The Design of an Elastic Element for a Modular Series Elastic Actuator

by

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Abstract

The goal of this report is to facilitate the design of better series elastic actuators for use in legged walking robots. This thesis focuses on the elastic element as one of the most important and difficult portions of the actuator to design. Mechanisms from past series-elastic actuators are reviewed and compared. Actuator design goals and guidelines for an ideal spring are presented. A torsional cross-section is chosen as the elastic element for further analysis. This type of spring is chosen for its ease of attachment to other actuator elements, the potential for infinite tunability of its force/displacement relationship, and the need for a greater understanding of how to characterize this relationship.

Designs are presented for actuators that use "solid" sections which are aligned in series with other actuator components, and "open" springs that wrap around other actuator components. For the solid springs, simple, solid cross-sections are considered using a theoretical approach. The rectangle is found to be the most compliant of these sections, and is modeled to meet the design requirements: 20 degrees of displacement at 20 Nm of applied torque. Chosen volume constraints, however, make the rectangle impractical.

Next, an attempt is made to optimize the cross-shaped springs used in COG, the MIT AI Lab’s humanoid torso. Finite element analysis (FEA) is used to gain insight into the stress distributions. Due to the complexity of the models and problems with the FEA software, no conclusive results are reached on how spring geometry effects stiffness.

Finally, "open" springs are explored. A theory is presented on how loading a torsion section about a parallel axis (not its axis of symmetry) to which it is rigidly linked, effects its stiffness. A non-linear relation between the distance of the axis of loading from the axis of symmetry of the rectangle to spring stiffness was confirmed.

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I also thank Jerry Pratt, the Leg Lab’s chief perfectionist, for his "we can work this out" attitude and infinite patience in answering my questions, both pertinent and trivial.

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My penultimate thanks go out to the people at ADINA, who helped me to learn the nuances of their software and work around bugs that will be fixed "in the next version, which should be released by the summer of 1997."

Finally, I must thank my parents for footing the bill and all of their support along the way. At roughly $120,000 a pound, I hope they like this thesis.

Contents:

List of Figures:

List of Tables:

I.Introduction

The ultimate goal of this project is to produce a better series elastic actuator for use in research-oriented walking robots. The goal of this report is to study the elastic element and present an improved element design in accordance with the project goal. The elastic element is the focus of this report because it is the heart of a series elastic actuator and has not been the focus of past research. A secondary goal of this report is to detail the background issues involved in actuator design so that the next designer can quickly and intelligently build upon this work.

A.Outline

This introduction gives a brief summary of series elastic actuation and further explanation for focusing on the elastic element in actuator design. Section 2 focuses on project goal definition, giving a history of the series elastic actuators developed in the MIT Artificial Intelligence Lab (AI lab) and analysis of their functional components. This information is used to present guidelines for an "ideal" actuator and an ideal elastic element. Section 3 focuses on the choice of the type of elastic element explored in the rest of the report. The chosen type is a torsional cross-section.

Section 4 gives an overview of relevant torsion theory and an approach to solving finite element (FEA) problems. Section 5 focuses on theoretical analysis of the torsional spring problem. Section 6 focuses on the FEA analysis of rectangular and cross-shaped sections, and gives theory for a rectangular section loaded about a parallel axis. Section 7 presents relevant results, and Section 8 gives recommendations for further study.

A.Series Elastic Actuators

Series elastic actuation, first conceived in 1993 at the MIT AI Lab, allows the robot designer to inexpensively add compliance, force control, and energy recovery to robotic limbs [6].

A series elastic actuator is comprised of an electric motor, gearbox, and elastic element, with the elastic element placed between the gearbox and actuator output shaft as depicted in Figure 1-1 below:

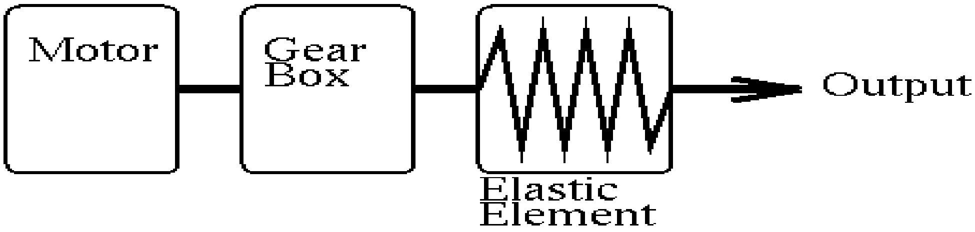

Figure 1-1: Schematic of a series-elastic actuator.

The added compliance greatly reduces the inertia transmitted by the gearbox, allowing the use of less robust motor and gearbox parts. This is especially useful when a robot limb impacts an immovable object.

Assuming the torque (or force) / displacement relationship of the elastic element is well characterized, a simple position detector can be used to "sense" the actuator torque output. Locating this force "sensor" beyond the gearbox in the drive train has the added benefit of masking gearbox backlash. A final advantage of series elastic actuation is the potential for the elastic element to store energy. Much like the elasticity of animal muscles and tendons, energy storage may greatly increase efficiency for tasks such as running. Figure 1-2 shows the schematic diagram of a series elastic actuator using both force and position control.

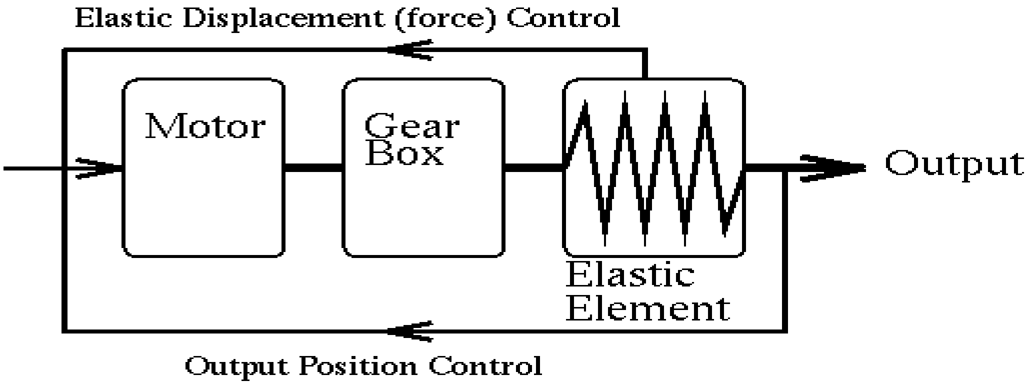

Figure 1-2: Schematic of a series-elastic actuator with feedback.

The main drawbacks of series elastic actuation are a compliance tradeoff between energy storage and control bandwidth, and the lack of precise position control. A more compliant spring can store more energy, but as the compliance of the actuator increases the motor must move more to attain a given torque. Therefore, increasing compliance decreases the maximum response frequency (bandwidth), particularly at higher loads. Also, position control suffers when the connection between motor output and actuator output is not a rigid link [6].

A.Focus on the Elastic Element

This report focuses on elastic element design because of the great variety of elastic elements available, and each type's correspondingly variant effects on actuator geometry (see Section 2.1). The elastic element could be a wire compression spring, wire extension spring, wire torsion spring, nonlinear power spring, constant-force spring, leaf spring, air spring, magnetic spring, torsional cross-section, or solid elastomer to name a few. Each requires a different mounting system and type of displacement sensor, and therefore different actuator geometry. On a basic level, compression springs will work best with linear systems, while torsion springs are better suited for rotational systems. Generally, there is no clear-cut "best" spring, but each type has definite design tradeoffs.

Motors and gearboxes, on the other hand, are readily available and pre-packaged so that they can be easily "plugged" into a system without modification. Compact, light-weight components are mass produced for the hobby industry. Once specifications have been established, finding these components is generally a matter of leg work, not design.

I.Goal Definition

This section elucidates the characteristics of good design for an elastic element to be used in the series elastic actuators of walking robots. Since the design of the actuator and elastic element are interwoven, the tasks are: a) to ascertain the characteristics of an ideal actuator, and b) use these to create spring design guidelines. A history of series elastic actuators is presented, with summaries of the assets and weaknesses of the different actuator components (Section 2.1.8). Actuator design guidelines are then presented, and spring design guidelines are given.

A. Past Work

Six different types of series elastic actuator have been designed and built in the MIT AI Lab. The assets and liabilities of the different actuators and their components are presented to familiarize the reader with: a) the issues involved in actuator design and b) the results of past research. The following descriptions are necessarily qualitative. Specific information on spring design is given in the body of the report where appropriate.

The actuator types discussed below are: COG's torsional cross sections, the Spring Turkey extension spring system, Trudy's compression packs, the elastic ball system, the Charcoal Chicken torsional actuator, and the self-contained Spring Flamingo actuator. A note is also made about the Chinese Windlass as a gear reduction mechanism. The actuators differ in: whether the design is robot-specific or self-contained, the type of gear reduction used, the type of elastic element, and the type of position sensor used. These differences are contrasted in the text, and important conclusions are summarized in Table 2-1.

1.The COG Torsional Cross Section

The first series elastic actuators were designed for use in COG, the AI Lab humanoid robot. The COG actuators were both robot- and joint-specific: the actuators were an integral part of COG's structure and springs were tailored to the different ranges of torque required by each joint. These actuators used planetary gear reduction. A torsional cross section torsion spring was the elastic element and strain gauges and potentiometers were used as position sensors.

The torsion section spring is the most unique feature of this actuator. Such a spring is created by machining the middle of a metal bar into a specific cross section. When the bar is loaded in torsion at its ends, the machined segment becomes the active part of a torsion spring. The section used for COG had a cross shape. The drawing of a current COG spring is depicted in Figure 2-1 below:

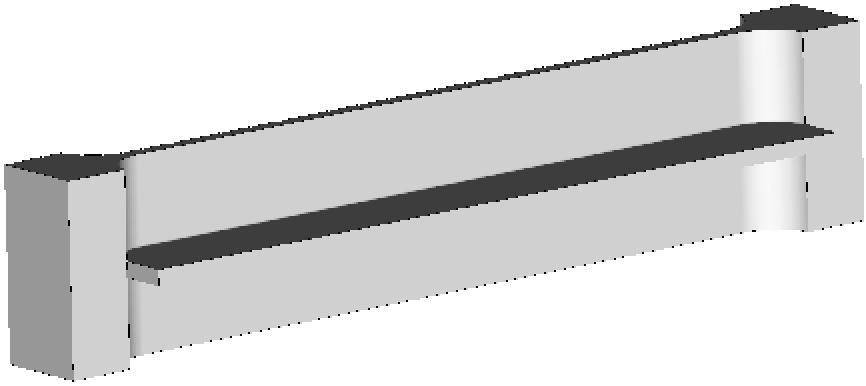

Figure 2-1: Drawing of a COG spring. This spring is approximately 5 inches long an has a rate of 1.8 Nm/degree, or a displacement of 10 degrees under a 17.9 Nm load.

Strain gauge systems were glued to the flanges of the cross in order to determine the displacement of the spring. Potentiometers were used to determine the position of COG's joints. The actuator was arranged in a linear fashion, with the motor, gearbox, and spring end-to-end-to-end.

The torsional sections are still in use and have functioned reliably since inception. Their key advantage is bi-directionality. This allows only one spring (see Section 2.2.2) to provide energy storage through both positive and negative displacements. Also, attachment of torsional sections is not difficult because the springs are created by machining, and end features may be designed with the spring.

The major drawback to torsional sections is that the relationships between geometry, stiffness, and maximum stress, particularly for the cross, are not fully understood. Designing these springs is largely empirical, which potentially leads to springs that are larger and less efficient than necessary.

The strain gauge system was an unobtrusive way to sense the spring displacement without increasing the size of, or friction imposed on the actuator. The major disadvantages of the strain gauge system were the need to precisely glue the gauges onto the actuator and the strain gauge amplifier necessary to interpret its signal.

1.The Spring Turkey Extension System

Spring Turkey was the MIT Leg Lab's (part of the AI Lab) first series elastic walking robot. This robot walked in two dimensions, constrained to walk in a circle by an attached boom. Spring Turkey had single-degree of freedom hip and knee joints on each of its two legs.

Its actuators were, as in COG, an integral part of the robot design and structure. These actuators used a harmonic drive gear reduction system, linear extension springs, rotary potentiometers for sensing joint position, and tape-measure-like linear potentiometers for sensing spring displacement.

The motors were located in the body of the robot and spring packs were located on the legs. Torque was transmitted from the motor to the springs via a steel cable and pulley system. Cables were chosen because they are extremely stiff, have negligible backlash, and allow the mass of the motors to be in the body, keeping the legs lighter. Spring Turkey is depicted in Figure 2-2 below:

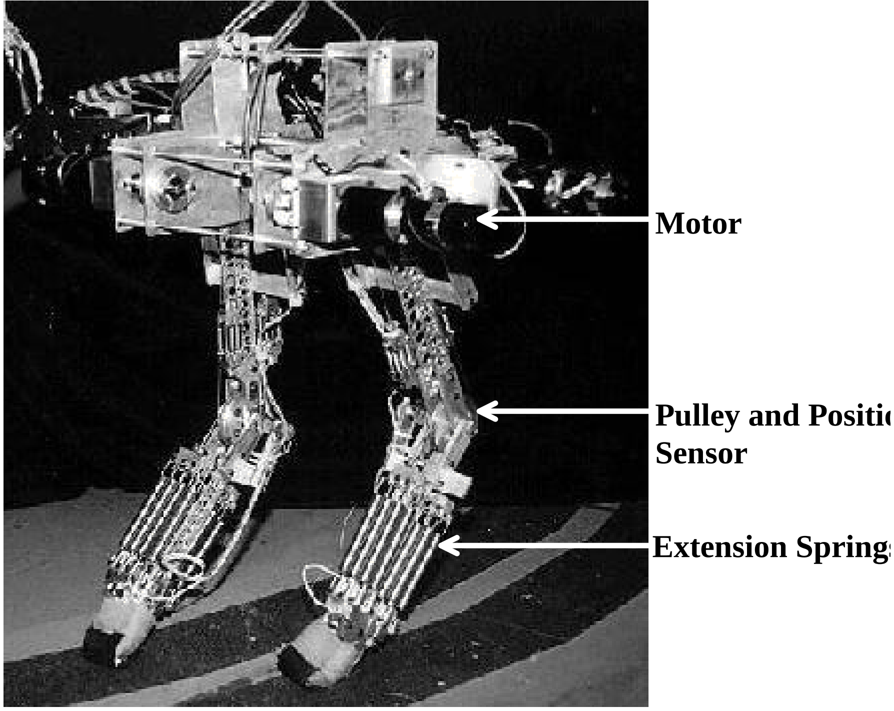

Figure 2-2: Spring Turkey, photo courtesy of the MIT Leg Lab.

The spring system for each joint was composed of a pulley and two opposing spring packs, as depicted in Figures 2-2 and 2-3. The springs were "attached" to the pulley at one end and to the leg at the other. Both spring packs were pre-loaded with the same force. When the pulley was turned by the drive motor, it increased the force on one spring pack and decreased the force on the other. The resultant force was two times (two spring packs) the spring displacement times the effective spring rate of a pack. The moment necessary to pivot the leg for walking was created by attaching the springs to the leg off of its radius of rotation.

In this fashion extension springs, which only resist motion in one direction, were used in a bi-directional application. The spring pre-load was chosen so that both spring packs exerted a force on the pulley at any given joint displacement, thus eliminating "play" in the spring system. At zero displacement, both springs sets exerted the same force (the pre-load), and there was no net joint torque. At the extremes of motion, one spring pack would be almost fully extended, and the other would be almost fully relaxed. A schematic diagram of this system is shown in Figure 2-3 below:

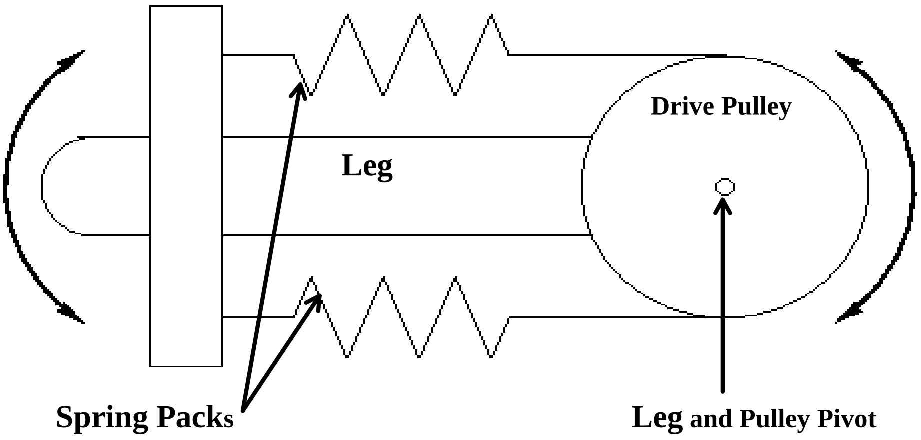

Figure 2-3: Schematic of Spring Turkey spring /pulley system.

The Spring Turkey extension spring system was beneficial because, as in animals, the linear springs could be easily and naturally distributed throughout the legs of the robot. Also, these springs were common and inexpensive, so replacing them was not difficult. Unfortunately spring rates tended to change when the springs were overextended and as the springs aged. These changes caused the control system calibration to drift, which led to overall control problems. Also, as with COG, making the actuators integral to the body design saved space, but necessitated the redesign of the actuators whenever the robot design was altered.

The linear potentiometers functioned well, but were expensive ($400 each) [5]. The harmonic drive system had very low backlash, but was heavy and cost $800 each.

1.Trudy’s Compression Packs

Trudy is the most mechanically complex of the current Leg Lab robots. This 16 degree of freedom, three-dimensional walking robot uses actuators very similar to those on Spring Turkey. These actuators are integral to the robot design, use linear springs in an extension configuration, and use linear potentiometers to measure the displacement of some springs. Trudy differs from Spring Turkey in the use of model airplane servos and traditional gears instead of a harmonic drive system. Also, Trudy’s "extension" springs are actually compression springs in special housings. Trudy is not yet functional, but intuition can yield some insight into the potential effects of these design changes.

The greatest benefit of switching from a harmonic drive to standard gearing is the significant reduction in the cost of drive components. A secondary benefit is the ability to distribute gear components throughout the legs of the robot. Flexibility of gear placement is important for Trudy, as looking like a dinosaur is one of her design goals.
Potential problems with this change are an increase in gear backlash and increase in the complexity of the drive system. The added backlash is probably of little concern because the series elastic system should be able to compensate for this flaw without degrading the performance of the actuator. Added complexity is more worrisome because it makes robot construction difficult and potentially reduces gear efficiency, as all of the gears must be properly aligned. Also, a more complex robot has more potential modes of failure. The complexity of this system can be seen in Figure 2-4 below: