

CARL: A Compliant Articulated Robot Leg for Dynamic Locomotion

G. Mennitto and M. Buehler¹

*Ambulatory Robotics Lab, Centre for Intelligent Machines,
Department of Mechanical Engineering, McGill University,
Montréal, Québec, H3A 2A7, Canada*

Abstract

We describe a new Compliant Articulated Robot Leg, CARL, which we constructed as a prototype for an autonomous robot quadruped. The leg has been designed for dynamic walking, trotting and bounding gaits, with an expected top speed of $3m/s$. It is an articulated 4 degree of freedom design with revolute joints as opposed to prismatic joints for improved mobility, simplicity and low friction. It employs electric actuation instead of hydraulics for indoor power autonomy, improved modeling, control and reliability. To minimize leg mass, CARL features an AnTagonistic LADD Actuation System (ATLAS) to convert motor power to high joint torques efficiently and at substantial weight savings compared to traditional transmissions. Energy efficiency will further rely on compliant operation, possible through new elastomer torsional springs at ankle, knee and hip joints.

Keywords: Legged locomotion; Compliance; LADD; Antagonistic actuation

1 Introduction

Beyond the sterile intelligence of a chess computer, most visions of intelligent machines involve physical interactions with an external world, as well as goal-directed mobility in

¹ Corresponding author. E-mail: buehler@cim.mcgill.ca; Tel.: (514) 398-8985; Fax: (514) 398-7348.

unstructured environments. To enable machines to move about, dynamic legged locomotion is the most versatile mode of operation when compared to wheeled or tracked mobility, providing the best combination of speed and mobility for a given machine volume.

We selected a four legged robot as a research platform to study the design and control of autonomous, dynamically stable legged creatures. Projected quadruped specifications are in line with those of a large dog and include a height and length of $0.75m$, a total mass of less than $40kg$ plus $10kg$ for on-board batteries and a top running speed of $3m/s$. One of the four identical legs to attain these specifications is CARL, the subject of this paper, shown in Figure 1. It consists of three limbs - an upper leg, lower leg and a foot, with four degrees of freedom - a hip fore/aft, a hip lateral joint, a knee and an unactuated ankle joint. All joints are revolute as opposed to prismatic for improved mobility, simplicity and low friction. The leg is completely modular and self-contained with integrated sensors, power amplifiers and control computer.

In the sequel we will describe the key components of CARL. Electric actuation is motivated and described in Section 2. Section 3 details our unconventional light weight transmission which forms the basis of a compact actuation package, ATLAS, described in Section 4. Energy efficient operation is not only attempted via weight minimization, but also by relying on compliant operation, achieved via novel elastomer torsional springs, detailed in Section 5.

2 Actuation

To be most versatile, we require non-polluting operation in indoor and outdoor environments. Mainly for this reason, we decided on battery based electric actuation, instead of pneumatics or hydraulics. The resulting clean and safe operation is also important since the quadruped could well be in frequent and close contact with people. While battery energy densities today are still a major challenge, this approach will be able to exploit battery improvements resulting from automotive electric vehicle developments. Furthermore, we expect to achieve again accurate models of our electrically actuated quadruped robot, similar to [9]. Such accurate models are critical for model based controllers, and are in general more difficult to obtain for hydraulic or pneumatic systems.

A key design challenge is how to exploit fully the limited power density of about $80W/kg$ (continuous) for fractional horsepower DC motors. We simulated a “planar dog,” that is, a **planar** compliant quadruped (2 legs) to obtain realistic torque-speed specifications. While the available power is adequate, transmission ratios of $50 - 80$ are needed to provide the necessary joint torque. We found that this is difficult to achieve with traditional transmissions, while still remaining within the leg’s weight constraints of between $9 - 10kg$. For this reason we decided to pursue a technology invented and pioneered by Jacobsen [5,6], based on fiber connected hoops, termed LADD transmissions, as described in the following section.

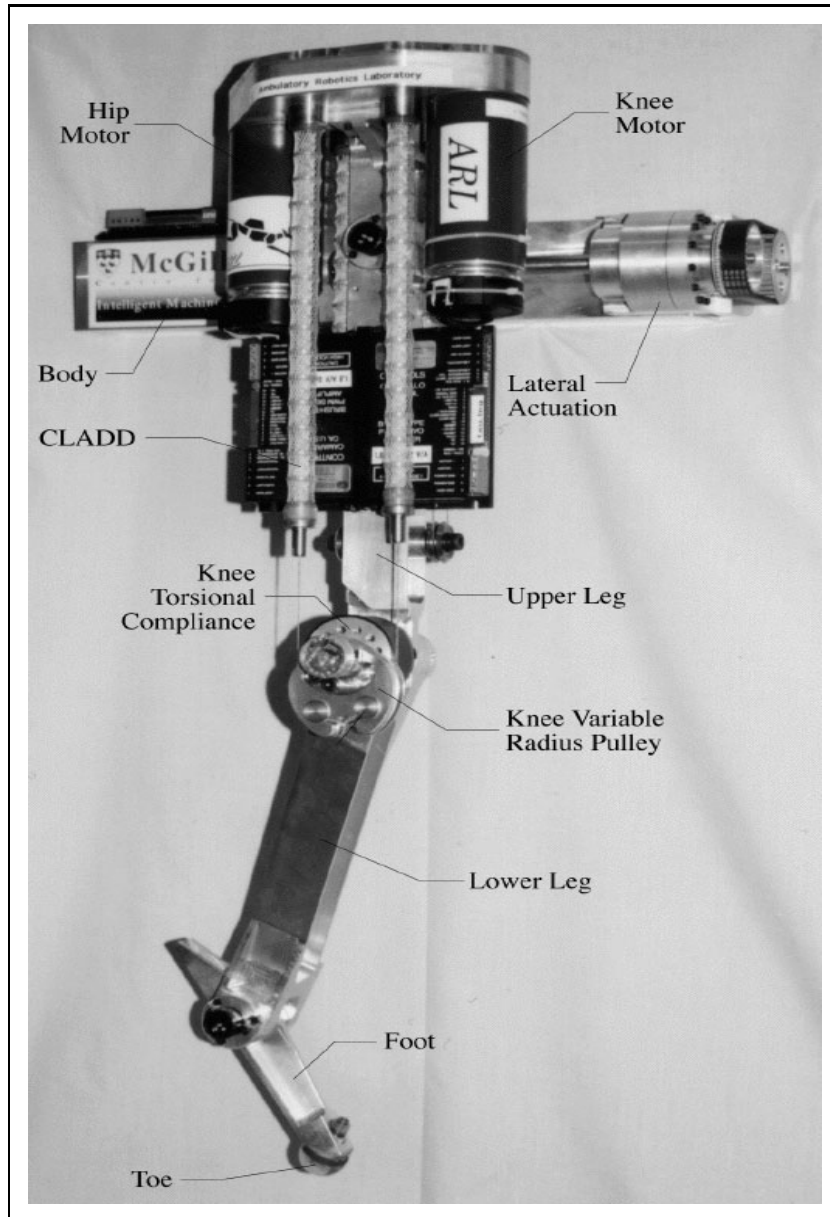


Fig. 1. CARL.

3 C/LADD Transmissions

LADD stands for Linear-to-Angular Displacement Device, and it is a transmission element converting rotational and translational (linear) motion. A LADD is composed of a number of single LADD cells fixed end to end. Each cell consists of two rings joined by high strength fibers, as shown in Figure 2. The behavior of this single cell describes the LADD's basic operating characteristics: As the cell is twisted, the distance between the rings decreases, thus rotary motion is translated into linear motion. Conversely, if a twisted cell is subjected to a linear displacement it will unwind, producing a rotary motion. Thus, operating boundary conditions for LADDs require only one degree of rotation and

translation.

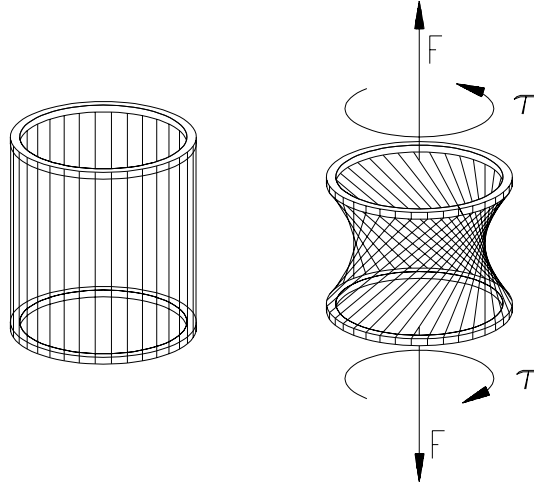


Fig. 2. Single LADD cell. Fully extended (left), and contracted under a load F maintained by a torque τ (right).

The key advantages of LADDs are their high strength, low weight, high efficiency and minimal acoustic noise generation. In addition, they are inexpensive to manufacture and do not require lubricants. Furthermore, a look at Figure 7 suggests that a system like ATLAS incorporating LADDs integrates very well along robot limbs in a similar fashion as muscles do in biological systems. Also, we have been able to exploit fully the maximum power regime of small electric DC motors, which is essential for autonomous operation. This is possible by taking advantage of the nonlinear LADD kinematics, combined with a properly shaped non-circular pulley at the joint which converts the LADD's linear motion to revolute joint motion. These properties make LADD systems highly attractive in both robotics and prosthetic applications [6].

A Concentric LADD (CLADD), shown in Figure 3 along with a simple LADD, is composed of two sizes of LADDs placed coaxially inside one another. In a CLADD based system, a stationary motor drives (rotates) one end of the inner LADD while the remaining end of the inner LADD is rigidly connected to one end of the outer LADD. At this connection point the external load is applied, and both inner and outer LADDs rotate and translate together. The remaining end of the outer LADD is fixed (no rotation or translation) at a position close to the motor.

One of the advantages of a CLADD over the single LADD chain is the removal of the slider mechanism at the load end which is necessary in LADDs to maintain the torque differential across the cells. This reduces both weight and complexity. With the CLADD, the reaction torque of the LADD cells occurs near the motor where the torque was initially generated. The load end of the CLADD rotates and a cable can be used to connect it to a pulley directly.

Besides eliminating the need for a linear motion guide, a CLADD configuration will increase a single LADD's effective length without physically doing so. The addition of cells

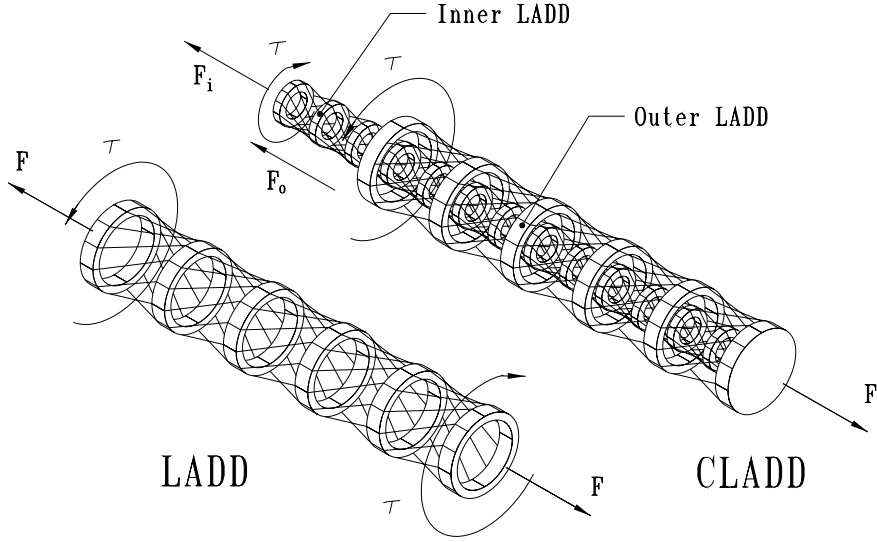


Fig. 3. *LADD and CLADD.*

allows the CLADD to operate at a higher mechanical advantage over a longer excursion than a single LADD chain with the same physical length. Also, the load applied to the CLADD is distributed over both the inner and outer LADDs, thus each LADD carrying a fraction of the load increases the CLADD's load carrying capabilities.

Modeling

In order to build a precise and high performance antagonistic actuation system as described below in Section 4, accurate LADD models are needed. To support our systematic experimental modeling validation efforts we constructed the set-up shown in Figure 4.

We found that the traditional non-elastic kinematic model [6]

$$\Delta l(\theta) = nD\sqrt{\left(\frac{L}{D}\right)^2 - \sin^2\left(\frac{\theta}{2n}\right)} - nL. \quad (1)$$

where $\Delta l, \theta$ are the LADD length change and rotation angle, n, D, L are the number of cells and the cells' diameter and length, resulted in errors of up to 18% full scale over the force and position operating range. Even worse, elastic models introduced so far were all based on fiber elasticity, which show an **increase** in LADD length from the inelastic length with force. We saw that in experiments the opposite is true. The LADD is always shorter than predicted from the inelastic model. As the load force increases, the LADD length approaches asymptotically the inelastic length. Closer inspection revealed the cause of this fundamentally different elastic behavior to be fiber bending as illustrated in Figure 5.

To account for this effect, we developed a local (LCM) and a global (GCM) compliance model, both of which reduce the modeling errors by an order of magnitude down to 1.5%.

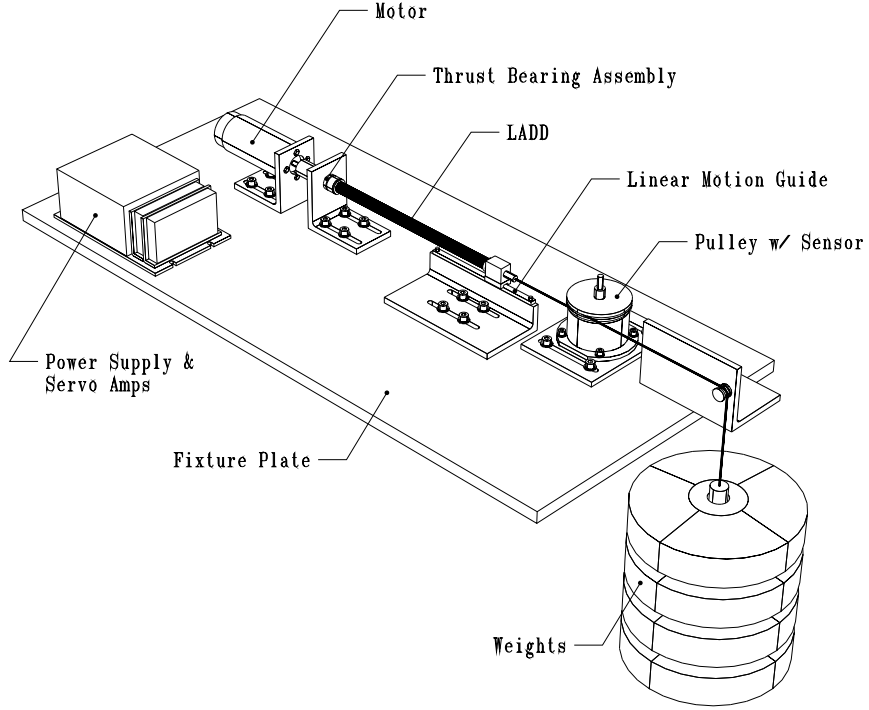


Fig. 4. *Experimental Set-up.*

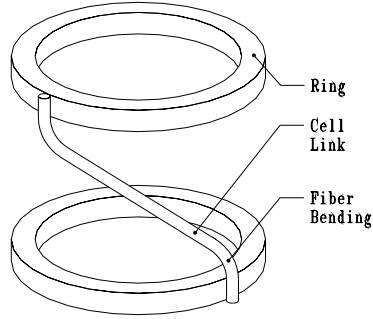


Fig. 5. *Fiber Bending.* A close look at a LADD cell in operation shows that the fiber links bend at the boundaries to the rings. This contradicts the inelastic model’s assumption that LADD cell fiber links remain straight during operation. The effect becomes more pronounced at large cell twist angles but reduces with increasing LADD loads, as reflected in Figure 6.

The LCM is identical to (1) except that the constant cell fiber length L is replaced with

$$L(\theta, F) = L - a(F)\frac{\theta^2}{n^2}, \quad a(F) = b_1 e^{b_2 F} + b_3$$

where b_i are functions of LADD design parameters. This enhancement models explicitly the fiber bending effect as a function of angle and load.

The GCM identifies a global compliance term $g(F)$. It is considered “global” because it

attempts to improve modeling by multiplying the overall contraction LADD length (1) by a factor that accounts for fiber bending as a function of LADD loading. Unlike the LCM, the GCM is developed after the inelastic model is developed, and is of the form

$$\Delta l(\theta, F) = \Delta l(\theta)_{inelastic} g(F) \quad (2)$$

where

$$g(F) = a_1 \exp^{a_2 F} + a_3 \quad (3)$$

and the coefficients a_i are determined using curve fits to experimental data. The resulting improvements for both local and global compliance models are displayed in Figure 6. The experimental contraction dl of a LADD ($:$) is plotted against the inelastic LADD model (“theory”) (solid line) given by (1). The LADD had a maximum full scale model difference of 18.3% at a $1kg$ load (top) and 9.2% at a $35kg$ load (bottom). We notice that as the motor angle θ increases, the magnitude of error increases as well and in contrast, as the load F increases, the error reduces. In the left plots, both compliance models (LCM, GCM) are indistinguishable from the experimental data. The error plots on the right show an error reduction down to 1.5% full scale independent of the applied load.

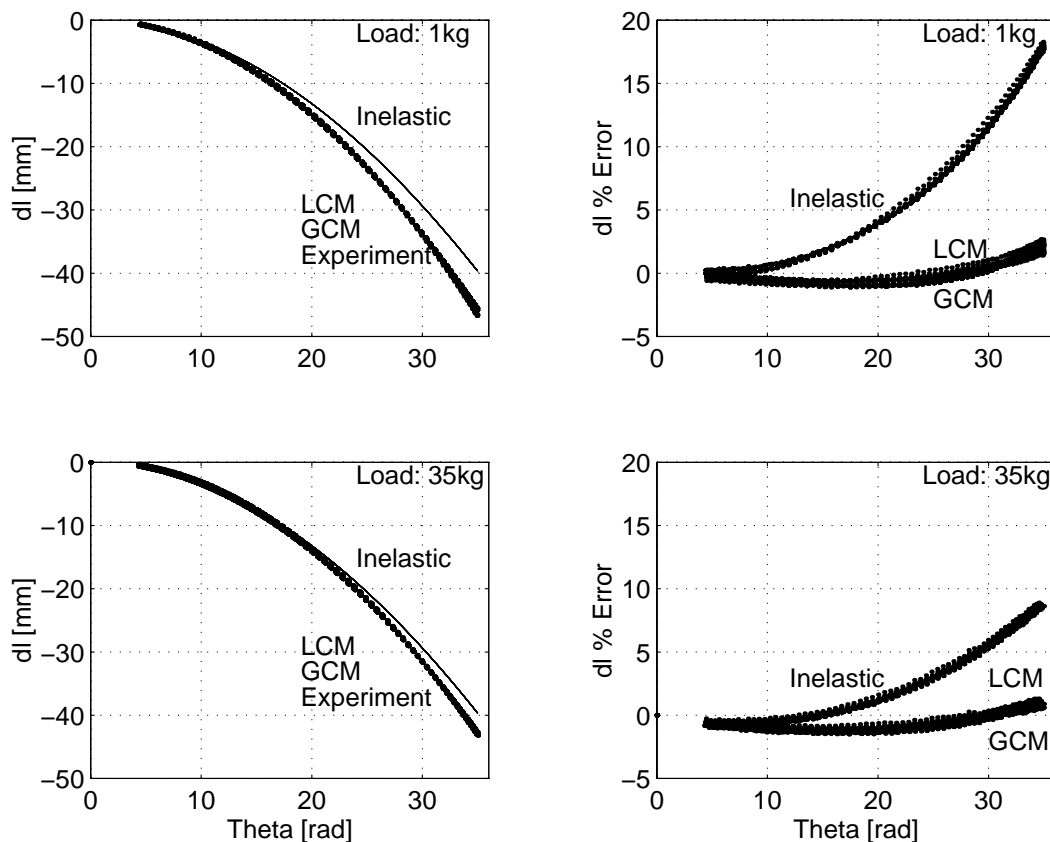


Fig. 6. *LADD Kinematics.*

CLADD Manufacture

Since CLADDs are not commercially available, we constructed our own. We chose the more recently available Spectra® fiber as opposed to Kevlar® used so far as the cell link material because of its superior resilience at the cost of additional fiber creep. Since the latter brought difficulties with long term modeling, we are presently searching for a better substitute. Each LADD is composed of 24 link fibers bonded to aluminum rings with CIBA-GEIGY general purpose epoxy structural adhesive. The end-pieces were manufactured from stainless steel and were designed to screw together to allow for easy assembly and disassembly for repairs and replacement. Further details about the selection of CLADD materials, the design and construction of a manufacturing set-up and a detailed list of construction steps can be found in [7].

4 ATLAS

ATLAS is an actuator system where a single electric motor drives an antagonistic pair of CLADDs, not unlike two muscles driving a joint, over a variable radius pulley (VRP) as shown in Figure 7. The purpose of the VRP is to maintain tension in the antagonistic CLADDs in the face of their kinematic nonlinearities.

In addition to compensating for CLADD kinematic nonlinearities to maintain constant internal force in the antagonistic pair, the VRP also results in a specified gear ratio. It can be either a constant or angle dependent. However, there are limitations. First, discontinuities are not possible, since the output of the CLADD is continuous. Second, large deviations over small rotations are not physically acceptable. Large decreases would not allow the previously larger lever to rotate out of the way, and large increases would cause the fiber to separate from the surface. In our current implementation, we designed the VRP for a constant combined CLADD/VRP transmission ratio of 25.

An additional gear ratio of 2 (giving a total of 50) is added through spur gears in the transmission housing shown in Figure 7 which provide a convenient method of distributing the motor input to both CLADDs. The same transmission housing provides gearing for both the knee and hip fore/aft actuation, as well as convenient support for the leg controller on top. Two tightening mechanisms allow proper adjustment of each cable that connects each CLADD to the VRP. Actuation is provided for each ATLAS system (knee and hip) with Maxon 80 Watt DC Motors which provide peak intermittent and average continuous torques of $1.8Nm$ and $0.4Nm$ respectively.

ATLAS has been designed to produce $60Nm$ knee and hip fore/aft actuation at a total weight excluding motors of $0.86kg$ and $0.95kg$ respectively. In comparison the lateral actuation based on conventional harmonic drive transmission weighs $1.2kg$.

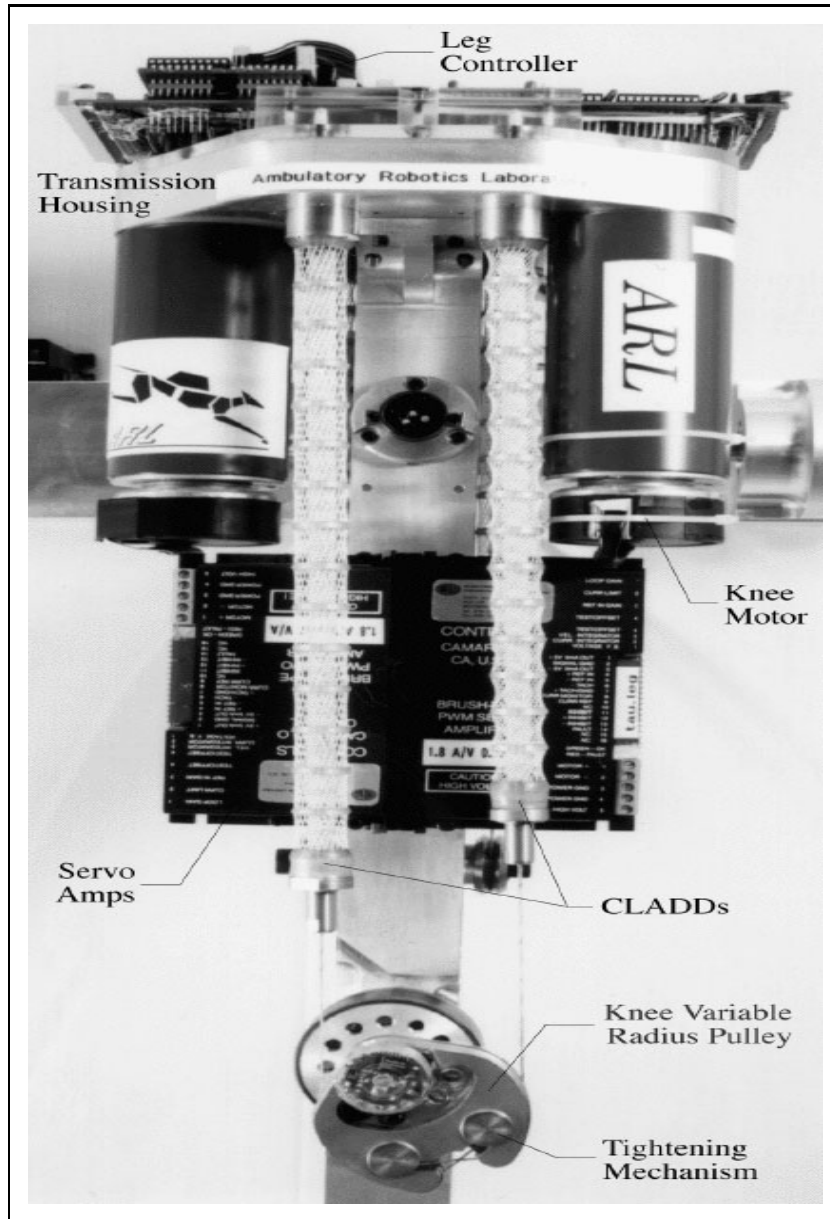


Fig. 7. AnTagonistic LADD Actuation System (ATLAS).

5 Torsional Compliance

Leg compliance is vital for energy efficient locomotion and power autonomy since much of the cyclic limb motion and the body's vertical oscillation can be provided by the nearly passive oscillation of a body's spring-mass systems [2,10]. This principle is used extensively in most mammals during dynamic gaits, and it saves as much as 50% in energy expenditure during locomotion. In animals, the tendons, muscles, cartilage and bones act as energy storing elements. While some robots have used single springs for this purpose in the past [8,9,10], CARL's distributed compliance permits full exploitation of this principle. Towards this goal we have developed a controller for a robot with two

compliant degrees of freedom [1].

The projection obtained from quadruped simulations require approximately $30J$ of energy storage per spring. We have pursued two elastomers, PolyUrethane as well as natural rubber. The torsional spring shown in Figure 8 is composed of a cylindrical shaped elastomer cast between two conical aluminum disks. The conical disk shape allows uniform strain of the material and thus optimal material exploitation. One device is located at the fore/aft hip, knee and ankle joints respectively. Each compliance is customized in terms of dimension and stiffness, determined from the dynamic simulation of a planar dog. The ankle joint is not actuated but compliant for energy storage and to minimize the unsprung leg mass whose kinetic energy would otherwise be lost at impact with the ground. The hip lateral joint is directly actuated via a harmonic drive transmission without compliance since the energy stored in lateral motion is relatively small and not periodic.

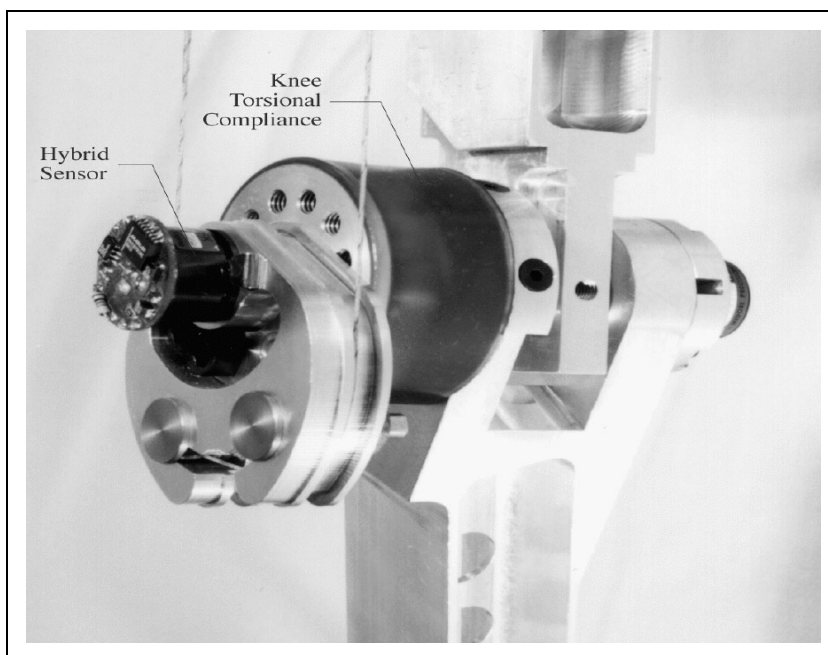


Fig. 8. *Torsional Knee Compliance.*

The torsion disk is a simple power transmission coupling which assumes a simple shear mode of deformation [3]. This deformation mode is used extensively for rubber springs and corresponds well with the predicted linear stress-strain relationship up to approximately 80% strain. In our application, the torsional springs do not sustain more than 75% strain in the worst case situation.

By exploiting the attributes of elastomers, we were able to achieve an efficient compliant system compared to conventional steel-coil springs. The material's extremely high energy density (150 times that of steel, see Table 1) makes the package light weight and compact: the spring at the knee weighs only 125g. Furthermore, since the elastomer is bonded directly onto the aluminum disks, no mechanical fasteners are required. Finally, we have measured very low damping coefficients, $\zeta < 0.05$, which permits efficient energy recovery.

Table 1
Energy Density of Different Materials, from [3]

<i>Material</i>	<i>Energy J/kg</i>
Grey cast iron	1.11
Extra-soft steel	9.18
Phosphor bronze	12.2
Rolled aluminum	22.6
Hardened and tempered spring steel	284
Hickory wood	365
Vulcanized rubber	44800

6 Conclusion

A new articulated leg prototype, targeted for an electrically actuated, autonomous quadruped has been constructed. We describe its key features – Electrically actuated CLADD based ATLAS and series torsional elastomer compliances. Both are promising technologies for electrically actuated legged devices which are integrated for the first time in a robot leg. While our current prototype leg’s total mass of $12kg$ would put the quadruped over the mass budget, we could readily bring the mass down to $9kg$ for the next iteration. Based on ATLAS we are exploiting small $80W$ DC motors weighing between $0.5kg$ (final version) to $1.3kg$ (current version) to provide more than $60Nm$ peak torque at the knee and hip fore-aft joints. A harmonic drive based system attains $120Nm$ at the lateral joint.

As a next step, we are planning to join CARL mechanically with our other planar one legged running robot, the ARL Monopod [4] to form a planar dog and implement and validate dynamic control strategies for quadruped operation on flat and rough terrains.

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