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# A New Mechanical Design for Legged Robots to Reduce Energy Consumption

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Many legged robots have been designed and built by universities, research institutes and industry; however, few investigations regard energy consumption as a crucial design criterion. This paper presents a novel configuration for legged robots to reduce the energy consumption. The proposed leg can be either used as a single leg or easily attached to bodies with four, six and eight legs. This mechanism is a parallel four-bar linkage equipped with one active and four passive joints. In fact, the usage of the passive elements leads to simple feed-forward control paradigms. Moreover, another distinctive feature of this design is the arrangement of one-way clutches and flat springs to store the potential energy for utilizing it in the next step. A locomotion prototype of the proposed mechanical structure is built and its simulation is also presented in this paper. Comparing the results with other structures demonstrates the superiority and efficiency of this work regarding energy consumption problem.

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## 1. INTRODUCTION

Multi-legged robots exhibit many advantages over wheeled and tracked counterparts on natural terrains. However, current implementations have the disadvantage of achieving poor energy efficiency along with the fact that walking robots are relatively complex compared to the wheeled and tracked robots [1-5]. In other words, the energy consumption plays a key role in the design and development of walking robots in regard to not only electronics systems and control algorithms but mechanisms as well [6]. Different approaches have been employed by a number of researchers to enhance the energy efficiency for the multi-legged robots [7-11]. One of these techniques is the employment of energy storage devices to recover the energy. Alexander [12] and Shin and Streit [13] are among the first investigators who used the springs to decrease the power demand in the legged robots. A 2D monopod, which uses leg and hip compliances has been designed [14] and implemented in [15]. This plan saves the energy in the leg and hip actuators and presents more efficient locomotion. Linear rotational springs have been implemented to store and release the kinetic and potential energy of the body and legs during each gait cycle for multi-legged walking vehicles [16]. Furthermore, series of elastic actuators have been implemented for biped robots in order to store a part of the impact energy, preserving the gait efficiency and stability [17,18]. Hyon and Mita [19] have proposed a one-legged running robot that contains an articulated leg, two hydraulic actuators as muscles and a tensile spring as a tendon. Iida and Pfeifer [20] have described a four-legged robot model and successfully applied the elastic materials for making efficient the rapid locomotion. In an under actuated one-legged hopping robot model has been proposed for researching the utilization of the elastic energy of flexible mechanical systems, repeatedly [21]. Scarfogliero et al. [22] have implemented compliant joints and elastic elements to store the energy in bio-inspired legged robots. A completely passive model has been introduced in literature [22] to reuse a part of the impact energy. He and Geng have studied the design and the applications of elastic underactuated mechanisms for improving the energy efficiency of a one-legged hopping robot [23]. In [24], spring clutches have been utilized in all active leg

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joints to absorb unused kinetic energy (maximum torque) and transmit it to the joints. Gürel et al. [25] have studied the trade-off between the cycle time and the energy consumption of a robot that produces identical parts in a robotic cell for loading and unloading of machines. A task energy characteristic model has been suggested by Cao et al. [26] as a polynomial function of the feedrate override to forecast the energy consumption of the polishing process. Sun et al. [27] have addressed an energy efficient robotic assembly line balancing problem with some criteria to minimize both the cycle time and total energy consumption. A mathematical model of the total energy consumption of cycle pick-and-place tasks, which considers operating motion and homing motion of a given trajectory with different joint configurations has been investigated by Feng et al. [28].

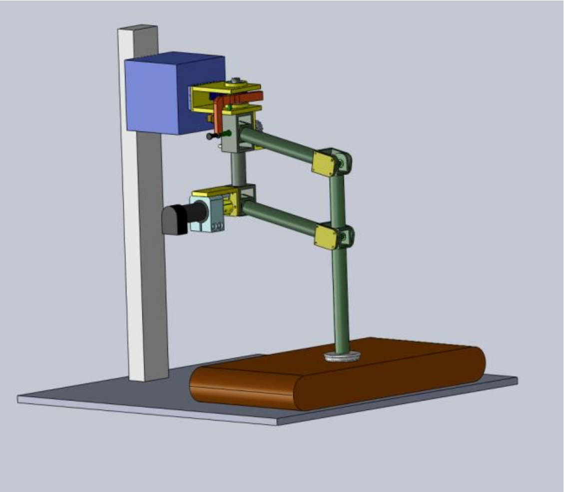
From this literature survey, it is obvious that improvement of the energy efficiency is an important factor, especially for the legged robots. Here, in an attempt to reduce the energy consumption via applying elastic springs and decreasing the number of actuators, a parallel four-bar linkage is proposed for the leg of the walking robots. In this model, there are four passive joints and only one active joint. A motor is installed on the location of the active joint and used to move the leg vertically. Further, the kinetic energy of the leg is stored as the elastic potential energy in the flat springs and applied to move it to forward. To the best of authors' knowledge, this is the most successful work to consider the energy-efficient problem for multi-legged robots, and conduct and implement experiments in a real-life environment.

The rest of the paper is organized as follows. Section 2 deals with mechanical design of the proposed one-leg model. The dynamical motion equations are explained in Section 3. Experiments and simulation results in the 20-sim software environment are compared in Section 4. Some concluding remarks are made in Section 5.

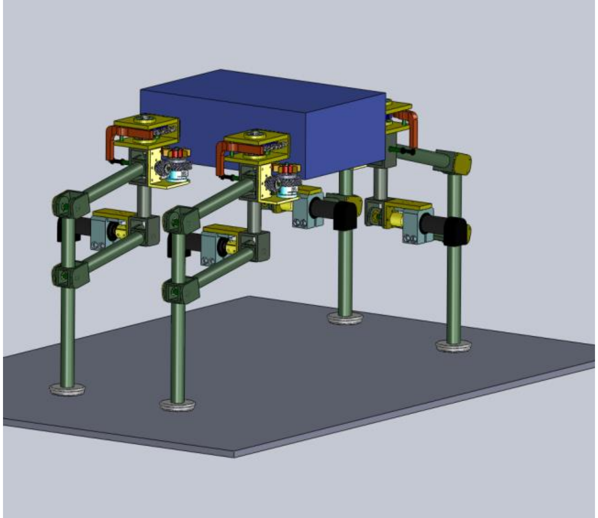
## 2. MECHANICAL DESIGN

The proposed leg is an ultra-lightweight mechanism and can be either used as a single leg (as a test-bed for general robotic research) or combined in quadruped, hexapod or octopod constructions (Figure 1). This model is a parallel four-bar linkage that has one active and four passive joints, i.e. the first, second, third and fourth joints' axes are parallel to each other and perpendicular to the fifth joint's axis (Figure 2). The first, second, third and fourth links are about 150 mm, 100 mm, 100 mm and 150 mm long, respectively. This skeleton is made of the Delrin rod with an easy snap-in system construction. The overall weight of the leg is about 500g. Furthermore, a motor is installed on the location of joint 3 and used to move the leg vertically. This motor is rated at 20 W (MAXON DC motor), coupled through a one stage 4.8:1 planetary gear head and has a three-channel encoder (MAXON HED_5540 encoder). When link 2 moves, then link 3 will rotate parallel to it around joint 4. A series of mechanisms is prepared on the location of joint 4 to store and transfer energy via the created torque on this joint.

At first, when the leg is going up by the motor, the first one-way clutch between the shaft and helical gear 1 does not transmit any torque (Figure 3). However, when the leg is going down, then the power is transmitted to the helical gears (ratio 2:1) through this clutch. In this situation, the second one-way clutch between the support and the shaft allows the shaft to rotate (similar to Figure 3), and the impact and kinetic energies of the leg will be stored as elastic potential energy in the flat spring set (Figure 2). During this locomotion, the gear lock mechanism is locked, and only when the leg is near the maximum height, this mechanism is opened by a cable,

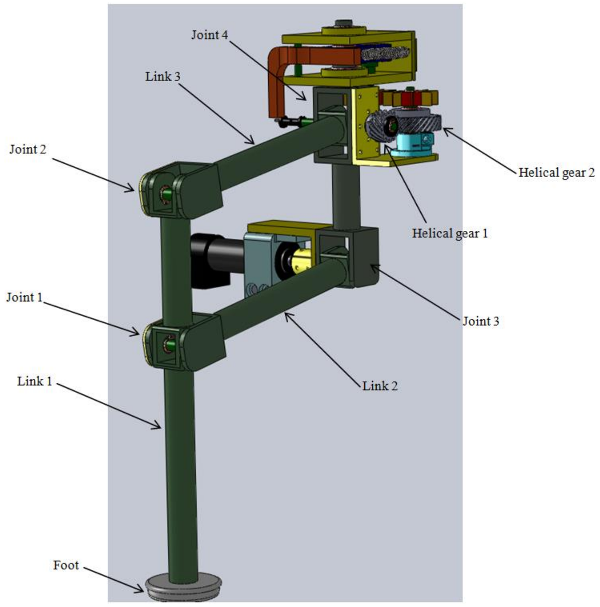


(a) Used as a test-bed for general robotic researches

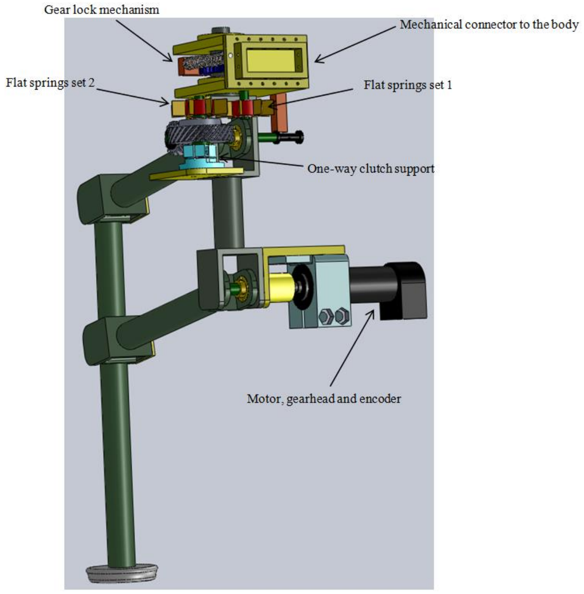


(b) Attached to a multi-legged body

**Figure 1.** Different applications of the proposed leg



(a) Front view



(b) Back view

**Figure 2.** An overview of the proposed leg

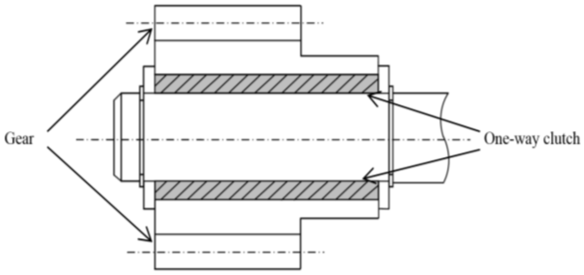


**Figure 3.** Structure of a one-way clutch with a gear and a shaft

and the elastic potential energy is released. Via two spur gears (ratio 1:1); this power will be transferred to rotate the leg to forward.

## 3. MATHEMATICAL MODELLING AND DYNAMICAL MOTION EQUATIONS

Figure 4 shows a simple configuration of the robot model (four links and five joints) that we use to represent a single leg of our walking robot. In this figure, $\theta$ and $\gamma$ represent the angles of link 2 with respect to $x$ and $z$ axis, respectively.

In order to derive the mathematical dynamic equations of the model, Lagrange's formulation [29] is used:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i \tag{1}$$

where, $L = K - P$ is the Lagrangian function. $K$ and $P$ are the kinetic and potential energy functions, respectively. $q_i$ denotes the generalized coordinate of the system, and $Q_i$ represents the corresponding external force/torque .

Initially, it is supposed that the proposed leg is gone up by the motor; therefore, the generalized coordinate is $q_1 = \theta$, and the corresponding external torque is $Q_1 = \tau_m$ ($\tau_m$ is the motor torque). Thus, the kinetic energy could be achieved by the following formulation:

$$K = \sum_{i=1}^{3} [\frac{1}{2} m_i v_i^2 + \frac{1}{2} J_i^z \dot{\theta}^2] \tag{2}$$

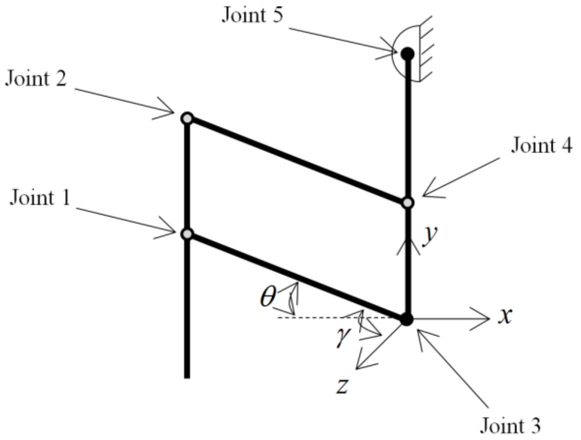


**Figure 4.** Frame assignment of the leg model. Black circles denote the actuated joints (joint 3 is actuated by a motor and joint 5 actuated by flat springs) and white circles show the passive joints

where, $i$ indicates the link number, $v_i$ is the velocity of the mass centre of link $i$ th. $m_i$ is the mass of link $i$th. Moreover, $J_i^z$ is the inertia moment of link $i$th with respect to rotation around $z$ axes. It is obvious that link 1 has a pure transfer motion, and $J_1^z = 0, v_1 = l_2\dot{\theta}$. Links 2 and 3 have pure rotation motion and $v_2 = \frac{1}{2}l_2\dot{\theta}, v_3 = \frac{1}{2}l_3\dot{\theta}$. That $l_i$ $(i = 1,2,3,4)$ indicates the length of link $i$ th. Therefore:

$$K = \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 + \frac{1}{2}J_2^z\dot{\theta}^2 + \frac{1}{2}m_3v_3^2 + \frac{1}{2}J_3^z\dot{\theta}^2 \tag{3}$$

Or

$$\begin{aligned} K &= \frac{1}{2}m_1(l_2\dot{\theta})^2 + \frac{1}{2}m_2(\frac{1}{2}l_2\dot{\theta})^{2\,2} \\ &+ \frac{1}{2}J_2^z\dot{\theta}^2 + \frac{1}{2}m_3(\frac{1}{2}l_3\dot{\theta})^2 + \frac{1}{2}J_3^z\dot{\theta} \end{aligned} \tag{4}$$

Furthermore, the potential energy function can be computed as follows.

$$\begin{aligned} P &= m_1gl_2\sin(\theta) + m_2g(\frac{1}{2}l_2\sin(\theta)) \\ &+ m_3g(\frac{1}{2}l_3\sin(\theta)) \end{aligned} \tag{5}$$

Thus,

$$\frac{\partial L}{\partial\dot{\theta}} = [J_2^z + J_3^z + \frac{1}{4}(4m_1l_2^2 + m_2l_2^2 + m_3l_3^2)]\dot{\theta} \tag{6}$$

And

$$\frac{\partial L}{\partial\theta} = -\frac{1}{2}[2m_1l_2 + m_2l_2 + m_3l_3]g\cos(\theta) \tag{7}$$

Finally, the equation of motion for the leg with respect to generalized coordinate $q_1 = \theta$ results in:

$$\begin{aligned} &[J_2^z + J_3^z + \frac{1}{4}(4m_1l_2^2 + m_2l_2^2 + m_3l_3^2)]\ddot{\theta} \\ &+ \frac{1}{2}[2m_1l_2 + m_2l_2 + m_3l_3]g\cos(\theta) = \tau_m \end{aligned} \tag{8}$$

Secondly, it is supposed that the proposed leg is moved forward by the flat springs; therefore, the generalized coordinate is regarded as $q_2 = \gamma$, and the corresponding external torque is defined as $Q_2 = \tau_s$ ($\tau_s$ is the flat spring torque). Via a procedure similar to the first generalized coordinate, the motion equation of the leg for second generalized coordinate $q_2 = \gamma$ results to:

$$(J_1^y + J_2^y + J_3^y + J_4^y)\ddot{\gamma} + C\dot{\gamma} = \tau_s \tag{9}$$

where, $J_i^y$ $(i = 1,2,3,4)$ is the inertia moment of link $i$ with respect to axes $y$. $C$ is the coulomb friction coefficient of the spur gears.

## 4. EXPERIMENTAL AND SIMULATION RESULTS

Figure 5 shows the one-legged robot designed and built based on the leg model proposed in the previous sections at the Robotics and Mechatronics (RAM) group, University of Twente. Its main specifications are given in Table 1. Moreover, the simulation of this model is conducted in 20-sim-4.2 to reflect the essential characteristics of the real robot in the 3D environment. It consists of four links and five joints in which the third joint is actuated by a motor and the fifth joint is actuated by a spring (compare Figure 2 with Figure 6). In Figure 6, a dynamical model of the one-legged robot is provided in the 20-sim 3D mechanics toolbox. Furthermore, Figure 7 shows a complete model of the proposed mechanism in the graphical editor environment of the software. Here, a spring and motor torque are used to actuate joints 3 and 5, respectively. Non-ideal gearbox mechanisms are applied to simulate planetary, spur and helical gears. Furthermore, to control the motor torque, a simple Proportional Derivative (PD) controller with coefficients and is implemented. The observations show

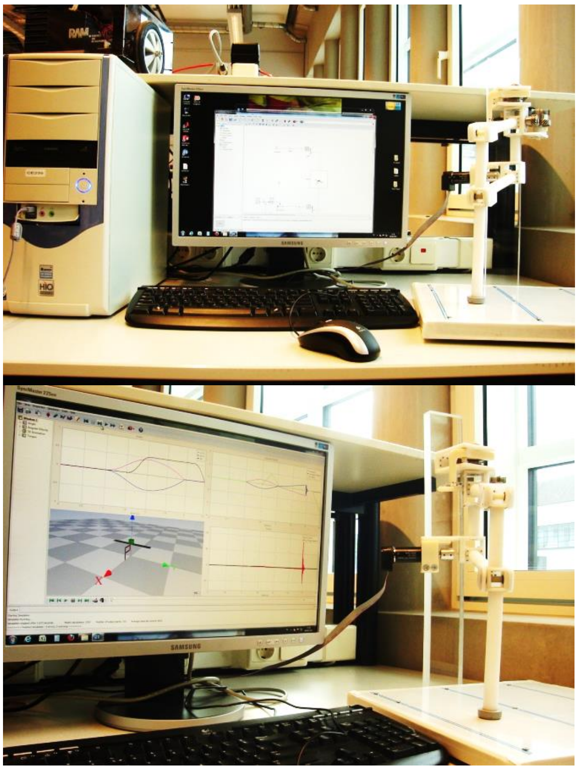


**Figure 5.** One-legged robot prototype developed at RAM group, University of Twente, the Netherlands

**TABLE 1.** Specifications of the leg model

| Parameter | Description | Value |
|---|---|---|
| $m_1$ | Mass of link 1 | 91.16 g |
| $m_2$ | Mass of link 2 | 68.45 g |
| $m_3$ | Mass of link 3 | 68.45 g |
| $m_4$ | Mass of link 4 | 60.05 g |
| $l_1$ | Length of link 1 | 293 mm |
| $l_2$ | Length of link 2 | 220 mm |
| $l_3$ | Length of link 3 | 220 mm |
| $l_4$ | Length of link 4 | 193 mm |
| $C$ | Coulomb friction coefficient | 0.07 |
| $r$ | Radius of the rod for the skeleton | 18 mm |
| $k$ | Flat spring constant | 36.6 N/mm |
| $\eta_1$ | Spur gears efficiency | 0.9 |
| $\eta_2$ | Helical gears efficiency | 0.8 |
| $\eta_3$ | Planetary gear head efficiency | 0.8 |
| $g$ | Gravity acceleration | 9.81 m/s$^2$ |

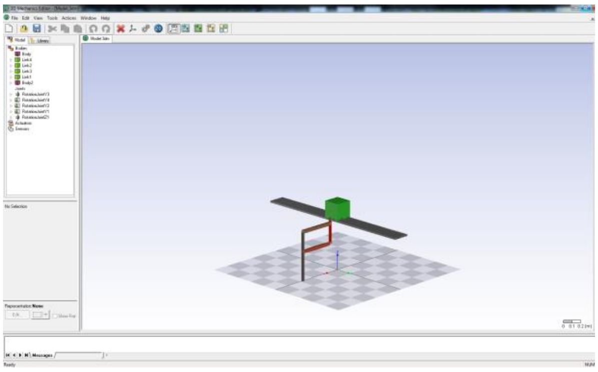
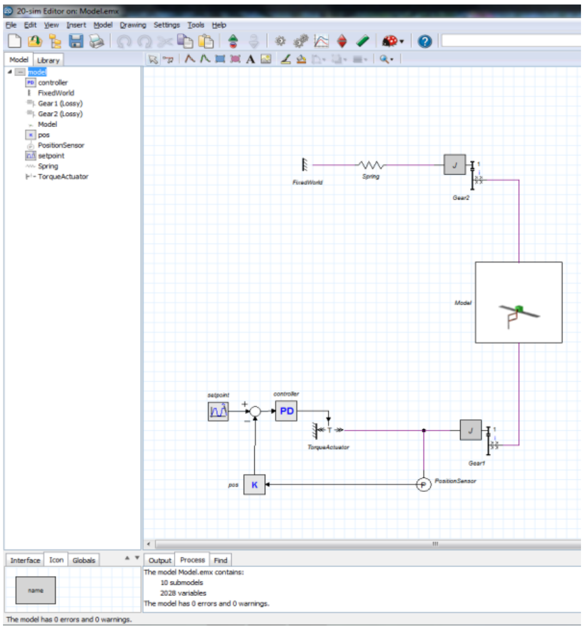


**Figure 6.** Proposed leg model in the three-dimensional mechanics toolbox of 20-sim software

that the simulated dynamical locomotion is fairly comparable to the real one.Figure 8 illustrates the typical time responses of the joint angles which characterize the movement of the robot body. As shown in this figure, the motor brings leg up during 1s to about 25 degrees. Then, the leg will go down in about 1s. Furthermore, when the leg is near the maximum height, the elastic potential energy is realized, and the leg rotates forward at about 37 degrees. Moreover, all angles go back to the beginning state of the of the leg step cycle, which ensures a periodic gain pattern.

The observations in Figure 9 further validatee the previous simulation results. In this figure, the electrical energy transforms to the gravity potential and kinetic energies of the leg between 1s and 2s. During this



```
The model Model.emx contains:
    10 submodels
    2028 variables
The model has 0 errors and 0 warnings.
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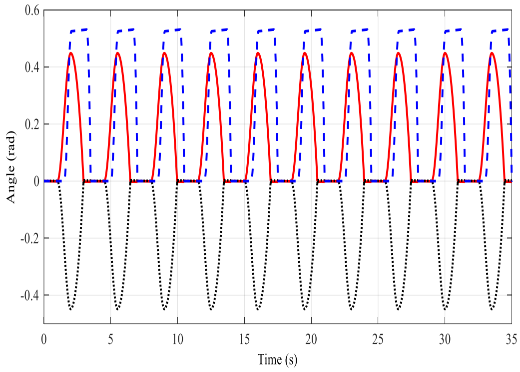
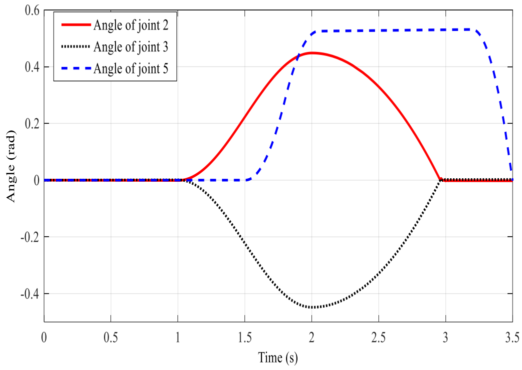
The model has 0 errors and 0 warnings.

**Figure 7.** A model of the proposed mechanism in the graphical editor environment of 20-sim



(a) ten leg step cycles



(b) one leg step cycle

**Figure 8.** Time responses of the joint angles during different step cycles

locomotion, the gravity potential energy changes from a minimum value ($P = 0$) to a maximum value ($P = 0.15j$), and the kinetic energy oscillate between a minimum value ($K = 0$) and a maximum value ($K = 0.0021j$). The elastic potential energy of the flat springs modelled as linear springs is realized between 1.75s and 2s. After 2s, the gravity potential, kinetic and impact energies of the leg transform to the elastic potential energy of the spring.

In the following, in order to complete our comprehensive behavior analysis, we compare our proposed structure with two other models in the term of the energy consumption. The first model shown in Figure 10(a) has been used in References [30-32] (first structure). This model has two active joints and three passive joints. Besides, the second model illustrated in Figure 10(b) has been applied in References [33, 34] and has three active joints (second structure). In this two models, all actuated joints are activated by the electrical motors, whereas the proposed structure has two stimulated joints that one of them implements the potential energy saved in the flat springs, and only the other one has a motor. The main specifications of these models are determined similar to our model such that their torque demands are comparable. Figure 11 shows a complete 20-sim model of these mechanisms in the graphical editor environment. Table 2 illustrates the simulation results in terms of the energy consumption for three different models in the one leg step cycle. From this table, we can see that our model can achieve an average of 2.5371 and 4.2897 times reduction for the energy consumption compared to the first and second structures, respectively.

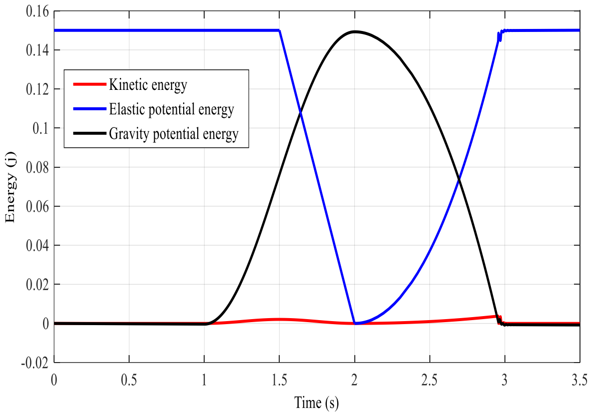
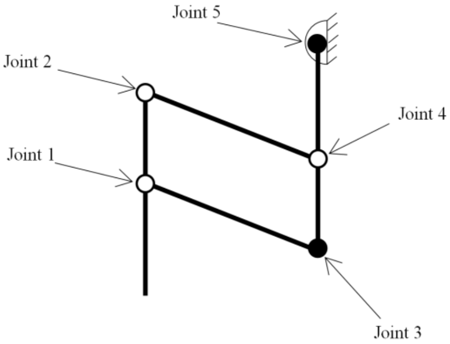
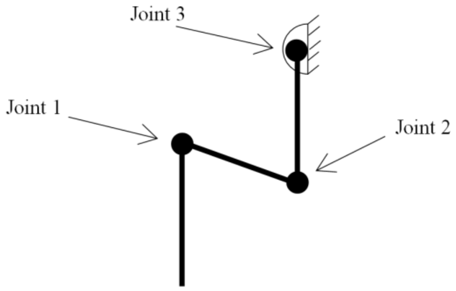


**Figure 9.** Time responses of the energy of the leg during one leg step cycle with respect to the first generalized coordinate

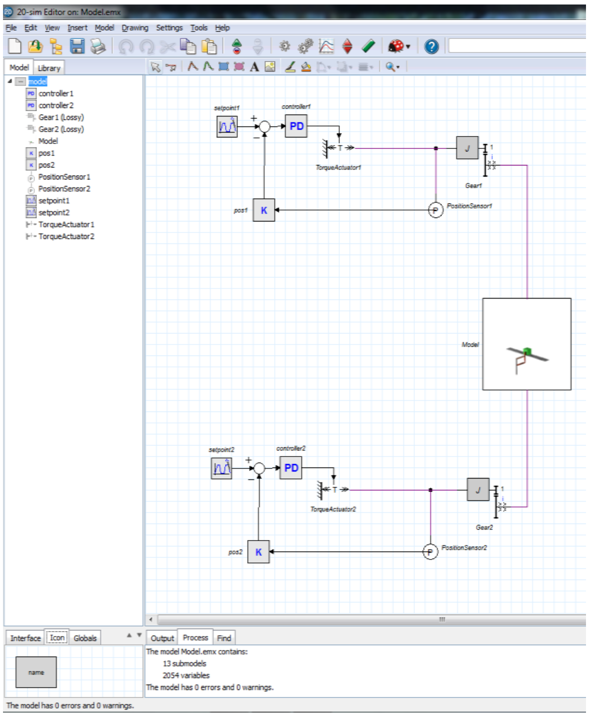


(a) First structure used in References [26-28]



(b) Second structure utilized in References [29,30]

**Figure 10.** Structures applied to compare with the proposed model. Black circles denote actuated joints and white circles represent passive joints



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    2054 variables
The model has 0 errors and 0 warnings.
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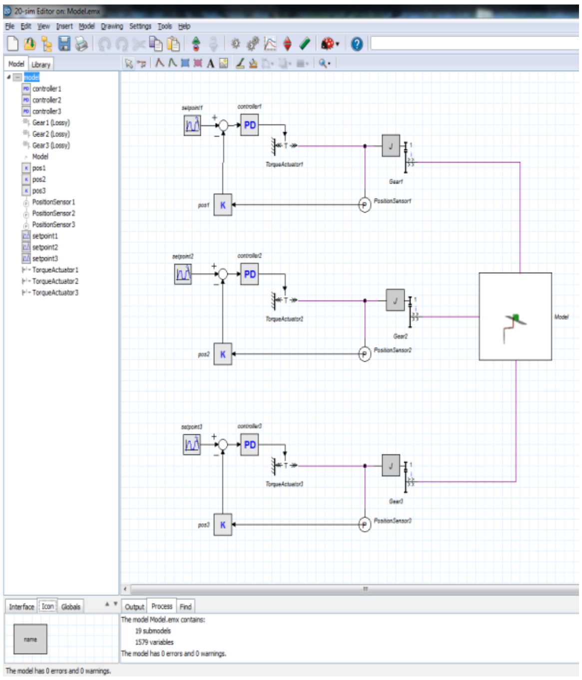
The model has 0 errors and 0 warnings.

(a) First structure implemented in References [26-28]



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The model Model.emx contains:
    19 submodels
    1579 variables
The model has 0 errors and 0 warnings.
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The model has 0 errors and 0 warnings.
```

(b) Second structure employed in References [29,30]

**Figure 11.** 20-sim models of the compared mechanisms

**TABLE 2.** Comparison of the energy consumption for the different models

| Model | Energy consumption (J) |
|---|---|
| First structure (Figure 10(a)) used in References [26-28] | 0.8924 |
| Second structure (Figure 10(b)) used in References [29,30] | 1.3346 |

## 5. CONCLUSIONS

The legged robots are preferred to the wheeled robots to move through environments which generally contain some irregularities. In such an environment, the legged robots offer better mobility than their wheeled counterparts. In the legged robot design, one of the most challenging problems is minimization of the energy consumption. A reduction in energy consumption results in robots thatcan not only travel more, but also require smaller actuators that typically yield a reduction in the robot's weight and cost. The main objective of the present study is to minimize the energy consumption of the multi-legged robots through the storing and releasing of the kinetic and potential energy of the leg during each cycle. The passive and elastic elements have been adapted to strongly increase the robots performances and keep it simple and cheap. The dynamical modelling of the proposed one-legged robot has been provided in the 20-sim 3D mechanics toolbox. Moreover, a real world sample of it has been successfully built at the Robotics and Mechatronics (RAM) group, University of Twente. The analyses of the results have demonstrated that this structure operates considerably better in terms of power demand in comparison with those introduced in the literature.

## 6. ACKNOWLEDGMENTS

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## Persian Abstract

### **چکیده**

روبات‌های دارای پا پادار بسیاری توسط دانشگاه‌ها، موسسات تحقیقاتی و صنایع طراحی و ساخته شده‌اند. با این حال، تحقیقات نسبتاً کمی بر روی مصرف انرژی این‌گونه ربات‌ها به عنوان یک معیار اساسی انجام شده است. در این مقاله، پیکربندی جدیدی برای ربات‌های دارای پا پادار به منظور کاهش مصرف انرژی در آن‌ها ارائه شده است. ساختار مکانیکی پیشنهادی را می‌توان به عنوان یک پا استفاده کرد یا به‌راحتی به ربات‌های دارای چهار، شش و هشت پا متصل نمود. این مکانیزم، یک اتصال چهار میله‌ای موازی مجهز به یک مفصل فعال و چهار مفصل غیرفعال است. در واقع، به‌کارگیری عناصر غیرفعال منجر به پارادایم‌های کنترل پس‌خور ساده می‌شود. علاوه‌براین، یکی دیگر از ویژگی‌های بارز این طرح، چیدمان کلاچ‌های یک‌طرفه و فنرهای تخت برای ذخیره انرژی پتانسیل به منظور استفاده از آن در مرحله بعد است. یک نمونه اولیه از مکانیزم مکانیکی پیشنهادی ساخته شده و شبیه‌سازی آن نیز در این مقاله ارائه شده است. مقایسه نتایج با سایر ساختارها، برتری و کارایی کار حاضر را از نقطه نظر کاهش مصرف انرژی نشان می‌دهد.