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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 used for mobile robot locomotion.**

I. 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.

For usage in uncontrolled environments such as in 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 [1]. Interaction control involves specifying a dynamic relationship between motion and force, and implementing a control law that attempts to minimize deviation from this relationship. 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 [2,3].

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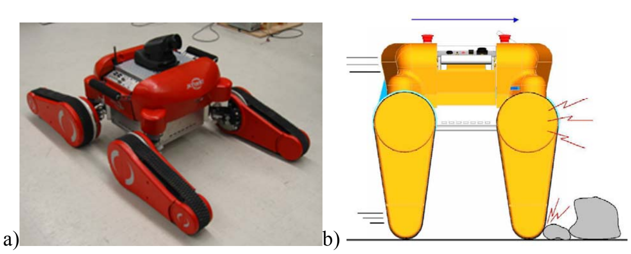
In fact, it is with the objective of improving the locomotion capabilities of a mobile robot platform in mind that we got interested in interaction control. Figure 1a shows AZIMUT, a legged tracked wheeled robot capable of changing the orientation of its four articulations [4]. Each articulation has three degrees of freedom (DOF): it can rotate 360° around its point of attachment to the chassis, can change its orientation over 180°, and rotate to propulse the robot. AZIMUT's first prototype was built using stiff transmission mechanisms, with motors and gearboxes placed directly at the attachment points of the articulations. These design choices made the platform vulnerable to shocks when moving over rough terrain, especially with its articulations pointing down as depicted in Figure 1b: an undetected obstacle touching the tip of an articulation would create an important reaction force at the articulation's attachment point to the chassis and inside his non back drivable gearbox.

Adding actuator compliance and being able to sense the forces from the environment are therefore important requirements for safe and efficient robots operating in real life settings. For mobile robots in particular, size and weight of actuators is an important requirement considering that the platform has to carry its own energy source, which affects the weight and torque requirements of its motors, all constrained with the intended application objectives and operation environment. Therefore, we initiated a design project of a new and compact high-force low-impedance rotary actuator for interaction control, with locomotion as the primary application. This paper presents this new actuator, named *Differential Elastic Actuator* (DEA). Compared to the abundantly studied *Series Elastic Actuator* (SEA) [5,6], DEA uses a differential coupling instead of a serial coupling



a) b)

Fig. 1 a) AZIMUT robot first prototype. b) This platform is vulnerable to shocks when moving over rough terrain especially with its articulations pointing down.

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.

This paper is organized as follows. Section II presents theoretical background and taxonomy of high performance actuators for robotic interaction tasks, situating the innovation behind DEA. Section III analyses the dynamic properties of DEA and compares them with SEA. Section IV presents our mechanical implementation of DEA and its dynamic performances in open loop. Section V concludes the paper with an outline of future work on this new concept.

II. 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 [7]. The main reason is that electric motors are most efficient at high speeds with low torque outputs [5], 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 (ICEDDA) 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 [8,9].

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.

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) [10,21] 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 [5,6]. 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).

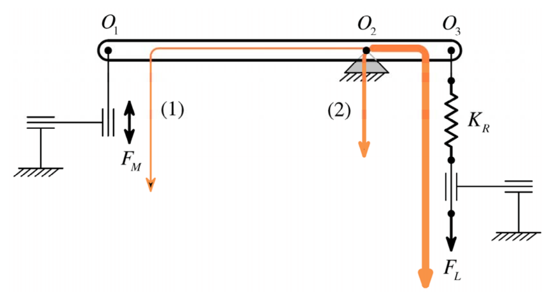


Fig. 3 Simplified representation of a SEA. Arrows represent force flux paths inside the mechanism.

Force Sensing and Compliant Actuators (FSCA) [11] propose a variant in which the flexible element is placed between the motor's stator and the robot's chassis. Figure 4 illustrates the concept. The advantage compared to SEA is that the flexible element and the force/torque sensor is attached to the chassis and doesn't move with the load. In applications requiring multiple revolutions capability of the actuator output, this avoids the necessity to use a slip ring to connect the torque sensor. Although the advantages procured by this configuration, FSCA implies both motor's stator and gearbox housing to move increased output mechanical impedance and vulnerability to shocks compared to SEA.

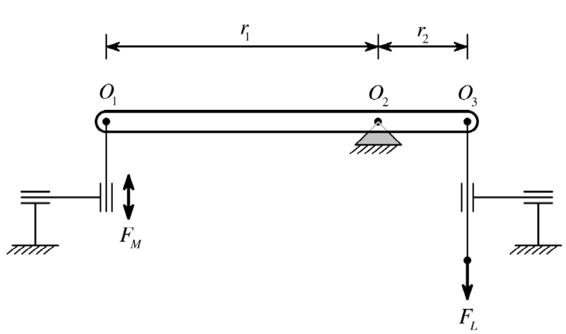


Fig. 2 Simplified representation of a conventional gearbox mechanism.

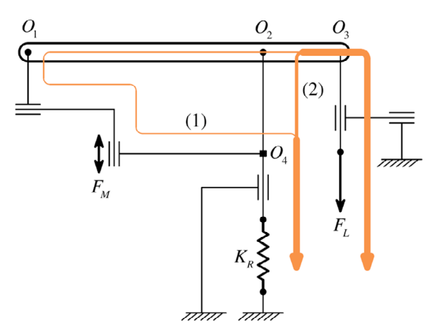


Fig. 4 Simplified representation of a FSCA. Arrows represent force flux paths inside the mechanism.

Other variants of high performance actuators are:

- *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 [12].
- *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 [13].
- *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 [14,15].

Figure 5 summarizes in a taxonomy all known categories of high performance actuators developed over the last 20 years for robotic interaction tasks.

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

III. 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 6 shows the fundamental difference, which lies

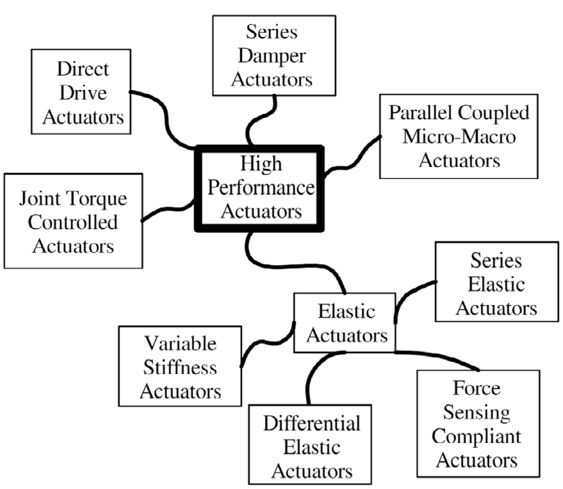


Fig. 5 Taxonomy of high performance actuators for robotic interaction tasks.

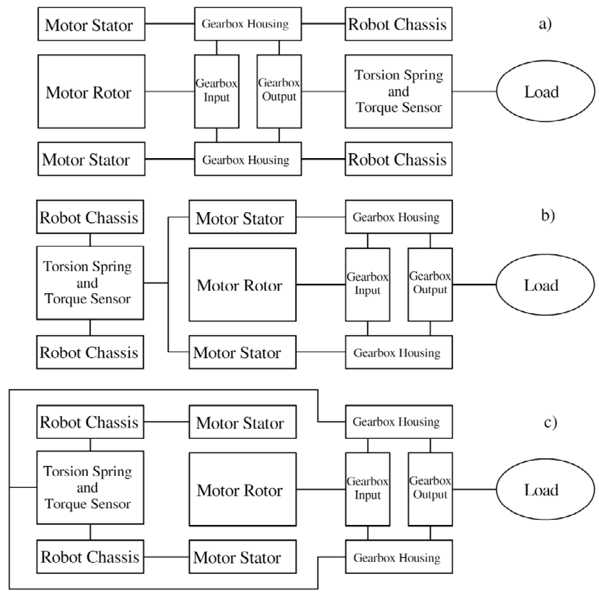


Fig. 6 Mechanical interconnection of the components: a) SEA, b) FSCA and c) DEA.

in the way the gearbox is connected to the rest of the mechanism.

One can easily understand the operation principle of DEA by looking at Figure 7. 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:

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

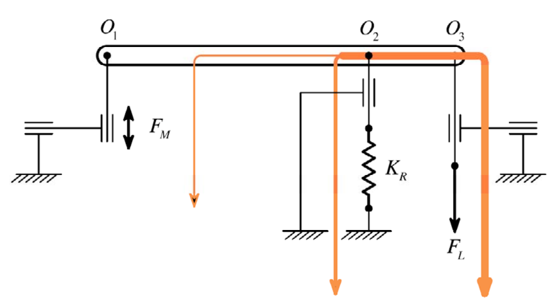


Fig. 7 Simplified representation of a DEA. Arrows represent force flux paths inside the mechanism.

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 8:

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

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):

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

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

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

Differential Dynamic Actuators (DDA) represented by the impedance diagram of figure 9 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.

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

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

From the load's perspective, the mechanical differential acts as a speed reducer for T2. Thus, if the intrinsic

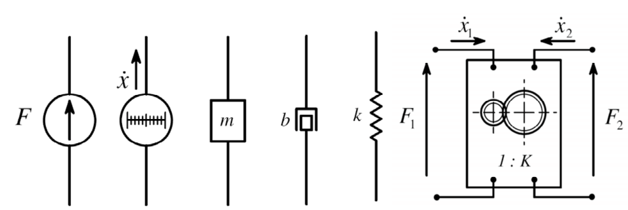


Fig. 8 List of symbols used in mechanical impedance diagrams, from left to right: an ideal source of force, an ideal source of velocity, a mass, a viscous damper, a spring and an ideal speed reducer.

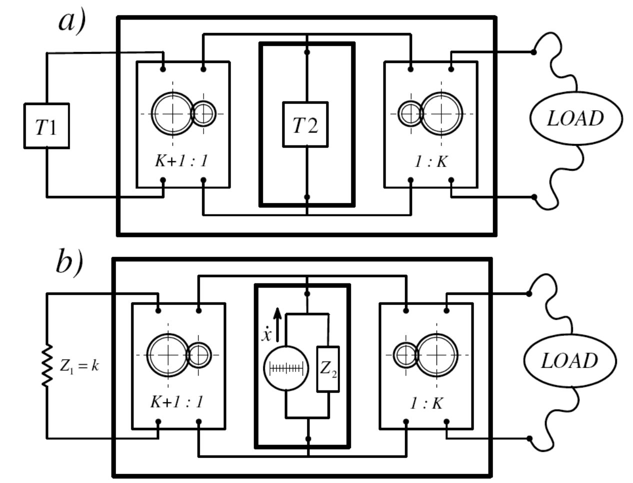


Fig. 9 a) DDA and b) DEA mechanical impedance diagrams.

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:

$$(K+1)^2 \cdot Z_2 >> Z_1 \quad (5)$$

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

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

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[6]).

IV. 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 10 shows our detailed implementation design.

Based on the work presented in [5,6,16], we derived a procedure to determine the specifications for the components (harmonic drive reduction gear ratio, electromechanical constant of the motor, and spring stiffness) of a DEA for our intended application [17]. In our case a 44 Nm continuous torque is required to actuate our AZIMUT platform.

V. 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 [5,6].

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

with:

F_L : output force/torque applied to the load
F_M : input force/torque provided from transducer 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 11 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

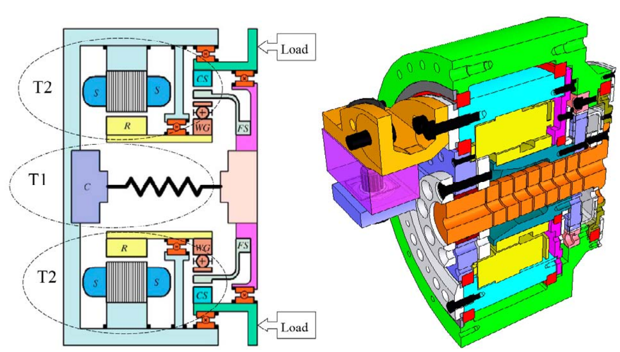


Fig. 10 DEA implementation using a harmonic drive, a torsion spring and a brushless motor.

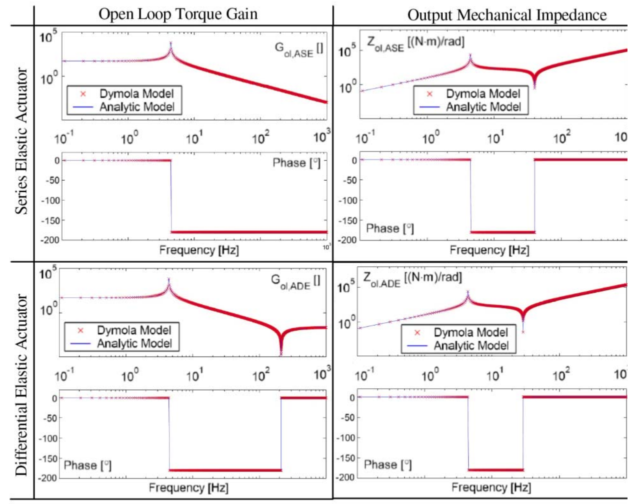


Fig. 11 Open loop torque gain and output mechanical impedance bode plots of SEA and DEA.

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.

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 [5,6] 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 12 and compared with our model obtained by simulation.

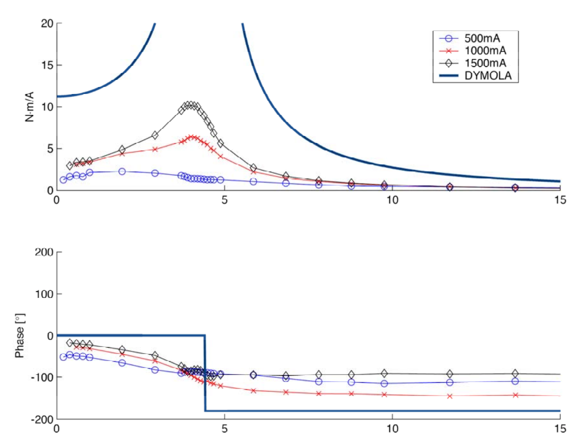


Fig. 12 DEA's measured open loop torque gain for three sets of sinusoidal input current waveforms of different amplitudes and comparison with a simulated model..

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.

Measuring the mechanical impedance can be determined by using a powerful motor as the load, viewed as an ideal velocity source (thus imposing x_L), and measuring F_L. Unfortunately, we did not have a testbed for the mechanical impedance measurement, and therefore we first focused on measuring the mechanical gain.

VI. 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).

Our results confirm the suitability of the differential elastic actuator designed for our AZIMUT robot, and we are currently moving forward with the fabrication of our next generation of leg-track-wheel robot (Figure 13). Once finished, locomotion capabilities of this improved prototype will be evaluated in terms of stability and adaptability over rough terrain, implementing closed loop impedance controllers (e.g., [7,18]). In future work, we also plan to build a testbed to measure DEA mechanical impedance and improve its analytical model by considering the non-linear effects in harmonic drives [19,20].

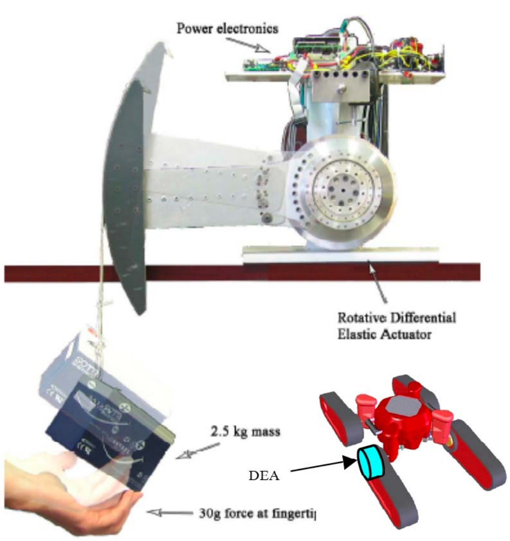


Fig. 13 DEA prototype being tested in a gravitation compensation experiment to demonstrate its accurate force control capability. Four DEA will be built and integrated into our new AZIMUT robotic platform to actuate its four legs.

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