

Design and Evaluation of the Bi-directional Clutched Parallel Elastic Actuator (BIC-PEA)

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Abstract—Parallel elastic actuators (PEAs) have shown the ability to reduce the energy consumption of robots. The problem with regular PEAs is that it is not possible to freely choose at which instant or configuration to store or release energy. This paper introduces the concept and the design of the Bi-directional Clutched Parallel Elastic Actuator (BIC-PEA^{*}), which reduces the energy consumption of robots by loading and unloading the parallel spring in a controlled manner. The concept of the BIC-PEA consists of a spring that is mounted between the two outgoing axes of a differential mechanism. Those axes can also be locked to the ground by two locking mechanisms. At any position, the BIC-PEA can store the kinetic energy of a joint in the spring such that the joint is decelerated to zero velocity. The spring energy can then be released, accelerating the joint in any desired direction. In our prototype of 202 g, the energy that can be stored in the spring is 0.77 J. When disengaged, the friction that the mechanism adds is negligible. The current maximum over-all efficiency is 62 %, which is about 55 % more than what generally can be achieved by recapturing the energy electrically. Its relatively high efficiency and controllability make the BIC-PEA a promising concept for reducing the energy consumption of robots.

I. INTRODUCTION

In robotics, there is a need for techniques that reduce the energy consumption. Clear examples of robots of which the energy consumption is crucial are mobile robots such as walking robots [1], household robots [2], prostheses [3, 4] and orthoses [5, 6]. One of the most promising research directions for the reduction of the energy consumption is the implementation of springs in series or in parallel with the motor to store and release energy.

Since the introduction of series elastic actuators (SEAs) by Pratt and Williamson [7], springs have been placed in series with electric motors in numerous robots (see e.g. [8–13]). A spring in between the joint and the motor decouples the velocities of the two. This can reduce the peak power of the motor since the spring acts as an energy buffer [14]. SEAs are also beneficial for torque control [7] and safety [15]. Recent research on series elasticity focusses on variable series elastic actuators [16, 17], in which the mechanical stiffness of the serial spring can be adjusted. Although (variable) series elastic actuators can reduce the energy consumption, the potential reduction in energy consumption is generally larger using springs in parallel with the motor.

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^{*}Patent pending

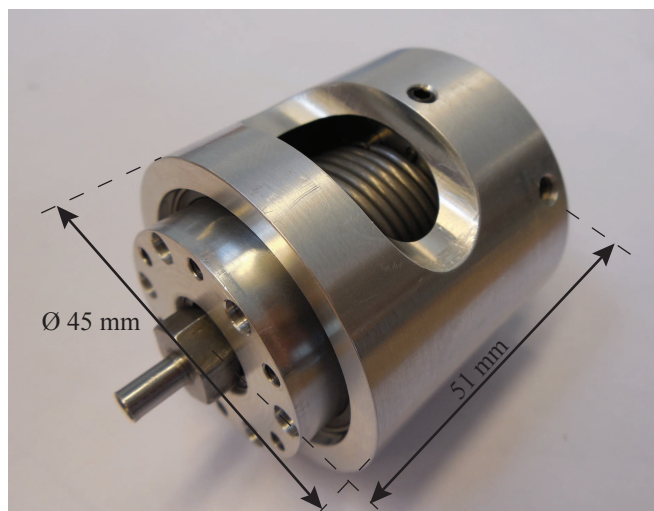


Fig. 1. A photograph of the BIC-PEA. It weighs 202 g, can store up to 0.77 J of energy and fits in a cylinder with a length of 51 mm and a diameter of 45 mm.

In the past decade, the use of parallel elastic actuators (PEAs) has become more popular (see e.g. [18–23]). With a regular parallel spring, there is a direct relationship between the energy in the spring and the displacement of the joint, called the spring characteristic. This spring characteristic can be adjusted to match the task that has to be performed (see for example [22, 23]). Since part of the torque that is required to perform the task is provided by the parallel spring, the motor has to apply less torque, reducing the energy consumption. The reduction of the motor torques also allows for smaller gearbox ratios, leading to less gearbox friction, which again reduces the energy consumption. In addition to using the parallel spring to reduce the energy consumption, it can also be used to increase the task execution speed [24, 25] or to statically or dynamically balance a system [19, 26].

The drawback of using regular parallel springs is that usually the characteristic cannot be adjusted during operation, which reduces the versatility of the robot in three ways. Firstly, energy that is stored in the spring while moving in one direction can only be returned while moving in the opposite direction. Secondly, the timing of the energy storage and release cannot be controlled, but exclusively depends on the joint position. And thirdly, when energy is stored in the spring, the spring exerts a torque on the joint, which is undesirable when the joint has to stand still.

The solution is to make the spring characteristic adjustable during operation. An interesting concept which provides this functionality was envisioned by Stramigioli et al. who proposed to use a so-called infinite variable transmission (IVT) [27]. The IVT can change the transfer ratio between the joint and the spring, effectively changing the spring characteristic. However, there are no studies showing the working principle or effectiveness of such an IVT. Other researchers have used clutches to change the spring characteristic [28]. Clutches can be used for two purposes: to lock the joint when it has to stand still and the spring is loaded [18] or to control the locking of the spring to the joint [29]. The latter group is called clutched parallel elastic actuators (C-PEA).

The problem that remains unsolved is the inability of PEA's to release the energy in an arbitrary direction. In this paper, we propose to solve this problem using the concept of the Bi-directional Clutched Parallel Elastic Actuator (BIC-PEA, see Fig. 1). The BIC-PEA consists of a spring, a differential mechanism and two locking mechanisms. The parallel spring can be connected to the joint at arbitrary position or speed when the kinetic energy has to be stored in the spring. When the velocity reaches zero, the spring is locked and the energy remains stored. Releasing the energy can be done in both directions, because of the differential mechanism.

The rest of this paper is structured as follows. Section II describes the working principle of the BIC-PEA in more detail. Then, section III shows our implementation by explaining the design. In section IV, the BIC-PEA is evaluated by measuring its performance. And finally, the paper ends with a discussion in section V and a conclusion in section VI.

II. WORKING PRINCIPLE

In this section we explain the working principle of the BIC-PEA in more detail. First, we will explain the components of the BIC-PEA (one differential mechanism, two locking mechanisms and a spring) and how they are connected. Second, we will explain the operating principle of the BIC-PEA. A schematic drawing of the BIC-PEA is shown in Fig. 2. This figure shows a hydraulic mechanism for explanation purposes. The final design of the BIC-PEA is a geared version and will be explained in section III.

A. Differential mechanism

A differential mechanism is a mechanism with three degrees of freedom (DOFs) and one constraint that can be written in the form:

$$x_J = N_1 x_1 + N_2 x_2 \quad (1)$$

where N_1 and N_2 are constant positive transfer ratios, x_J is the position of the input and x_1 and x_2 are the positions of the output of the differential. These three positions are the three DOFs of the differential mechanism. Examples of such mechanisms are a planetary gear, a planetary differential, an automotive differential and a 'movable pulley and cables' differential. We call a differential mechanism ideal if $N_1 = N_2$, which is generally the case for the planetary

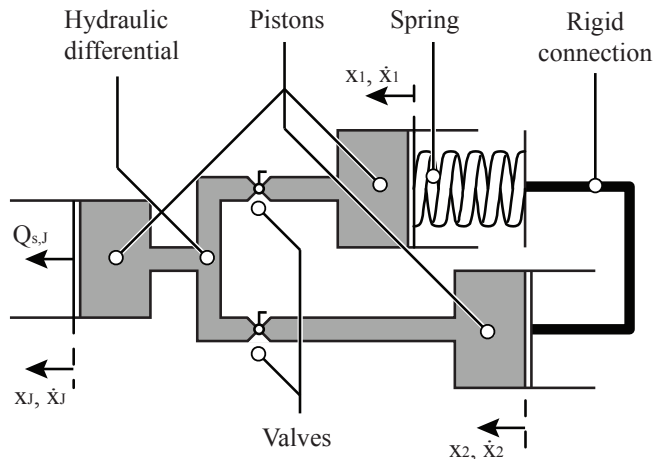


Fig. 2. A schematic drawing of the concept of the BIC-PEA, visualized as a hydraulic system. It consists of a differential, a spring and two valves (locking mechanisms). The differential mechanism causes the joint piston to move with the sum of the velocities of the other two pistons. The valves can lock the two pistons.

differential, automotive differential and 'movable pulley and cables' differential. In the BIC-PEA, the input position x_J is connected to the joint of a robot, hence the subscript J .

B. Locking mechanisms

A locking mechanism is a component that can switch between allowing and preventing relative motion between two other components (see [28]). In the BIC-PEA, the two locking mechanisms are placed between the ground and the two output positions x_1 and x_2 . The discrete states of the two locking mechanisms are denoted by L_1 and L_2 which have value 0 if the output position is locked to the ground and have value 1 if the output position is not locked. Eq. (1) can be re-written in terms of velocities:

$$\dot{x}_J = N_1 \dot{x}_1 + N_2 \dot{x}_2 \quad (2)$$

with $\dot{x}_i = 0$ if $L_i = 0$.

C. Spring

A spring is a compliant component with (in our case) two connection points. The potential energy that is stored in the spring is a function of the relative position of the two connection points. In the BIC-PEA, a spring is placed between the two output positions of the differential mechanism. Therefore, the displacement of the spring is equal to

$$\Delta x = x_1 - x_2 \quad (3)$$

where the positions are defined such that $\Delta x = 0$ is an equilibrium position of the spring. The potential energy in the spring is a function of this displacement:

$$E_s = f(\Delta x) \quad (4)$$

The generalized force $Q_{s,i}$ exerted by the spring on the i -th DOF is given by

$$Q_{s,i} = - \frac{\partial \Delta x}{\partial (x_i)} \frac{\partial f(\Delta x)}{\partial \Delta x} \quad (5)$$

Where force is defined in the same direction as position. Examples of commonly used springs are compression springs, extension springs, torsion springs and spiral springs. Most springs have a constant and positive stiffness, which means that $\frac{\partial f(\Delta x)}{\partial \Delta x}$ is a monotonically increasing and linear function of Δx :

$$\frac{\partial f(\Delta x)}{\partial \Delta x} = k\Delta x \quad (6)$$

where k is the spring stiffness.

D. Operating principle

Using the two locking mechanisms, there are four modes of operation:

1. $L_1 = 1$ and $L_2 = 1$: The two output positions are not locked and therefore the spring deflection Δx is independent of the joint position x_J . Although the spring might deflect due to inertias and friction, these deflections are negligible as long as the spring stiffness is sufficiently large.
2. $L_1 = 0$ and $L_2 = 1$: Output position 1 is locked, meaning that $\dot{x}_1 = 0$. Since x_1 is now constant, the spring deflection linearly depends on the joint position. Combined with eq. (1), this results in:

$$\Delta x = c_1 - x_2 \quad (7)$$

$$= \left(1 + \frac{N_1}{N_2}\right)c_1 - \frac{1}{N_2}x_J \quad (8)$$

where c_1 is equal to x_1 at the moment that x_1 was locked. Substituting in eq. (5) leads to:

$$Q_{s,J} = \frac{1}{N_2} \cdot \frac{\partial f(\Delta x)}{\partial \Delta x} \quad (9)$$

3. $L_1 = 1$ and $L_2 = 0$: Output position 2 is locked, meaning that $\dot{x}_2 = 0$. Since x_2 is now constant, the spring deflection again linearly depends on the joint position:

$$\Delta x = x_1 - c_2 \quad (10)$$

$$= \frac{1}{N_1}x_J - \left(1 + \frac{N_1}{N_2}\right)c_2 \quad (11)$$

where c_2 is equal to x_2 at the moment that x_2 was locked. This leads to the generalized force:

$$Q_{s,J} = -\frac{1}{N_1} \frac{\partial f(\Delta x)}{\partial \Delta x} \quad (12)$$

4. $L_1 = 0$ and $L_2 = 0$: The two output positions are locked and thus the joint position is locked as well. If the spring is deflected, it will remain deflected while being in this mode of operation.

From eqs. (9) and (12), it follows that for the same deflection of the spring, the joint force can be negative or positive. Now suppose that \dot{x}_J is positive. If we want to decelerate the joint, we switch to mode 3, where the force on the joint is negative. Once the joint is decelerated to zero velocity and the kinetic energy is transferred to potential energy in the spring, we switch to mode 4. From mode 4, we

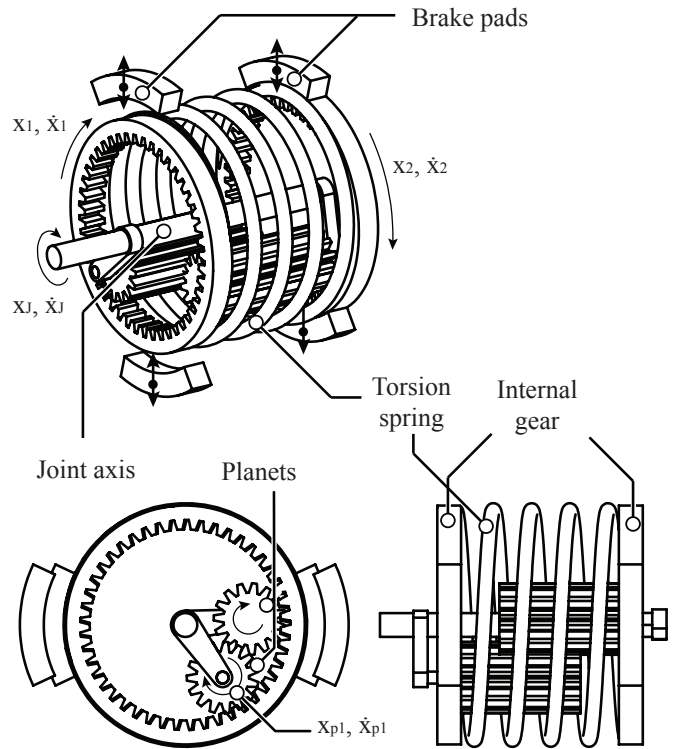


Fig. 3. A schematic drawing of the final design of the BIC-PEA. It consists of a planetary differential, a torsion spring and two brakes. The planetary differential consists of two internal gears, two planet gears and one sun (the joint axis). The planets have a lateral offset, such that each planet meshes with a different internal gear and they mesh with each other in between the internal gears. The planet axes are connected to the joint axis by cranks so that the distances between the joint axis and the planet axes are fixed. The planets can rotate around their axes independently from the rotation of the joint axis. The spring connects the two internal gears. The differential mechanism causes the joint axis to rotate with the average velocity of the two internal gears. The brakes can lock the internal gears with respect to the ground.

can release the potential energy by accelerating in positive or negative direction (respectively mode 3 and 2). Similarly, if \dot{x}_J had been negative, we would have switched to mode 2 to decelerate the joint.

From eqs. (9) and (12), it is also clear why an ideal differential is advantageous: if $N_1 = N_2$, the stiffnesses while accelerating in positive and negative direction are identical.

III. DESIGN OF THE HARDWARE PROTOTYPE

In this section, we explain the design of our hardware prototype (see Fig. 1). A section view of the design is shown in Fig. 4. We respectively discuss the differential mechanism, the spring, the locking mechanisms and the design properties.

As a differential mechanism, we use a planetary differential (see Fig. 3). The positions and velocities in this mechanism are rotational. Therefore, the generalized forces are actually torques. A planetary differential consists of two internal gears, one or multiple pairs of planet gears and a joint axis. Within one pair of planet gears, each gear engages with a different internal gear and the gears engage with each other. Our prototype has two pairs of planet gears, as can be seen in Fig. 5b. The motion of the separate sides of this planetary

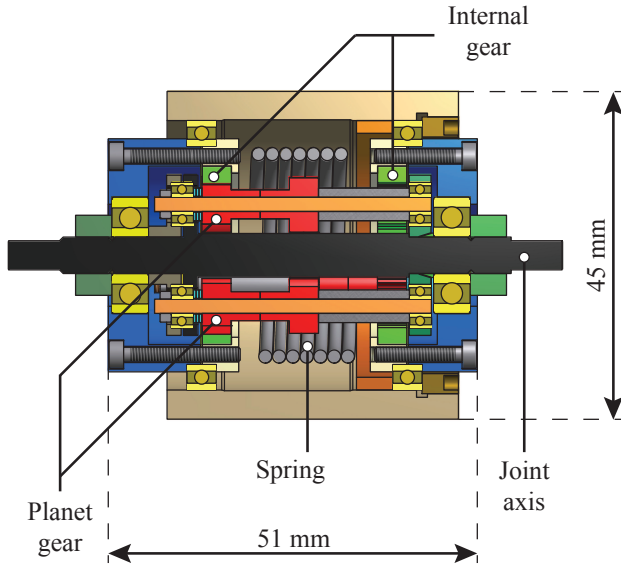


Fig. 4. Section view of our prototype. The torsion spring is placed between the two internal gears. The planet gears that connect the internal gears are placed in the core of the spring. The locking mechanisms (not shown) are connected to the internal gears.

differential are described by:

$$x_1 = x_J + r_p x_{p1} \quad (13)$$

$$x_2 = x_J + r_p x_{p2} \quad (14)$$

where r_p is the effective radius of the planet gears and x_{p1} and x_{p2} are the positions of the planet gears (see Fig. 3). Since the two planets mesh with each other such that $x_{p1} = -x_{p2}$, the overall motion is described by:

$$x_J = \frac{1}{2}x_1 + \frac{1}{2}x_2 \quad (15)$$

This differential mechanism is an ideal differential (i.e. $N_1 = N_2 = 0.5$).

As a spring, we used a torsion spring with a spring stiffness of $k = 0.17 \text{ Nm/rad}$. We attached two pegs to each side of the spring to connect to the internal gear (see Fig. 5a).

We used two large brakes as locking mechanisms to lock the internal gears. These brakes consist of rubber plates that are each pushed against a steel braking disk by a solenoid (see Fig. 6). The solenoids can be controlled manually by two switches.

The BIC-PEA without brakes as shown in Fig. 1, has a mass of 202 g and fits in a cylinder with a length of 51 mm and a diameter of 45 mm. The transfer ratio of the joint axis to the spring (when one brake is locked) is 1:2. This means that the apparent spring stiffness at the joint is 0.68 Nm/rad .

IV. PERFORMANCE MEASUREMENTS

In this section, we evaluate the performance of our prototype. First, we explain the measurement setup we used. Second, we describe the four test cases. And third, we show the results of the measurements, including the amount of energy that can be stored, the efficiency of the energy storage and the spring characteristic.

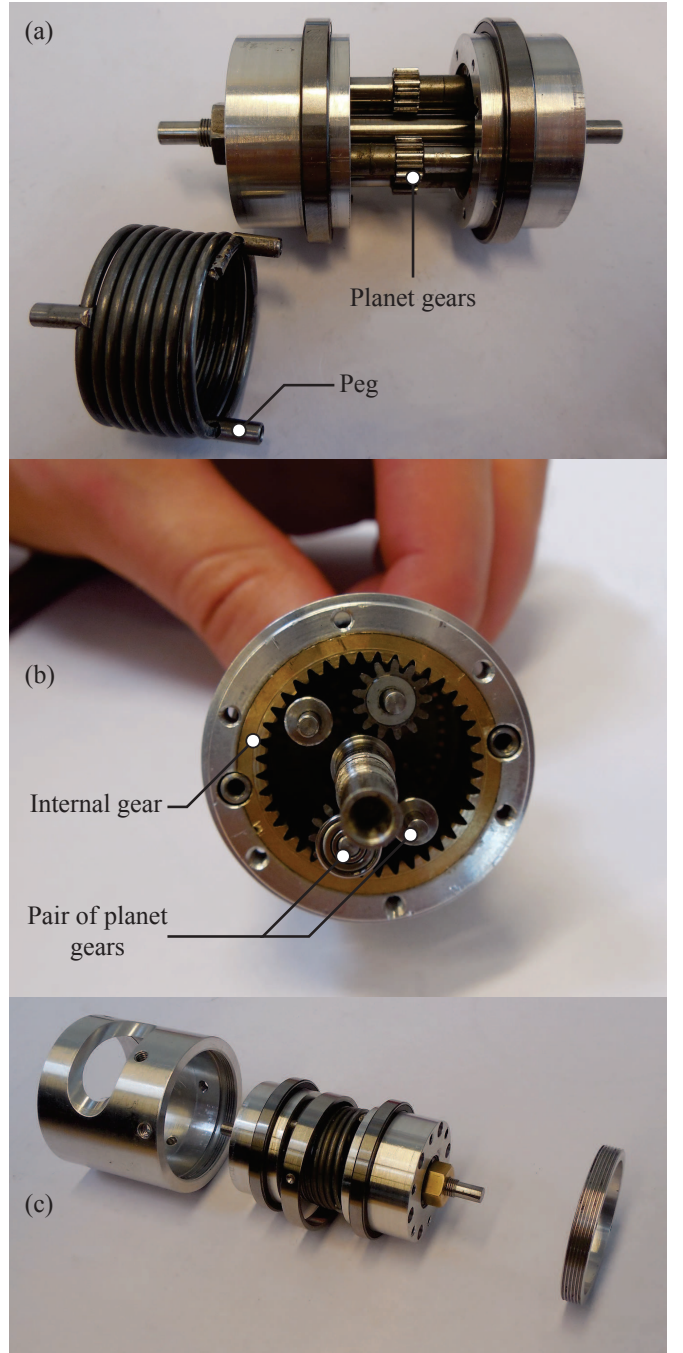


Fig. 5. Photographs of the inside of our prototype.

A. Measurement setup

Fig. 7 shows the measurement setup we used to evaluate the performance. A pulley with a radius of 15.5 mm is connected to the joint axis. This pulley is connected through a cable wire to a Futek LBS200 25 lbs load cell, on which force can be applied manually. Torque in the other direction can be measured by wrapping the cable around the pulley in the opposite direction. An encoder is placed between the joint axis and the ground to measure the angular position of the axis. Both the signal from the load cell and the encoder position are recorded at 1kHz using Matlab xPC Target.

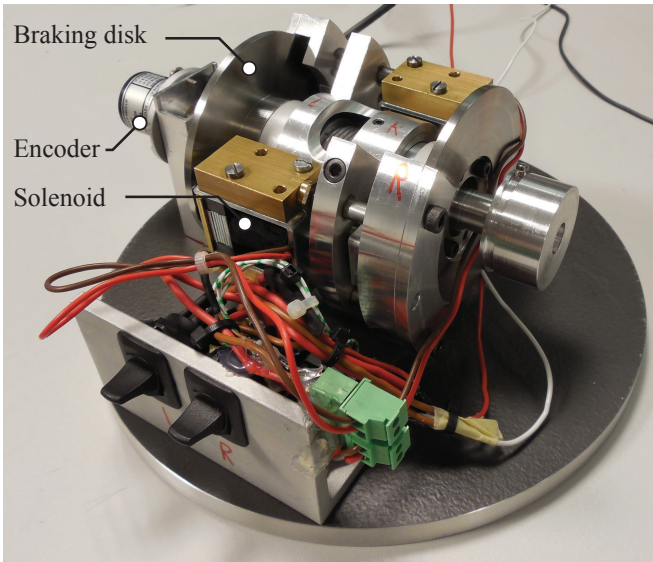


Fig. 6. The prototype with two brakes and an encoder.

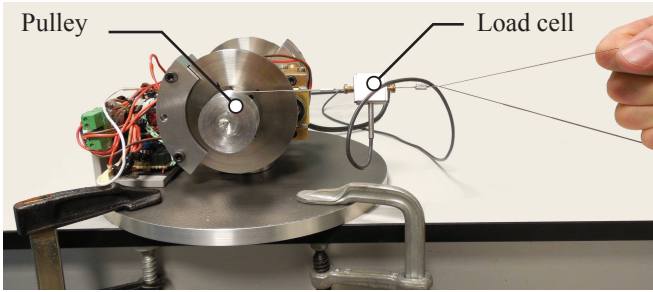


Fig. 7. The measurement setup we used to evaluate the prototype. A torque is applied to the joint axis by manually pulling a cable that is wrapped around a pulley. The load cell measures the amount of force that is applied.

B. Test cases

We performed four tests to evaluate the performance with different loading and unloading directions (CW = clockwise and CCW = counterclockwise):

1. **CCW loading and CW unloading.** During both the loading and the unloading phase, the same output angle is locked ($L_1 = 0$ and $L_2 = 1$). Since the unloading is in the opposite direction of loading, the system acts like a regular spring.
2. **CW loading and CCW unloading.** During both the loading and the unloading phase, the same output angle is locked ($L_1 = 1$ and $L_2 = 0$). Again, since the unloading is in the opposite direction of loading, the system acts like a regular spring.
3. **CCW loading and CCW unloading.** The spring is loaded in clockwise direction while $L_1 = 0$ and $L_2 = 1$. Unloading is in the same direction while the other output angle is locked (i.e. $L_1 = 1$ and $L_2 = 0$).
4. **CW loading and CW unloading.** The spring is loaded in clockwise direction while $L_1 = 1$ and $L_2 = 0$. Unloading is in the same direction while the other output angle is locked (i.e. $L_1 = 0$ and $L_2 = 1$).

TABLE I
PERFORMANCE OF THE BIC-PEA

Test	Energy in (J)	Energy out (J)	η_{in}	η_{out}	η_{total}
1	1.02 (± 0.09)	0.59 (± 0.07)	75 %	77 %	58 (± 2) %
2	1.02 (± 0.04)	0.63 (± 0.03)	75 %	82 %	62 (± 2) %
3	1.03 (± 0.25)	0.40 (± 0.11)	75 %	52 %	39 (± 6) %
4	1.02 (± 0.10)	0.44 (± 0.06)	75 %	57 %	43 (± 4) %

All test cases are repeated four times and the efficiency and energy results are averaged.

C. Results

We will now present the results per test case. A summary of the results is presented in Table I. The results show the mean of 4-6 repetitions, where more repetitions were used when the variation in the measurements was higher.

1. **CCW loading and CW unloading.** The results of this test case are shown in the fourth quadrant of Fig. 8. The results show a linear characteristic with a substantial amount of hysteresis. The average rotation of 1.5 rad corresponds to a stored energy of 0.77 J. The average energy needed to load the spring was 1.02 J and the average energy returned was 0.59 J. This means that the efficiency of loading the spring was 75 %, the efficiency in unloading the spring was 77 % and the overall efficiency was 58 %.
2. **CW loading and CCW unloading.** Almost the same results were obtained while loading and unloading in the opposite direction of test case 1 (see Table I). Fig. 8 shows that the behavior of the BIC-PEA is symmetrical. The overall energy efficiency was slightly higher than in test case 1 (62 %).
3. **CCW loading and CCW unloading.** Fig. 9 shows the results of this test case. The loading phase is comparable to the loading phase in test case 1 (see Fig. 8). Since the spring is unloaded in the same direction as loading, the sign of the torque switches. The system does not always switch at the same position since the loading and unloading is performed manually. The overall efficiency is 39 %, which is lower than in test cases 1 and 2.
4. **CW loading and CW unloading.** Fig. 10 shows the results of this test case. The results are similar to those of test case 3 (see Table I). The overall efficiency is slightly higher (43 %). The spread of the switching positions is larger than in the other test cases. This shows that the system works independent of the switching position.

V. DISCUSSION

This paper introduced the concept of the Bi-directional Clutched Parallel Elastic Actuator (BIC-PEA) and evaluated our prototype. In this section, we discuss the results and the general concept.

A. Discussion of the results

The results show that in our prototype the stored energy was 75 % of the inserted energy. The efficiency when unloading the spring differs per test (approximately 80 % in test 1

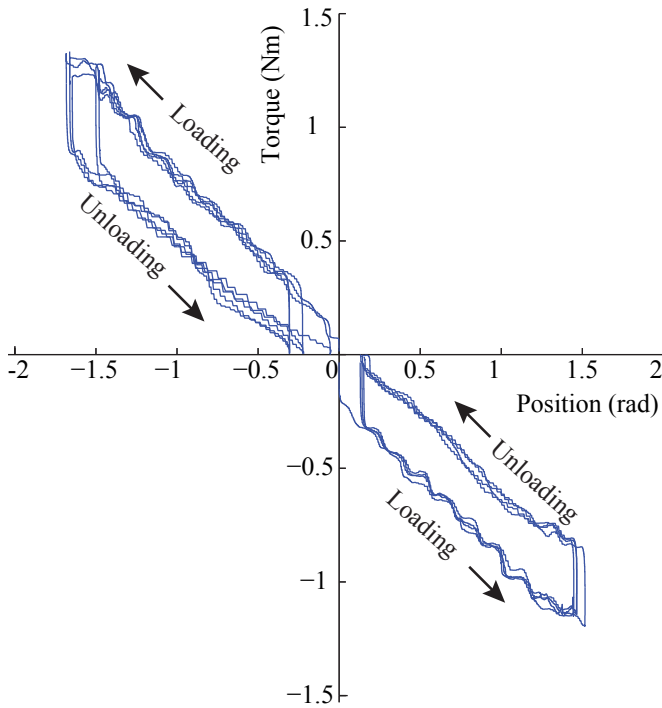


Fig. 8. The measurements of test case 1 and 2. Test case 1 is shown in the fourth quadrant and test case 2 is shown in the second quadrant. This figure shows that the results are symmetrical since the results in positive and negative direction are the same.

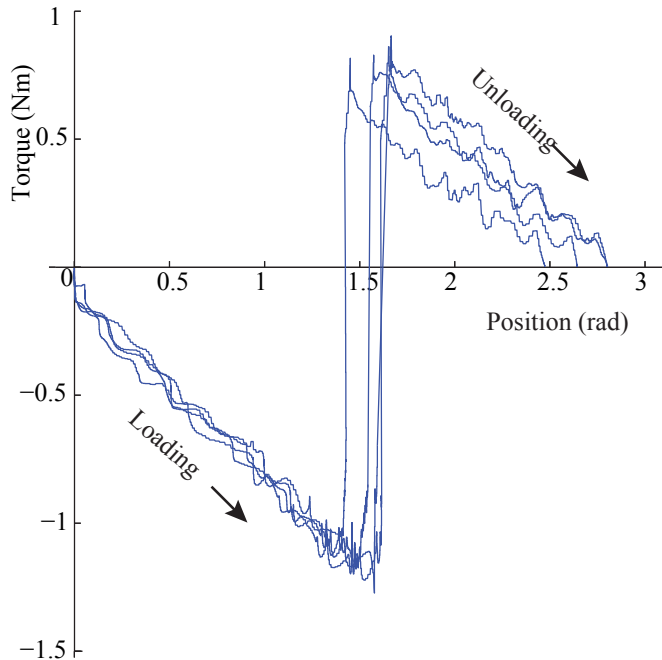


Fig. 9. The measurements of test case 3. This figure shows the function of the differential mechanism in the BIC-PEA: the sign of the torque can be switched, allowing energy release in the same direction as energy storage.

and 2 and 55% in test 3 and 4). This results in an overall efficiency of 39-62%. This is higher than the energy recovery of one of the best electric motors currently used. The motor on the Cheetah robot recovers 63% of the mechanical work

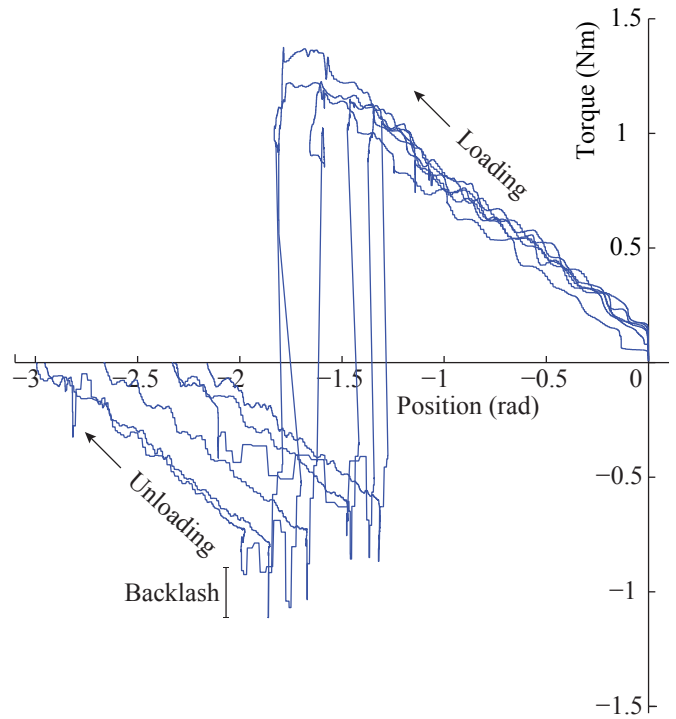


Fig. 10. The measurements of test case 4. In this figure, the backlash in the differential mechanism can be seen.

in the battery [30]. Assuming that the efficiency from battery to joint is also 63%, the overall efficiency becomes only 40%. So the maximum overall efficiency of the BIC-PEA is up to 55% higher than that of an electric motor.

The lower unloading efficiency in test case 3 and 4 is mainly due to backlash during the measurements, which can most clearly be seen in Fig. 10. When the locking mechanism is released, there is a peak in the torque. This indicates that the internal gear that was released has accelerated over a small distance while the joint axis was standing still due to backlash between the joint axis and the internal gear. When the backlash was overcome and the gears reengage, the internal gear is decelerated, causing a peak in the torque measurement. This issue can be mitigated in future prototypes by minimizing the backlash in the gears. Lowering this backlash might induce more friction, but we expect that the overall performance can easily be improved, since we used off-the-shelf low-quality gears.

Fig. 8 shows that the difference between the loading and unloading torque at every position is almost identical. This indicates that the hysteresis is mainly due to Coulomb friction in the gears. This friction is approximately 0.3 Nm. We expect that this can be mitigated by using low-friction gears. We estimate that the efficiency of the spring itself is approximately 95% and that, when the gear system is improved, the total efficiency can be increased to 85%.

B. Size and weight

The mechanism (planetary differential and spring) has a mass of 202 g and fits in a cylinder with a length of 51 mm and a diameter of 45 mm. This is equal to the size of a

medium-sized gearbox. This size and weight do not include the brakes, which we did not optimize for size and weight. Adding two small and lightweight brakes is part of future work. We expect that a complete set of spring, differential and brakes with the same performance as the current design can be designed to be 400 g and can easily be fitted in a cylinder with a length of 80 mm and a diameter of 50 mm, which is equal to the size of a medium-sized motor.

C. Applicability

The current prototype retracts approximately 1 J when decelerating a joint. This corresponds to a link with an inertia of 0.22 kgm^2 moving at 3 rad/s. These are common quantities when it comes to repetitive tasks of robotic arms [22]. However, the applications of BIC-PEAs far exceeds robotic arms. In fact, all machines that decelerate and accelerate again in a repetitive fashion would benefit from an efficient way of energy recapture.

D. Future work

There are still three major issues that should be addressed in future work.

Firstly, in the current system, it is not possible to only partially store the kinetic energy in the spring or to only partially release the potential energy. Theoretically, this would be possible, however, this would require locking mechanisms with an infinitely small reaction time. Although for many applications, the current functionality suffices, this issue should be solved to extend the applicability.

Secondly, in the current system, once one of the output angles of the differential is locked, the torque-position relationship is set. In some applications it might be useful to be able to adjust the spring stiffness before decelerating or accelerating. A variable transmission between the output joint of the BIC-PEA and the joint of the robot would provide such functionality.

And finally, as mentioned before, small and lightweight locking mechanisms should still be developed. A promising concept are statically balanced brakes, which we are currently developing [31].

VI. CONCLUSIONS

In this paper we introduced the concept of the Bi-directional Clutched Parallel Elastic Actuator (BIC-PEA) and evaluated our design. The concept of the BIC-PEA consists of a differential mechanism, a spring that is placed inside the differential mechanism and two locking mechanisms, which lock the two sides of the spring to the ground. At every position, the BIC-PEA can store the kinetic energy in a parallel spring such that the joint is decelerated to zero velocity. The spring energy can then be released at an arbitrary later point in time, accelerating the joint in any desired direction. In our prototype, the energy that can be stored in the spring is 0.77 J and the added friction when the mechanism is disengaged is negligible. The maximum over-all efficiency was measured to be up to 62 %, which is 55 % more than generally can be achieved by recapturing the energy electrically.

ACKNOWLEDGEMENT

This work is funded by research programme STW, which is (partly) financed by the Netherlands Organisation for Scientific Research (NWO), and by a Marie-Curie career integration grant PCIG13-GA-2013-618899.

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