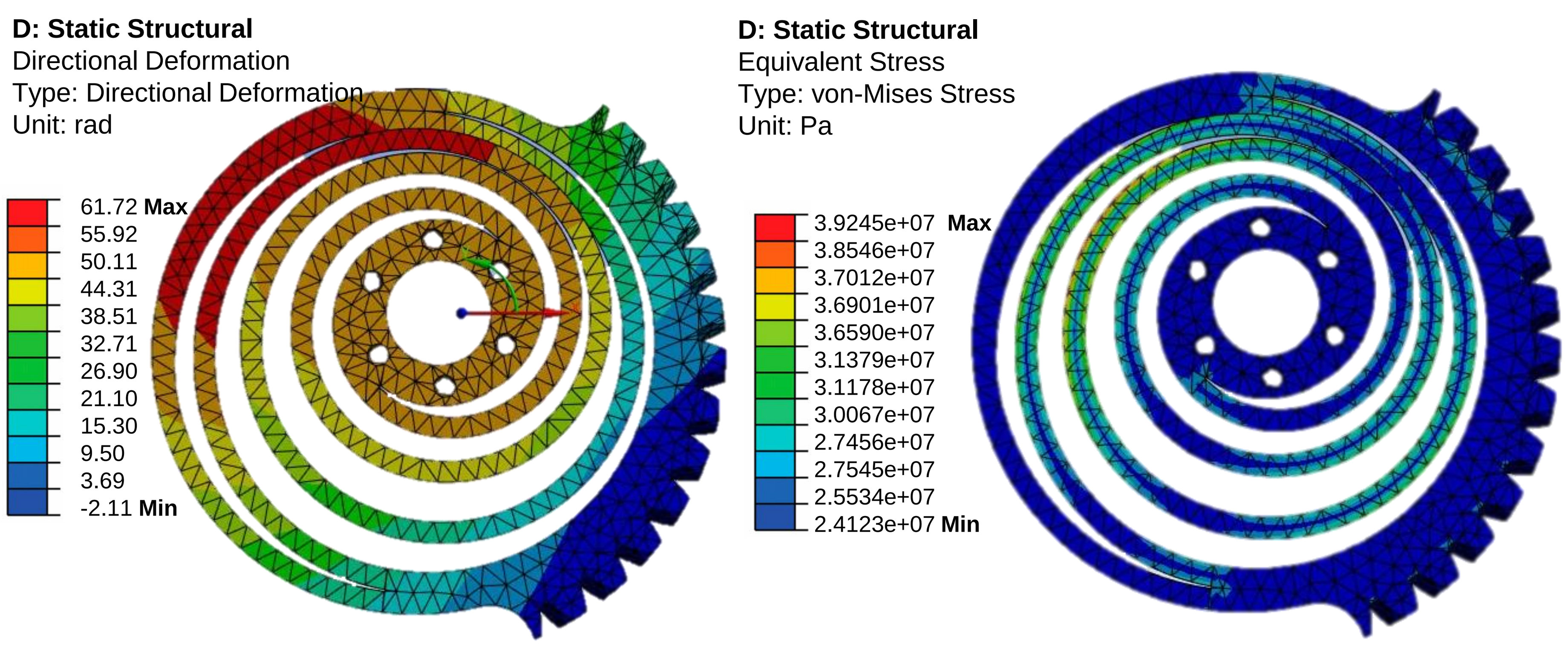

Fig. 3 – Finite Element Analysis (FEA) of a Spring for the Extreme Case.

Figure 3 presents finite element calculations for the case when the robot's leg is fully folded.

Table. 1 – Comparison of the robot's performance under different circumstances **(Varying Mass** m, **Oscillation Frequency** f, **Amplitude** A and **Starting Height** h_0) with and without the spring.

m, kg	f, Hz	A, m	h_0, m	E	E^*	μ^*, $\frac{\text{N}\cdot\text{m}}{\text{rad}}$	α_0^*, rad
4.1	1.88	0.05	0.2	2285.9	14.2	8.56	-2.23
4.1	1.88	**0.08**	0.2	2114.2	30.2	8.77	-2.15
4.1	1.88	0.05	**0.15**	2627.1	103.1	7.05	-2.52
8.1	1.88	0.05	0.2	6813.9	44.1	13.78	-2.28
4.1	**0.94**	0.05	0.2	2365.2	44.7	17.1	-1.4
4.1	**3.77**	0.05	0.2	4193.6	6.4	6.07	-2.84

4 Conclusion

The integration of a parallel adaptive spring mechanism into a robotic leg demonstrates significant potential for reducing energy consumption during cyclic movements. The experiments showed that the use of the spring reduces energy consumption over than 90% in the simulation.
By dynamically adjusting stiffness and equilibrium position, the system minimized motor torques, enhancing energy efficiency and adapting to variable conditions. These results validate the approach, and the prototype demonstrates the feasibility of implementing such an adaptive system in robotic legs. Future work will explore extending the method to multi-joint systems.