Differential Elastic Actuator for Robotic Interaction Tasks

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Abstract:
For complex robotic tasks (e.g., manipulation, locomotion), the lack of knowledge of precise interaction models, the difficulties to precisely measure the task associated physical quantities (e.g., position of contact points, interaction forces) in real-time, the finite sampling time of digital control loops and the non-collocation of sensors and transducers have negative effects on performance and stability of robots when using simple force or simple movement controllers. To cope with these issues, a new compact design for high performance actuators specifically adapted for integration in robotic mechanisms is presented. This design makes use of a mechanical differential as its central element. Results shown that differential coupling between an intrinsically high impedance transducer and an intrinsically low impedance mechanical spring provides the same benefits as serial coupling, but in a more compact and simple design. This new actuator, named Differential Elastic Actuator (DEA), provides interesting design implementations, especially for rotational actuators.

Keywords: Elastic actuator, robotic mechanical interaction task, high-force low-impedance rotary actuator

Introduction

Robots are usually depicted as cold and stiff articulated machines. This is due to the fact that most industrial robots are fast and precise manipulators acting in constrained environments, using *position-* or *velocity-controlled* joints and stiff transmission mechanisms. More versatile robots have their end effectors equipped with force sensors, allowing them to react to forces from the environment by using a hybrid *position/torque controller*. However, their use is mostly limited to assembly of very simple mechanical parts.

Robots could play a more significant role in our lives if they could safely manage intentional and unintentional physical contacts with humans, even while performing tasks involving high amplitude interaction forces. Robots that must physically interact with their environment face a unique set of challenges in achieving both stability and performance [1]. For usage in uncontrolled environments such as real life settings, a new approach referred to as *interaction control* regulates the robot's dynamic behavior at its ports of interaction with the environment. Interaction control involves specifying a dynamic relationship between motion and force, and implementing a control law that attempts to minimize deviation from this relationship [2]. It is used in various applications such as robotic aids for physical therapy, haptic devices, teleoperated master-slave systems, human extenders, robotic surgery, powered prosthetic devices and would also be quite beneficial for robots moving over natural terrains.

Adding compliance at actuator level and being able to sense the forces from the environment are therefore important requirements for safe and efficient robots operating in real life settings. Therefore, we initiated a design project of a new and compact high-force low intrinsic stiffness rotary actuator for interaction control. Figure 1 shows this new actuator, named *Differential Elastic Actuator* (DEA) that will be presented in this paper. Compared to the abundantly studied *Series Elastic Actuator* (SEA) [3,4], DEA uses a differential coupling instead of a serial coupling between a high impedance mechanical speed source and a low impedance mechanical spring. This results in a more compact and simpler solution, with similar performances.

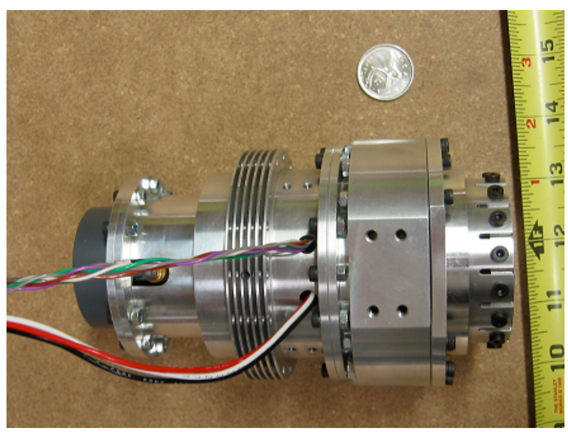


Fig. 1: *Differential Elastic Actuator.*

Theoretical Background and Taxonomy For High Performance Actuators

The most common way to build electric actuators for robotics is to combine an electromechanical transducer, more specifically an electromagnetic motor, with a gearbox. This approach increases the actuator torque density at the expense of its interaction control capability. The main reason is that electric motors are most efficient at high speeds with low torque outputs, while robotic applications usually require high torque at low velocities outputs. Another way to actuate robots is to use Impedance Controlled Electrical Direct Drive Actuators for which the load is connected directly to the motor output, but the low torque densities that can be obtained are not sufficient for our intended use [5,6].

The DEA concept will now be explained using a simplified model. First of all, let's represent a simple force amplification mechanism by the lever shown in Figure 2, with F_M being the input force generated by some motor, F_L being the output force generated by some load and O_2 the instantaneous center of rotation of the lever. Generally, O_2 corresponds to the gearbox housing, which is attached to the robot chassis, providing only 1 DOF to the overall mechanism. The amplification ratio of the transmission mechanism is set by the distances r_1 and r_2.

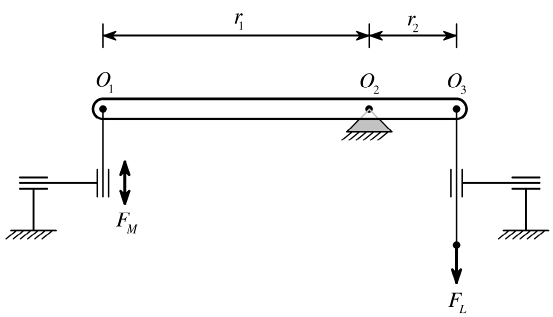


Fig. 2: *Simplified representation of a conventional gearbox mechanism.*

Force produced by the actuator at the load's attachment point (O_3) can be in theory deduced from the motor's force and the amplification ratio. However, a gearbox is a mechanical component that introduces non-linear friction losses, making such method imprecise in practice. Also, the gearbox will amplify rotor inertia and bearing friction by the square of the amplification ratio. Such high reflected mechanical impedance is appropriate for speed and position control but not for interaction control. *Joint Torque Controlled Actuation* (JTCA) [7] adds a force sensor between the gearbox output and the load, and use a closed loop controller to lower the apparent mechanical impedance of the actuator. However, output impedance will remain stiff at frequencies higher than the sampling rate of controller limiting its application for interaction tasks.

To cope with this drawback, elastic actuators add a flexible element (e.g., a torsion spring) in the transmission mechanism. This provides the actuators with intrinsic compliance [3,4]. However, there is a price to pay. Adding compliance outside the control loop reduces both bandwidth and the ability to closely regulate position. SEA put the low impedance element (a mechanical spring) in series with the gearbox as shown by Figure 3. Analyzing the force flux paths inside the mechanism shows that F_L passes through the flexible element and is divided between pivot O_2 (reaction force between O_2 and the chassis) and pivot O_1 (F_M).

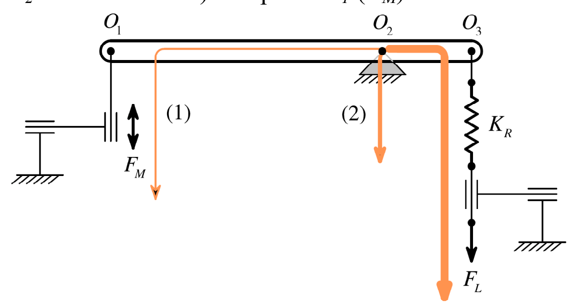


Fig. 3: *Simplified representation of a SEA. Arrows represent force flux paths inside the mechanism.*

Other variants of high performance actuators are:

- *Force Sensing and Compliant Actuators* (FSCA) [12] propose a variant to SEA in which the flexible element is placed between the motor's stator and the robot's chassis.
- *Variable Stiffness Actuators (VSA)*: they use a variable stiffness transmission mechanism. All the proposed implementations make use of two non-linear mechanical springs working in antagonistic configuration (like muscles). One additional transducer changes the mechanical impedance of the actuator during motion [8].
- *Series Damper Actuators (SDA)*: they use a magneto-rheological (MR) fluid damper in series between a high impedance transducer/transmission mechanism and the load. Variable impedance is obtained by changing the excitation current of the MR-fluid damper and/or by control [9].
- *Parallel Coupled micro-Macro Actuators (PaCmMA)*: they use a high power series elastic actuator in parallel with a low power direct drive transducer. The serial elastic actuator contributes for low frequencies/high amplitude forces while the direct drive actuator contributes for high frequencies/low power forces [10,11].

For all these categories, it is difficult to implement actuators in small volumes and with large force/torque outputs. Specifically for rotational actuators, none of existing solutions was adapted for compact integration in our robotic mechanisms. This motivated us to develop a new actuator mechanism.

Differential Elastic Actuator Concept

Compared to SEA and FSCA, DEA uses a differential coupling instead of a serial coupling between the electromechanical transducer, the mechanical spring and the load. Figure 4 shows the fundamental difference, which lies in the way the gearbox is connected to the rest of the mechanism.

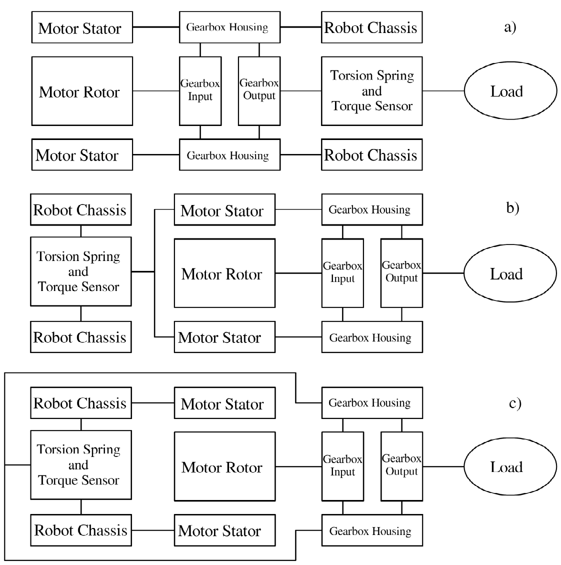


Fig. 4: *Mechanical interconnection of the components: a) SEA, b) FSCA and c) DEA.*

One can easily understand the operation principle of DEA by looking at Figure 5.

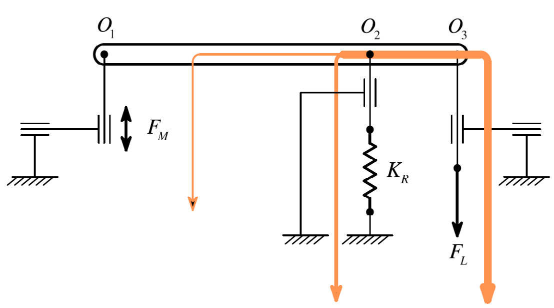


Fig. 5: *Simplified representation of a DEA. Arrows represent force flux paths inside the mechanism.*

In a DEA, the flexible element is introduced between O_2, which corresponds to the gearbox housing, and the robot chassis. F_L is divided similarly to SEA, with the flexible element receiving part of the force applied at the load.

The concept behind DEA can also be explained by computing the output mechanical impedance. Mechanical impedance can be associated to any mechanism having one degree of freedom. This complex variable determines the dynamic properties of the mechanism from the load perspective. It can be seen as the transfer function described by equation (1) linking the input *Velocity* and the output *Force* measured at the interface between the actuator output and the load:

$$Z(s) = \frac{Force(s)}{Velocity(s)} \tag{1}$$

Inspired by broadly used electrical impedance diagrams, we modeled DEA using a mechanical impedance diagram. We used the following analogies between electrical and mechanical domains with symbols shown in Figure 6:

- Force/torque ⇔ Voltage.
- Velocity ⇔ Current.
- Mass ⇔ Inductance.
- Spring ⇔ Capacitor.
- Viscous damper ⇔ Resistor.
- Ideal speed reducer (gearbox) ⇔ Ideal electric transformer.

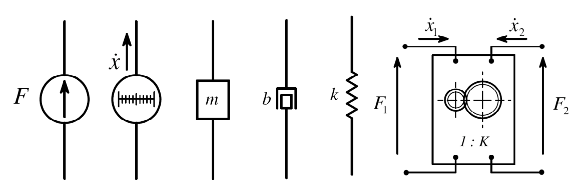


Fig. 6: *List of symbols used in mechanical impedance diagrams, from left to right: an ideal source of force, an ideal source of velocity, a mass, a viscous damper, a spring and an ideal speed reducer.*

A mechanical differential is a mechanism that provides a coupling between three mechanical ports. Basically, any «two ports» mechanism that provides force/torque amplification by a factor K can be used in a «three ports» differential configuration mode. The kinematical relationship between the three rotational/linear speeds ($\dot{x}_1, \dot{x}_2$ and $\dot{x}_3$) is given by the Willis equation (2):

$$\dot{x}_1 + K \cdot \dot{x}_2 = (1+K) \cdot \dot{x}_3 \tag{2}$$

Additionally, the simple kinetic relationships between the three force/torques (F_1, F_2 and F_3) are given by Equation (3).

$$\begin{cases} F_2 = K \cdot F_1 \\ F_3 = (K+1) \cdot F_l \end{cases} \tag{3}$$

Differential Dynamic Actuators (DDA) represented by the impedance diagram of figure 7 behave similarly to two electrical transformers connected in parallel with transducers T1 and T2, having respectively the two mechanical impedances Z1 and Z2. DEA, a special implementation of DDA, use a controllable source of speed for T2 and a mechanical spring for T1.

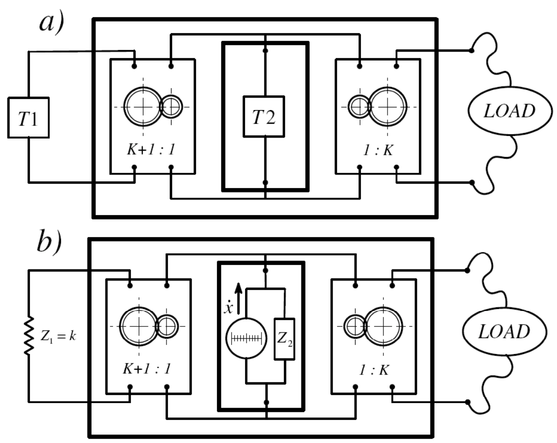


***Fig. 7:** a) DDA and b) DEA mechanical impedance diagrams.*

The equivalent mechanical impedance Z_{eq} seen from the load's perspective is given by Equation (4):

$$Z_{eq} = Z_1 \frac{K^2}{(K+1)^2} // Z_2 \cdot K^2 = \frac{Z_1 \cdot Z_2 \cdot K^2}{(K+1)^2 \cdot Z_2 + Z_1} \tag{4}$$

From the load's perspective, the mechanical differential acts as a speed reducer for T2. Thus, if the intrinsic mechanical impedance of T2 is low, the gear ratio and the intrinsic friction of the differential contribute to increase the equivalent impedance of T2 seen from the load. The most important aspect is that expression (5) must be verified:

$$(K+1)^2 \cdot Z_2 >> Z_1 \tag{5}$$

Accordingly, the expression of Z_{eq} can be approximated by Equation (6):

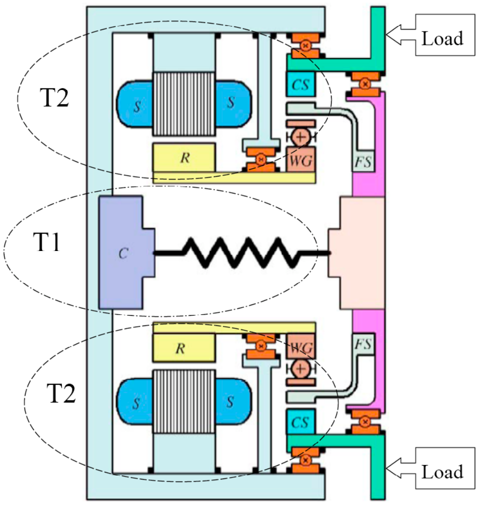
$$Z_{eq} \approx \frac{K^2}{(K+1)^2} \cdot Z_1 \tag{6}$$

Therefore, the fundamental property of DDA is that there is a precise known relationship between the mechanical impedance of the actuator and the output mechanical impedance of T1. The mechanical impedance of T2, which is in general very difficult to model, does not influence the mechanical impedance of the actuator. High intrinsic mechanical impedance of T2 is suitable but not absolutely necessary, as it does not affect the working principle of differential actuators. That means that interaction control between the actuator and the load can be achieved uniquely with impedance and/or force control of T1. When T1 is a mechanical passive spring (DEA), interaction control can be performed using a force/torque sensor in series with the spring and a force/torque control loop (similarly to SEA[4]).

Implementation of a DEA

The physical implementation of the mechanical differential does not change the working principle of the differential actuation concept. Possible implementations of a mechanical differential include the utilization of a standard gearbox, harmonic drive, cycloidal gearbox, bar mechanism, cable mechanism and all other mechanism that implement a differential function between three mechanical ports. For the implementation reported in this paper, we choose to use a harmonic drive for a very compact design.

Depending of the nature of transducer T1, several categories of high performance DDA can be imagined. For the implementation reported here, T1 is a passive torsion spring (thus the name Elastic), with a known impedance characteristic corresponding to the spring stiffness. T2 is implemented using an electrical DC brushless motor. A non-turning sensor connected in series with the spring measures the torque output of the actuator. Figure 8 shows our detailed implementation design.



S=Stator, R=Rotor, C=Torque Sensor, WG=Wave Generator, FS=Flexible Spline, CS=Circular Spline, Zigzag line represents the torsion spring

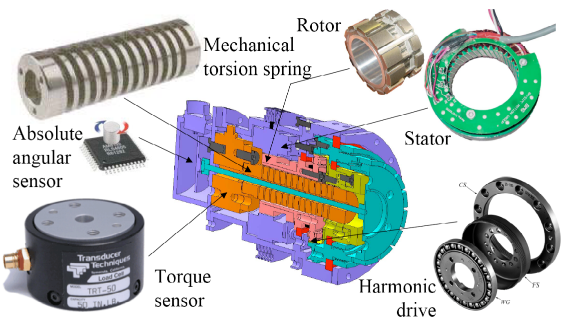


Fig. 8: *DEA implementation using a harmonic drive, a torsion spring and a brushless motor.*

Open Loop Mechanical Gain and Output Impedance

As expressed by Equation 7, two transfer functions characterize a double input single output elastic actuator in open loop: its mechanical gain and its output impedance [3,4]:

$$F_L = G_{OL}F_M + Z_{OL}X_L \qquad (7)$$

with:

F_L : output force/torque applied to the load

F_M : input force/torque provided from T2

X_L : input load displacement

G_{OL} : force/torque amplification gain

Z_{OL} : output mechanical impedance

We derived these transfer functions analytically from free body diagrams and kinetic equations for two categories of elastic actuators (SEA and DEA) and validated our results with DYMOLA, a mechanical simulation software. Figure 9 illustrates these results for SEA and DEA.

Frequencies that present a practical interest are low frequencies for the open loop torque gain bode plot (robotic interaction tasks) and high frequencies for the output mechanical impedance bode plot (shock tolerance). We observe that below the cut-off frequency, both SEA and DEA have the same constant torque amplification gain, which correspond to the gearbox ratio. For very high frequencies, identical low output impedances, corresponding to the spring stiffness and the output shaft inertia, are observed for both SEA and DEA. Finally, both SEA and DEA have the same cut-off frequency of 4,4Hz. Consequently, DEA have the same dynamic properties than SEA for the frequencies that present a practical interest in our application.

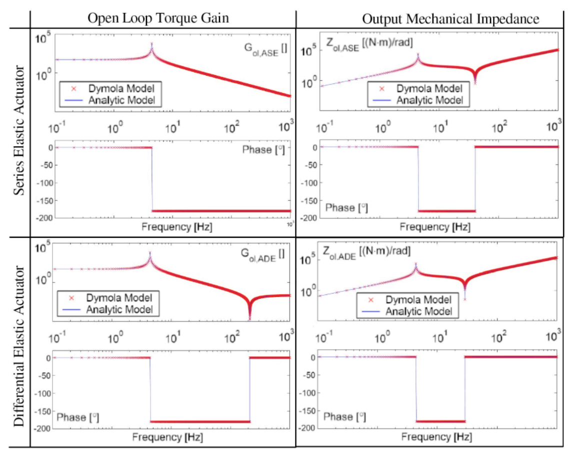


Fig. 9: *Open loop torque gain and output mechanical impedance bode plots of SEA and DEA.*

There is a simple proportional relationship between current I_M and torque F_M when using a brushless DC motor. Thus, the open loop mechanical gain can be measured by immobilizing the load and measuring the output torque F_L for a specific motor current I_M (as done in [3,4] for SEA). For our measurements, we used a sinusoid input current waveform. We changed its frequency from 0 to 15Hz. We repeated this operation for three sets of current amplitudes. These measurements are presented in Figure 10 and compared with our model obtained by simulation.

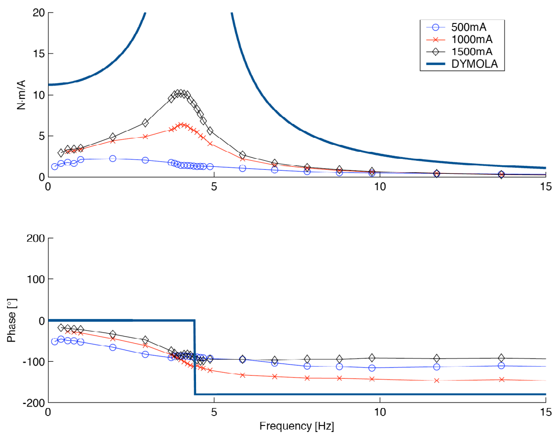


Fig. 10: *DEA's measured open loop torque gain for three sets of sinusoidal input current waveforms of different amplitudes and comparison with a simulated model.*

We observe significant differences between the measurements and the simulated model. Additionally, our three sets of data show us that there is a dependence between the gain and the input amplitude. That means that our implemented DEA hasn't a linear system behavior. These two observations may be explained by the fact that we didn't take into account the non-linear friction of the harmonic drive gearbox and bearings in our models but this hypothesis hasn't been verified yet.

Conclusion

This paper demonstrates that differential coupling offers similar performances but with implementation advantages compared with serial coupling, especially for high performance rotational actuators because it leads to a more compact and a simpler design (e.g., T1 is a limited angle transducer connected to a fixed point, eliminating the need for slip rings). Thus, our results confirm the suitability of the differential elastic actuator for robotic applications involving mechanical interaction tasks.

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