A clutched parallel elastic actuator concept: Towards energy efficient powered legs in prosthetics and robotics

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A clutched parallel elastic actuator concept: towards energy efficient powered legs in prosthetics and robotics

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***Abstract*— Parallel passive-elastic elements can reduce the energy consumption and torque requirements for motors in powered legged systems. However, the hardware design for such combined actuators is challenged by the need to engage and disengage the parallel elasticity depending on the gait phase. Although clutches in the drive train are often proposed, compact and low cost solutions of clutched parallel elastic actuators have so far not been established. Here we present the design and control of an initial prototype for a parallel elastic actuator. The actuator combines a DC motor with a parallel spring that is engaged and disengaged by a commercially available, compact and low-cost electric clutch. In experiments that mimic the torque and motion patterns of knee extensor muscles in human rebounding tasks we find that the parallel spring in the prototype reduces the energy consumption of the actuator by about 80% and the peak torque requirement for the DC motor by about 66%. In addition, we find that a simple trigger-based control can reliably engage and disengage the electric clutch during the motion, allowing the spring to support the motor in rebound, to remove stored energy from the system as necessary for stopping, and to virtually disappear at the actuator output level. On the other hand, the hardware experiments also reveal that our initial design limits the precision in the torque control, and we propose specific improvements to overcome these limitations.**

I. Introduction

Parallel elastic elements have the potential to largely reduce power and torque requirements for actuators that drive cyclic motions in legged systems [1], [2]. For example, [2] report for the design of an exoskeleton a theoretical reduction in peak torque requirements of 48% for ankle actuation and up to 66% for hip actuation when using parallel springs around these joints in addition to motors. Other examples that exploit parallel elasticity to reduce actuation requirements include the Virtual Scenario Haptic Rendering Device of TU Munich [3], the gravity compensating mechanism in the knee joint of the robot Saika-4 [4], and the powered ankle-foot prosthesis of MIT [5], [6].

A disadvantage of parallel elastic actuators (PEAs) is that they limit movement dexterity. As the parallel spring is always engaged, these actuators tend to recoil elastically stored energy and force joint motions that counter desired ones in acyclic movements. For example, PEAs that act against gravity in legged systems clearly benefit from elastic store and recoil to push off in steady locomotion, but require large active torques to counter the elastic recoil for rapid stopping in stance or leg placement in swing. To overcome this limitation of PEAs, [1] suggest further investigation of "mechanisms with position-dependent clutch function". And although strategies for engagement and disengagement of elasticities [7], [8], [9], [10], [11], [12], [13], [14], [15] have been proposed, a low-cost, low-complexity, and low-weight compact solution for a clutched parallel elastic actuator (CPEA) has not been established.

We seek to develop such a compact solution for low energy and light weight actuation in powered legs for humanoid robots and prosthetic limbs, and present the design and control of an initial prototype actuator. In this concept study, a commercially available, compact and low-cost electric clutch used in copier machines (Reell EC30XP) was used to engage and disengage a spring in parallel with a Maxxon RE40 motor. The actuator is specified to meet the dynamically scaled performance of the vastus muscle group, the largest muscle group in the human leg, for a humanoid system of half the size of a human and a quarter of its weight.

The main purpose of this work was to assess the possible reduction in energy consumption by employing the passive elasticity compared to an actuator generating all the required torque actively. Hereto, we first present the design and develop a simple trigger-based control of the CPEA (section II), and then compare its performance in simulation and hardware experiments for characteristic leg rebounding motions like hopping and running, as well as sudden stopping maneuvers (section III). The results show that the prototype actuator reduces the energy consumption up to about 80% in rebounding motions and that the implemented design and control can cope with sudden clutch disengagements under full load for stopping (section IV). The clutch disengagement does not work as well in the experiments as in the simulation since our actuator test bed introduces unmodelled elasticities and friction forces. We discuss in section V improvements to overcome these issues and propose a compact design of a concentric clutch mechanism to integrate the clutched parallel elasticity in the drive train of rotary series elastic actuators frequently used in robotic leg systems.

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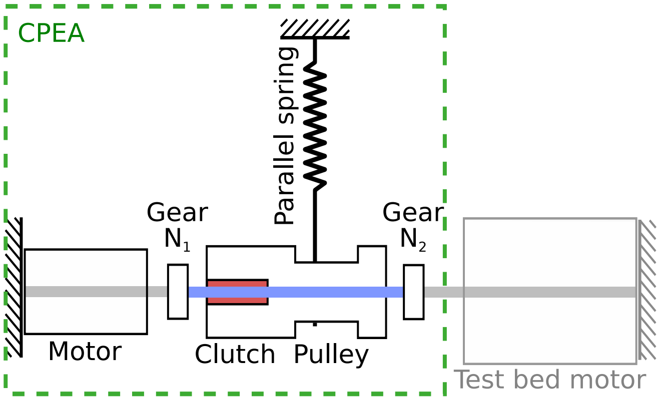

Fig. 1. Schematic of the CPEA (inside dashed box) and test bed. If the clutch is disengaged, the shaft (blue) connecting the two gear stages can rotate independent of the pulley. Only when the clutch is engaged, the pulley rotates together with the shaft, thus extending the spring. The gear ratios are $N_1 = 4$ and $N_2 = 9$.

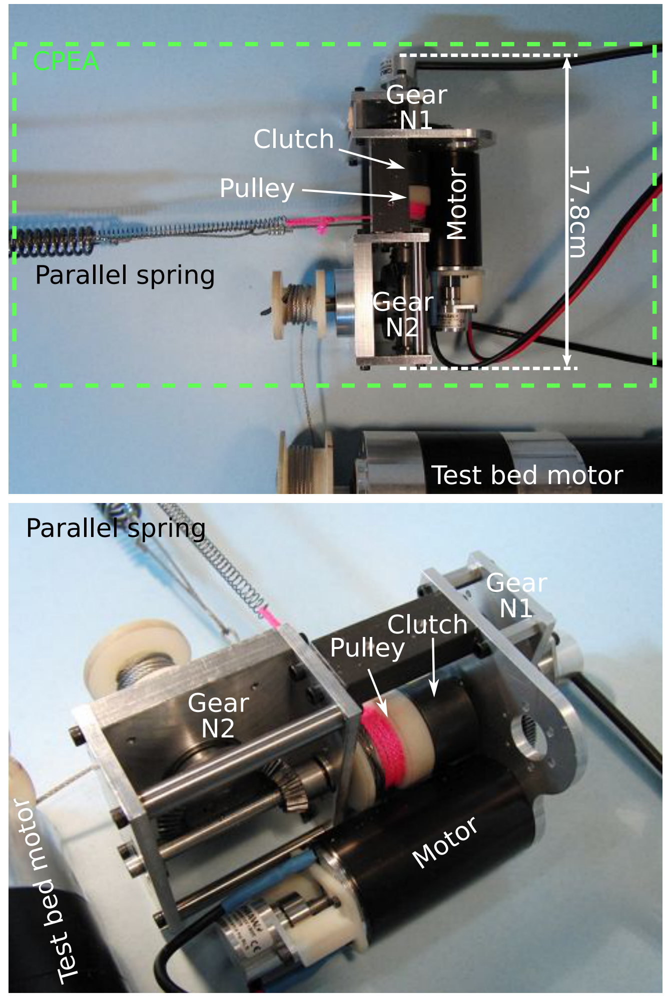

Fig. 2. Prototype development testbed of the clutched parallel elastic actuator. The size of the prototype without parallel spring and output pulley $17.8 \times 9.5 \times 8\,\mathrm{cm}$. The weight is $1.45\,\mathrm{kg}$. During the experiments, the CPEA and test bed motor were clamped to a common board (not shown).

II. Design and Control of the Clutched Parallel Elastic Actuator

The CPEA prototype (Figures 1 and 2) is based on a previous design for a series elastic actuator [16] that is specified to meet the dynamically scaled performance of the vastus muscle group in a half-sized humanoid system. The original actuator weighs $1.8\,\mathrm{kg}$ and uses two parallel Maxon RE-40 brushed DC motors to achieve a no-load speed of $22\,\mathrm{rad/s}$ (corresponding to the maximum knee joint velocity given the maximum contractile velocity of $0.68\,\mathrm{m/s}$ for the scaled vastus muscle group and a constant knee radius of $3\,\mathrm{cm}$) and a continuous torque of 13 Nm at the knee joint (corresponding to one third of the maximum isometric force of 1500 N for the scaled muscle group). In the CPEA prototype, only one Maxon RE-40 motor is used in parallel with an electric clutch (Reell EC30XP, peak torque $3.4\,\mathrm{Nm}$, energy consumption at engagement $3.5\,\mathrm{W}$). The clutch operates through a solenoid action which causes a spring to wrap onto the central shaft. This couples the shaft to the clutch hub through the wrap spring. After electrical engagement the clutch still rotates by Φ before it hits the mechanical lock and exerts torques on the shaft. It then engages the parallel spring. To meet the clutch torque specifications, the clutch is mounted between the two gear stages of the actuator (Figure 1). The clutch is connected to a pulley-driven extension spring with a stiffness of $k_{\mathrm{lin}} = 5549\,\mathrm{N/m}$. A second low-stiffness spring is used to keep the connecting cable under tension when the clutch is disengaged. In contrast to the weight of the original actuator, the CPEA prototype only weighs $1.45\,\mathrm{kg}$.

The CPEA is modeled according to

$$T = N_2 \eta_2 \left(I_M k_T N_1 \eta_1 + T_{\mathrm{PS}} \right) \tag{1}$$

$$U_M = U_0 \left(\frac{\dot{\theta} N_1 N_2}{n_0} + \frac{I_M k_T}{M_h} \right) \quad , \tag{2}$$

where the outputs T and U_M are the knee torque and motor armature voltage, I_M is the motor current, θ and $\dot{\theta}$ are the knee position and velocity, and T_{PS} is the torque generated by the parallel spring that is mounted to the clutch between gear stages 1 and 2 (ratios N_1 and N_2). The parameters $\eta_{1,2}$ describe the gear efficiencies. The parameters k_t, n_0 and M_h represent the torque constant, no load speed, and stall torque of the DC motor. The torque T_{PS} depends on the clutch state,

$$T_{\mathrm{PS}} = \begin{cases} -k_{\mathrm{PS}} \left(N_2\theta - N_2\theta_c + \Phi \right) & N_2\theta < (N_2\theta_c + \Phi) \\ & \text{\& clutch engaged} \\ 0 & \text{else} \end{cases} , \tag{3}$$

where θ_c is the knee angle at which the clutch is engaged. The motor current I_M of the CPEA required to generate a desired knee torque T can be calculated by solving equation 1 for I_M. The resulting current is controlled by a digital servo-amplifier (Elmo Solo Whistle 20 A,48 V) that drives the DC motor.

The implemented clutch control switches between the the engaged and disengaged states using four trigger events (Fig. 3). For normal locomotion, the parallel spring in a knee extension actuator is ideally engaged at the moment of touch-down and released at take-off. As the clutch rotates by Φ

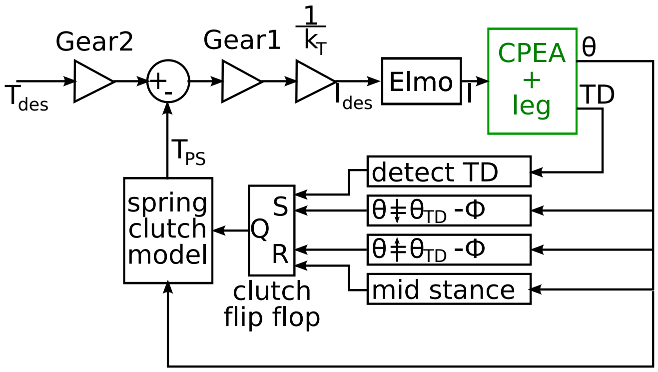

Fig. 3. CPEA control scheme for hopping. Gear1 and Gear2 account for gear ratio and efficiency. The Elmo current control is modeled as a gain of 1. The model of the spring and the clutch depends on knee angle Θ and clutch engagement state, which is set by the RS flip flop state Q. The clutch engagement is triggered by either a touch down signal (TD) or a knee reference angle, at which the clutch is also disengaged when passing the reference angle in the opposite direction. The mid stance release trigger is only connected for the experiment II, and not during periodic hopping.

before it locks, the benefit of parallel elasticity is maximized if the clutch engages at a knee angle $\theta_c = \theta_{\text{TD}} - \Phi$ shortly before landing, where θ_{TD} is the anticipated angle at touch down. To account for touch downs that happen before θ_{TD} is reached, the control alternatively engages the clutch when the system detects a touch down, $\theta_c = \theta(t_{\text{TD}})$. The clutch is disengaged if the knee joint reaches θ_{TD} during rebound in stance. On the other hand, if a stopping maneuver is commanded, the control releases the clutch at the lowest point θ_{min} of the rebound motion in stance, detected by the transition of the knee velocity from negative to positive values.

To identify the required stiffness of the parallel spring, we develop a simplified simulation model of the half-sized humanoid robot that generates knee angle and torque profiles for rebounding motions. The model consists of a point mass for the trunk and two rigid bodies that represent the thigh segment and the combined shank-foot complex (masses and inertias estimated from the first leg prototype of the half-sized humanoid with a total leg length of $0.5\,\text{m}$ and a total weight of $20\,\text{kg}$; the reflected inertia of the CPEA is included in the shank inertia). The model is constrained at the hip and foot to only move in the vertical axis against gravity.

We generate desired knee torque and angle profiles, $T(t)$ and $\theta(t)$, with this model by simulating the vastus muscle group as a Hill-type muscle and its neural control for hopping motions [17]. The simulated cyclic hopping pattern is characterized by a hopping height of $3\,\text{cm}$ at a hopping frequency of $3.4\,\text{Hz}$. Dynamically scaled to a full size human, these values correspond to $6\,\text{cm}$ and $2.4\,\text{Hz}$, respectively, which are typical values for hopping height and frequency observed in human experiments [18], [19]. The resulting torque and angle profiles show peak values during stance that translate into $\Delta T_{\text{PS}} = 4.9\,\text{Nm}$ and $\Delta\theta_{\text{PS}} = 2.7\,\text{rad}$ at the level of the clutch between the two gear stages of the CPEA. To exert about 50% of this knee torque at peak deflection, a parallel rotational spring requires a stiffness $k_{\text{PS}} = 0.9\,\text{Nm/rad}$. We approximate this rotational stiffness in the hardware prototype by using a linear spring with stiffness $k_{\text{lin}} = 5549\,\text{N/m}$ connected to a pulley with radius $r = 1.25\,\text{cm}$ (resulting $k_{\text{PS}} = 0.87\,\text{Nm/rad}$).

III. Actuator performance in simulation and experiment

We conduct three different experiments in simulation and hardware to test the performance of the CPEA prototype: (I) periodic hopping with prepared clutch landing, (II) breaking motion with the goal to stop the rebound after landing, and (II) unprepared landing where the clutch is engaged when touch-down is detected. In the first experiment, the desired actuator output torque matches the knee torque profile $T(t)$ identified in the previous section (Figs. 4 and 5). In the second experiment, the clutch is released at mid-stance (θ_{max}) and the desired torque profile is replaced at this point with a PD control on knee angle with the goal to slowly return to upright standing ($\theta_{\text{set}} = \pi$) (Fig. 6). Finally, in the third experiment, only the parallel spring is engaged while the DC motor stays off to focus on the reaction of the clutch-spring mechanism to unprepared engagements at touch-down (Fig. 7).

To compare energy advantage of the CPEA in these experiments, we estimate energy consumption E from the motors armature voltage and current,

$$E = \int_{t_0}^{t_1} U_M(t) I_M(t) dt \quad . \tag{4}$$

U_M and I_M are obtained from equations 1 and 2. We use the motor parameters provided in Maxxon's RE-40 spec sheet ($U_0 = 48\,\text{V}$, $n_0 = 794\,\text{rad/s}$, $M_h = 2.5\,\text{Nm}$, $k_T = 60.3\,\text{mNm}$), assume a gear efficiency of $\eta_{1,2} = 0.9$, and measure the torque T in the hardware experiments using the current consumed by the test bed motor that enforces the simulated knee motion on the CPEA (Figs. 1 and 2).

A. Predicted energy advantage

The simulation experiments for periodic hopping (experiment I) predict an energy consumption of the CPEA during stance of $E = 27.29\,\text{J}$ if only the DC motor generates the movement and of $E = 6.90\,\text{J}$ with the parallel elastic spring engaged. The saved energy in each stance phase is $\Delta E = 20.39\,\text{J}$ or 75%. Furthermore, simulation experiments with alternative stiffness values for the parallel spring reveal that a smallest energy requirement of $E = 3.22\,\text{J}$ or 88% reduction can be achieved with a spring stiffness $k_{lin} = 8500\,\text{N/m}$, which is about 50% higher than the stiffness of the parallel spring used in the test bed. This spring would basically generate the full required torque and the CPEA motor only modulates the torque to match the nonlinear output of the vastus muscle model.

B. Hardware experiments setup

To test the performance of the CPEA prototype, the knee motion from the hopping simulation is imitated at the CPEA

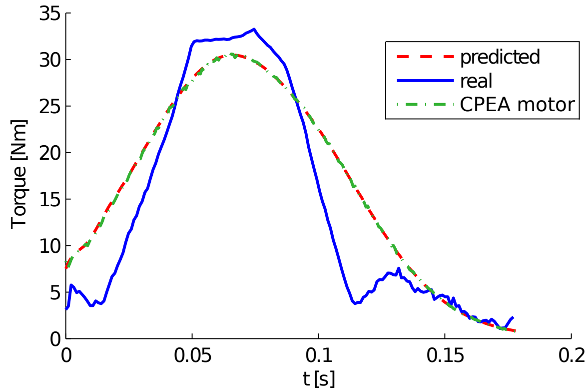

Fig. 4. Test of torque profile measurement. The DC motor of the CPEA was commanded the ground contact torque pattern for hopping (required current shown in green). The test bed motor was commanded to hold the knee and the applied torque was estimated from measuring the current I_{TB} of the test bed motor required to maintain the knee position (blue curve). Differences in the torque profiles likely are the result of observed test bed elasticity and inertia, as well as inexact estimates of the CPEA gear efficiency.

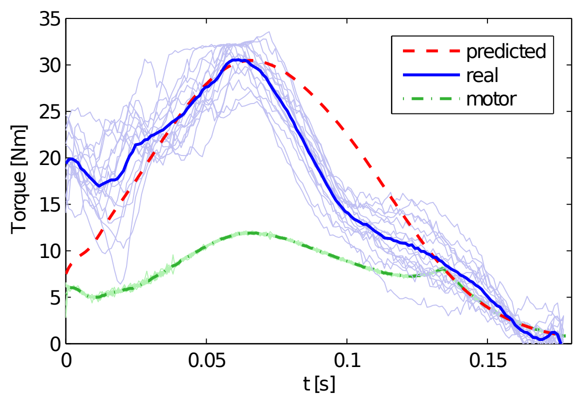

Fig. 5. Experiment I: CPEA torque history for periodic hopping. Shown is the stance phase with touch down at $t = 0$. Red dashed curve is the CPEA model's predicted torque. Blue curves show measured torques (light blue) and their mean across all trials (dark blue). The green dashed curve shows the contribution of the DC motor in the CPEA to the total torque.

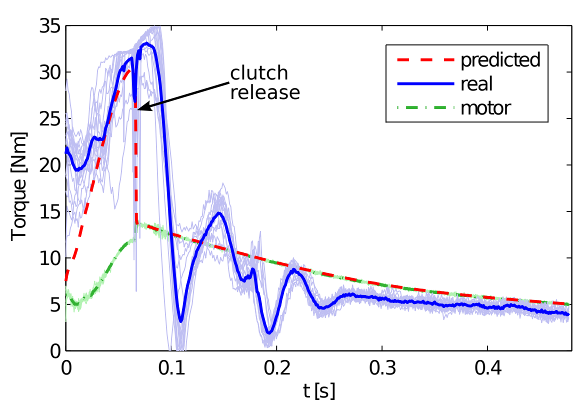

Fig. 6. Experiment II: CPEA torque history for landing phase (touch down at $t = 0$) with clutch release at mid-stance (marked by arrow). Color code as in figure 5.

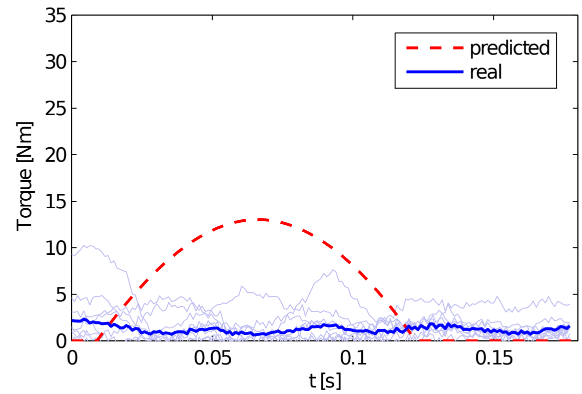

Fig. 7. Experiment III: CPEA torque history for unprepared landing with clutch engagement at touch down. The DC motor of the CPEA is turned off. Color code as in figure 5.

output by a strong test bed motor. The test bed motor (Midwest Motion Products S27-411G, gear ratio 19.2:1, output peak torque $120\,\mathrm{Nm}$, $22\,\mathrm{rad/s}$) generates desired knee motions by position control with feedforward inertia compensation. A pulley with a radius of $3\,\mathrm{cm}$ at the test bed motor emulates the knee disk of the humanoid robot (scaled muscle lever arm). This pulley is connected to the CPEA output pulley by a steel cable (Fig. 2). The test bed motor and the CPEA are controlled via Matlab/Simulink Real Time Windows Target (The MathWorks, Inc.) at $1\,\mathrm{kHz}$ sampling frequency.

We estimate the output torque T of the CPEA by measuring the controlled current I_{TB} of the test bed motor. To calibrate for the test bed motor's inertia and friction losses, the current $I_{\mathrm{TB\_0}}$ required for a "free" motion without connected CPEA is subtracted from the current measurements. Thus, the CPEA torque is estimated as $T = (I_{\mathrm{TB}} - I_{\mathrm{TB\_0}})k_{\mathrm{T\_TB}}N_{\mathrm{TB}}$, where $k_{\mathrm{T\_TB}} = 0.096\,\mathrm{Nm/A}$ and $N_{\mathrm{TB}} = 19.2$ are the torque constant and gear ratio of the test bed motor. Figure 4 shows how the torque produced by the CPEA compares to its estimate obtained from measuring I_{TB}. The estimate shows some deviations, but captures the trend and amplitude.

With the torque T given, DC-motor voltage and current (Fig. 8) can be calculated. Thus, the energy consumption of the DC motor in the CPEA can be estimated according to equations 4 and 2. In addition, the energy consumption of the clutch can be estimated from its active time. It is engaged for about 0.093s and thus consumes $E = 3.5\,\mathrm{W} \cdot 0.093\,\mathrm{s} = 0.33\,\mathrm{J}$ in each cycle. We define the energy cost of the CPEA as the combined cost of the DC motor and the clutch.

C. Prototype results

All hardware trials were repeated ten times. The torque output of CPEA in the different experiments is shown in figures 5, 6 and 7. In the periodic hopping experiment, the torque generated by the CPEA reaches the desired peak torque, but shows some deviations in the torque profile (Fig. 5). The CPEA torque as measured by I_{TB} is too large shortly after touch down and too small after mid stance. In general, however, it follows the requested profile. The

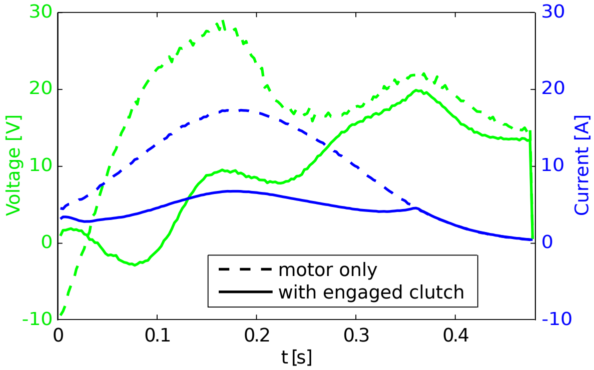

Fig. 8. Motor voltage and current during stance phase. The dashed lines represent the case, where only the DC motor produces all required torque and the spring is not engaged. The solid line shows the reduced voltage and current requirements in the DC motor when the clutch engaged the parallel spring.

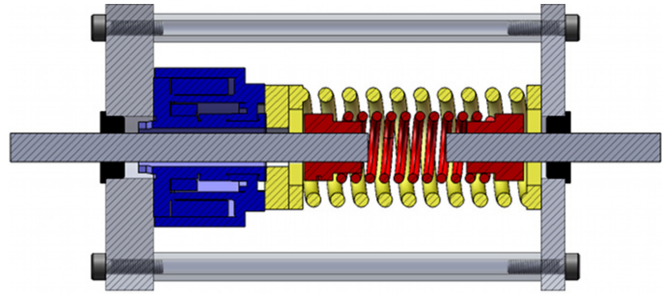

Fig. 9. Concept for concentric clutch mechanism for series and parallel elasticity. The series spring (red) is located inside a larger parallel spring (yellow). The larger spring is anchored at one end and connected to the clutch at the other. Upon clutching, the large outer spring engages the drive train (before the series spring) and stores energy as it is deflected.

computed energy consumption of the CPEA shows $E = 33.5 \pm 2.1$ J without the parallel spring and $E = 7.07 \pm 0.44$ J with the spring engaged, reducing the energy consumption by 79%, in line with the predicted reduction of 75%. In addition, the maximum torque requirement for the DC motor drops from 30Nm to 10Nm at the knee joint.

In the second experiment (Fig. 6), the CPEA torque drops shortly after the commanded release of the clutch at $t = 0.08s$ (marked by arrow), but not as quickly as expected ($\Delta t_{\text{expected}} = 0\,\text{s}$ vs. $\Delta t_{measured} \approx 33\,\text{ms}$). In addition, the measured torque profile suggests undesired oscillations after the clutch is released.

Finally, in the third experiment (Fig. 7), where the clutch engages with the touch down to simulate an unexpected ground contact, the measured CPEA torque does not show the predicted torque pattern of the passive clutch-spring mechanism, although the clutch engaged in the actual experiments and visibly stretched the parallel spring to some extend.

IV. Discussion and Future Plans

A spring in parallel to a motor does reduce the energy consumption and torque requirements for motions with torque patterns that fit the parallel spring [7], [1], [3]. In other motions or gait phases however, it can hinder the movement. To resolve these limitations, a mechanism to engage or vary the stiffness is necessary. Although clutch mechanisms [20], [21] or variable compliance mechanisms [8], [9], [11], [12], [13], [14], [15] in series to the actuator in the drive train are well established, low cost, low-complexity solutions of clutched parallel elastic actuators (CPEA) have so far not been established. We presented a prototype for such a CPEA and a simple trigger-based control of it for rebounding tasks in legged locomotion.

The main purpose of this work was to assess the possible reduction in energy consumption by employing the passive elasticity compared to an actuator generating all the required torque actively. The parallel spring in the actuator allows to passively store and recoil kinetic energy during rebound, reducing the energy consumption of the actuator by about 80% and the peak torque requirement for the DC motor by about 66%, well in agreement with theoretical values reported in the literature [2]. In addition, for a similar torque specification, the CPEA reduces the weight of the actuator by about 20% from 1.8 kg to 1.45 kg.

Although our simple trigger-based control could reliably engage and disengage the electric clutch during the motion, allowing the spring to support the motor in rebound and to remove stored energy from the system as necessary for stopping, the hardware experiments also revealed that improvements in modeling, design and control are needed to provide accuracy in the torque control of the CPEA.

The first major source of error between model-predicted and measured CPEA torque output was elasticity in the test bed. This elasticity was clearly visible in high speed video recordings and was mainly due to elasticity in the steel cable connecting the two pulleys of the test bed motor and the CPEA (Fig. 2). The torque disturbances introduced by this elasticity point to a major drawback of the current prototype; it does not have a reliable measurement of its output torque. The test bed elasticity could also explain the apparent lack of a spring contribution to the output torque in the third experiment (Figure 7), in which only the parallel spring was engaged and the DC motor was turned off. Since the clutch engaged in the experiment and visibly stretched the spring to some extend, we speculate that the reason for this apparent lack of a contribution are estimation errors of the CPEA torque when based on measuring the test bed motor's current I_{TB}.

We currently seek to introduce direct torque measurement in the CPEA for precise torque control by adding series elasticity to the actuator and measuring force as spring deflection, a method that is successfully used in series elastic actuators [22], [23], [24], [25]. Figure 9 shows our initial design concept for a compact module that combines series and parallel elasticity [16]. The module contains two concentric springs. The outer spring is anchored at one end and connected to the electric clutch at the other. When engaged by the clutch, this spring connects to the drive train and acts in parallel to the DC motor (not shown), both connected by the main shaft to the inner, series spring.

The second major error source was clutch dynamics that we did not account for in modeling and control. In the second experiment, in which the goal was to support the DC motor during the breaking phase of a landing movement, disengaging the clutch under load did not happen as quickly as desired and it caused oscillations in the system (Figure 6). High speed video recordings revealed that the torque oscillations are caused by oscillations of the clutch and spring after the release. The clutch is actually released at the right time, but it seems that the friction force of the clutch immediately after the release still maintains connection to the shaft and transmits high torques generated by oscillations of the parallel spring. We expect, that already the concentric implementation of the parallel spring would decrease axial load and therefore friction forces in the clutch. Additionally, we plan to improve the CPEA performance by including these clutch dynamics in modeling and control algorithms. An accurate model of the clutch and the engaged parallel stiffness would allow a low-level controller to deal with the discontinuities introduced by the clutch and to exert precise torques "requested" by a higher-level controller. Thus, CPEA and low level controller could be an actuator unit exerting torques like a bigger DC motor, while saving energy by engaging the clutch.

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