Massachusetts Institute of Technology
Department of Mechanical Engineering PhD Thesis Proposal

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Series Elastic Actuators: Theory and Practice

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PhD Thesis Proposal
Series Elastic Actuators: Theory and Practice

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Abstract

I propose to develop a more complete theoretical and practical understanding of force controllable robotic actuators which have compliant elements intentionally placed in series with the output. This will be done for both the electro-mechanical as well as the hydro-mechanical domains. Emphasis will be placed on physical prototypes to aid in this understanding. The springs in the actuators as well as the actuator control and operation will be thoroughly analyzed. This research will lead to design guidelines and experience for further actuator and robot development.

1 Introduction

Force control has been an important branch of robotics research for several decades [28] and continues to be important now. There are many driving applications for force control and force controllable robots. Advanced robotic manipulation, assembly, grinding, and polishing enhance automated manufacturing capabilities. Haptic devices are being used in virtual reality applications. Force reflective teleoperation has lead to work in human scaling, both magnifying and reducing, as well as rehabilitation and therapy robots. Force control research is also being being conducted on biomimetic robots such as in legged robot locomotion and robot swimming.

The premise for force control is that humans and other terrestrial animals with biological actuators (muscles) are force control machines. We have difficulties in repetitive, exact positioning tasks and are much better at generating appropriate forces to accomplish a given task. Traditional robots on the other hand, are very good at precise positioning and tracking tasks. One major reason for this is that robotics has evolved out of the machine tool industry where precision, accuracy, and stiffness are paramount. This has been followed by research in control systems which have helped robots achieve a high level of proficency in positioning oriented tasks [5, 23]—a natural fallout of robot evolution from machine tools. But when these same robots interact with the environment, their evolved positional causality and construction make force control difficult. Robots have still been able to work within a given environment but for some applications it would be advantageous to alter their causality and construction to make them work with unknown environments like we do.

Actuators are usually the limiting factor in force controllable robot performance. Currently, the most ubiquitous robot actuator is the electric motor. They are clean, fairly inexpensive, and easy to maintain. They can also be modeled as linear systems with some degree of accuracy. This allows for simplified analysis and control.

An electric motor's most efficient operating condition is at high speed and low force. This is just opposite of most biological motions which operate at relatively low speeds and high forces. A physical as well as a mathematical power transformation can occur with a gear train or transmission. While mathematically this works wonderfully, physically it presents problems for both position as well as force control. Gearing introduces backlash, friction, and stiction which leads to torque noise. If we try to eliminate one of these problems, another one will increase in magnitude. For example, non-backlash gears will increase drive friction [9]. Gearing also increases the dynamic mass of the motor by N^2 where N is the reduction. For geared motors, the large reflected inertia leads to broken gear teeth and ruined actuators when large unexpected loads appear.

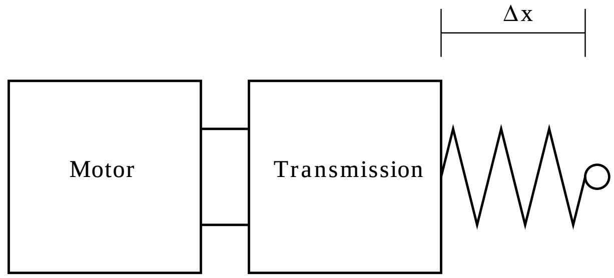

Figure 1: A spring is intentionally placed in series with the output and the spring deflection is controlled thus inferring force control.

While hydraulic actuators suffer similar problems, they do have many good qualities. Hydraulics opperate best in the high force, low speed regime good for biomimetic motions. They also represent a relatively high force/mass, high power/mass class of actuators. Hydraulics can be good at position control. But, because of friction, stiction, and supply pressure variations, force control can prove difficult [2]. The fluid has a large inertia as well. In order to reduce friction, the seal tolerance can be lifted. But, that has a direct effect on system efficiency not to mention the problems of keeping the work environment clean.

It is interesting to note that biological actuators, force generating muscles, are connected in series to a link output through elastic tendons [1]. Furthermore, in robotics, it has been demonstrated that increasing compliance in a robot actuator aids in the stability of force control [8]. Following this train of thought, electric motor actuators with intentional compliant elements in series with the transmission and output, Series Elastic Actuators [29], have been constructed and used with some success. The strain in the spring is measured. In the case that the spring is linear, Hooke's law, $F = k\Delta x$, is used to servo the motor to the correct spring displacement for a desired force (see figure 1). The spring acts as a lowpass filter for shock loads from the environment as well as a filter for friction and backlash from the reduction. Series elasticity has not yet been applied to other power domains like hydraulics but could be with potentially similar results.

There remain many open questions regarding series elastic actuators. In order to better understand series elasticity more completely, I propose an in depth study of the actuators. This will be done with both theoretical models as well as experiments and demonstrations of real actuators for both electro-mechanical and hydro-mechanical domains.

2 Related Work

Force control has been a subject of research for many decades. Good summaries of compliance control and other active force control methods are given in [14, 28]. These methods include damping control, stiffness control, impedance control and hybrid position/force control. Each of these methods, while using different algorithms, calculate joint forces to obtain a desired endpoint reaction force. Passive force control for particular tasks such as passive peg-in-hole assembly has also been investigated [7].

A major limitation for many of the active techniques have been the actuators. In order to clarify the baseline characteristics of various actuators, Hollerbach, Hunter, and Ballantyne presented a comparative study of robot actuator technologies [10]. This study includes traditional actuators such as electric motors, hydraulics, and pneumatics as well as shape memory alloys, conductive polymers, and piezo electric materials. These are all compared to each other and to human muscle in terms of force/mass and power/mass. While there are many different methods of producing robot motion, the discussion that follows will focus on the electro-mechanical and hydro-mechanical domains.

By eliminating transmissions and using DC brushless motors connected directly to robot links, Asada et. al. created direct-drive actuators and robots [3]. This construction eliminates friction and backlash and creates a very force sensitive actuator. Also, since the joint torques are sensed and commanded directly at the joints, the robot is more stable and robust to disturbances. Unfortunately, to compensate for the loss of transmission, direct-drive motors must be large in order to achieve high enough torques. High torque require high current. This in turn comes at the expense of increased motor mass and decreased efficiency. In weight sensitive and power sensitive robot applications such as mobile robots, direct-drive actuators are often unacceptable.

As an extension of direct-drive actuators, Salisbury and Townsend successfully created stiff, low-friction, *clean*, light-weight cable transmissions [25] for brushless DC motors. This led to novel robots such as the *Whole Arm Manipulator* [22] used in robot catching, and th *PHANToM* [21] used as a haptic interface.

While direct drive actuators trade off cost, efficiency, and weight for good force control and high bandwidth, those are not the only trade offs that can be made. In many applications such as mimicking animal motions, large bandwidth and perfect stiffness are not important. In fact, they are not even necessary for the robot to perform its function. Howard [11], Pratt[17], and Williamson [29] built electric motor rotary actuators with transmissions followed in series by a spring to the output. By measuring the spring deflection, a good estimation of force output can be obtained. These actuators have stability to shock loads and mechanically filter friction and backlash and other non idealities in transmissions. Versions of these actuators have been demonstrated in several biomimetic robots including: *COG* [4], *Spring Turkey*, and *Spring Flamingo* [18].

Elastic transmissions are an integral part of Morrell's parallel coupled micro-macro actuators [15]. In this scheme, a small direct drive actuator is coupled in parallel with a larger geared motor through an elastic transmission. While increasing the complexity of the actuator, an increase in dynamic range is achieved.

Springs and other compliant mechanisms have also been used for hydraulic actuators. Following examples from biology [1], Raibert's hydraulic legged robots use springs to recover impact energy when running [20]. Kleidon demonstrated a hydraulic piston in series with a pneumatic piston that could dynamically change the impedance properties of the actuator system [13]. Wells showed a hydraulic piston with accumulators which gave the actuator intrinsic compliance [27]. The actuator was much better able to tolerate external disturbances.

Placing a mechanical spring at the end of a hydraulic actuator and measuring the spring's displacement for force control is noticeably absent from the literature.

3 Approach

There are three main ideas that this thesis will attempt to address.

- Build and Demonstrate Actuators.
- Examine Requirements and Effects of Springs.
- Examine Actuator Control and Operation.

These ideas or research areas are interdependent and therefore cannot be completely isolated from each other. Their division, however, helps to clarify research goals. The three topics are discussed below.

3.1 Demonstrate Actuators

Demonstrating hardware is a vital part of this thesis. It is therefore addressed first. The idea of building hardware is not just to demonstrate it once and say, "See it worked." The hardware needs to be constructed at various levels both theoretical and physical.

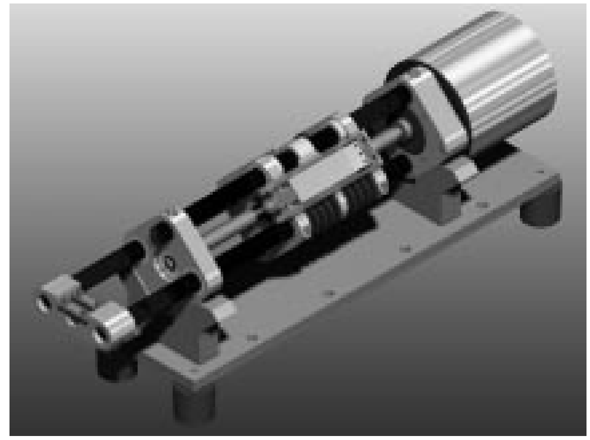

Figure 2: Prototype Series Elastic Actuator for use in a walking biped robot and a running quadruped robot.

The first step will be to build a physical actuators for both the electro-mechanical and hydro-mechanical domains. These actuators are not meant to be the end all actuators but rather will help guide the research in several ways. Most importantly, it will keep the theoretical models honest.

The physical actuators will help in the verifying non-dimensional linear and nonlinear mathematical models of the actuators. A great deal of insight is hoped to be gained in generating the linear models. It will also be important to define how closely the actuator matches the linear model if simple design rules are to be generated for component selection and matching.

In order to test the physical prototypes, a testbed must also be constructed. This testbed will be able to monitor actuator performance as well as simulate various load and environment conditions. The load will physically be a second order mass-spring-damper system (m, k, b). During testing impact loads and various combinations of m, k, b parameter values will be examined. For example free space would be no load at all. A rigid wall would be infinite mass (ie lock the load in place.)

Qualitative performance criteria defined by Jacobsen and Smith [12, 24] are being considered to quantify the actuators, both physical and mathematical. Morrell suggests similar performance criteria [15]. Traditional control system performance criteria such as rise time and settling time are included in the tests, but

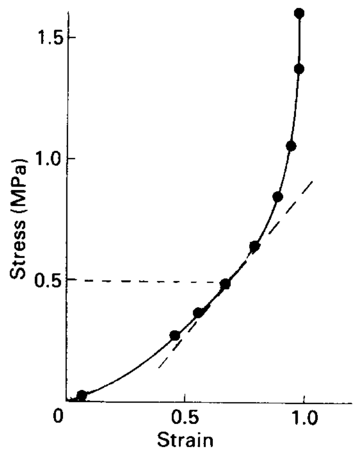

Figure 3: A graph of stress against strain for a deer tendon obtained from experiment. The gradient of the tangent is the tangent Young's modulus at a stress of 0.5 MPa. The graph is from Alexander [1]

alone are insufficient to describe the actuators. The proposed criteria are: positional and force quickness, positional and force accuracy, dangle, active and passive stability, strength, saturation avoidance, dynamic range, and grace.

Finally, the tests and actuator models along with the research done on the springs and control systems, will yield insight into how to design new actuators. Subsequently, a second round of actuators will be designed, constructed, and tested.

3.2 Springs

Springs are the defining characteristic of the actuators and require special attention. There are many issues regarding springs that are not well understood and need to be systematically addressed and clarified. These issues include: spring hysteresis, nonlinear stiffening springs, spring rate, deflection requirements, and spring design (materials, geometry).

It is suspected that with increased spring hysteresis, the actuator becomes much more difficult to control. If force is measured directly with hysteretic springs and used as the feedback signal, a limit-cycle may be produced around the commanded set point leading to noise and potential instability. However, if strain is measured inferring force then the actual force output is incorrect but the system maintains stability. It will be important to quantify and understand these two feedback scenarios.

Biological springs (tendons) are stiffening. One theory behind this is that at low forces or during contact tasks the low stiffness helps maintain stability. At much higher forces, low stiffness is unnecessary and undesirable. While some work has been done on understanding the effects of different linear spring rates [19], it will be important to understand non-linear spring rates as well. This should be done both theoretically and experimentally.

With more understanding of the effects of linear and nonlinear springs, it may also be important to investigate spring design for implementation in the actuators. At a minimum, guidelines for selecting or designing springs should be outlined. Things to consider in these guidelines are required deflection, stiffening properties, space constraints, material, and life cycle.

3.3 Control and Operation

While control and operation is tied to constructing and demonstrating the actuators, it can be considered its own research focus. Standard linear controllers have been used on actuators built up to this point. These controllers have done well and a PID controller will be used as the baseline for further improvements.

With the introduction of a nonlinear spring into the system, nonlinear control techniques may be required to prove actuator stability. There are complexity trade offs when going to more advanced controllers which must be balanced with the actuator's operational improvements.

Springs have been used in robots before with the idea of energy storage and recovery as is done in animals [1, 20]. One of the primary reasons for the development of these actuators is for walking and running robots. The actuators need to be very efficient in order to help "untether" the robots and make them autonomous, at least power wise. Therefore, a study of the dynamic operational efficiency of these actuators will be done. This will lead to isolating unnecessary power losses and eliminating them in the second round of actuator prototypes. Furthermore, from the operational efficiency study, it should then be possible to create models for specific power (power/mass) and specific force (force/mass) for both input to and output from the actuator. This model can be generated for the actuators alone. But, for autonomous mobile robots, regardless of the power domain, there are *accessories* that must accompany the actuators: batteries and current controllers for electric and compressors and accumulators for hydraulic. To understand specific force and power as well as efficiency for autonomous robots, these *accessories* will be included in an additional weight model of the actuators. This will help as a design "rule of thumb" when these ac-

Quarter	*Task*
Q4 1998	Construct Electric Prototype
	Create Mathematical Models
	Begin Hydroelastic Actuator
	Begin Test Stand
Q1 1999	Complete Hydroelastic Actuator
	Complete Test Stand
	Correlate Prototypes with Models
	Develop Weight Models
Q2 1999	Study Springs and Controllers
	Study Operational Efficiency
Q3 1999	Finish Studies
	Begin New Actuator Designs
Q4 1999	Finish Actuator Construction
	Test New Actuators
Q1 2000	Complete Testing
	Revise Thesis
Q2 2000	Defend Thesis

Table 1: Thesis task breakdown and timeline for completion.

tuators are used in autonomous robot construction.

3.4 Thesis Contribution

Below is a list of items that this thesis hopes to address and accomplish.

1. Demonstration of force controllable series elastic actuators for electro-mechanical and hydro-mechanical domains.

2. Define the effects of both linear and nonlinear springs with the springs associated nonideal characteristics.

3. Demonstrate the effects of various linear and nonlinear controllers.

4. Perform an efficiency study and create models for specific power and specific force.

5. Create design guidelines and rules for component selection and for further actuator development.

3.5 Timeline

The proposed timeline for this thesis is shown in table 1.

3.6 Thesis Risk

The proposed work for this thesis has moderate risk. Previous success with the actuators suggests that for the electro-mechanical domain the thesis should be able to be completed. The hydroelastic actuator holds great promise but has yet to ever be realized. Construction and demonstration of a hydroelastic actuator will receive high priority because of the uncertainties surrounding it. Once verified the thesis should progress as outlined.

4 Applications

The recent driving force behind series elastic actuator development has been to use them in walking and running robots. In a size scale from dogs to humans, electric series elastic actuators have already been shown to be an effective tool. However, if these robots scale larger (ie something to carry a human) then hydro-elastic actuators will probably be more appropriate.

In other biomimetic robots, series elastics will be of benefit to water vessels which use foil propulsion [26]. Recent research of this field has been in biomimetic *Robofish*, but small prototypes of traditional boats using foil propulsion have also been built [6]. Using series elasticity, it may be possible to set up resonant foil propulsion. The inertial losses of accelerating and decelerating a foil will be minimized and more power will be put directly into propulsion. Also, similar to legged robots, as the size and power requirements scale, hydro-elastic actuators would be better suited than electric motors.

Even though biomimetic robots have been the primary focus of the actuators, traditional manufacturing processes such as manipulation, assembly, grinding, and polishing may benefit as well.

With the development of hydro-elastic actuators, potentially for the first time, force control for hydraulics will be feasible. New control schemes for teleoperation require force controllable actuators to guarantee stability for operations such as human scaling [16]. Force reflective backhoes could potentially be developed. These same actuators may also be of interest in the virtual reality environments such as flight simulation or other military vehicle simulation platforms. The entertainment industry may follow with similar interest. Regardless of the application or industry, there seems to be sufficient interest to warrant continued investigations and research.

5 Conclusion

This proposal has given relevant background as well as research intent for developing a complete theoretical and practical understating of force controllable robotic actuators which have springs intentionally placed in series with the output. Force control is achieved by controlling the displacement of the springs which therefore implies force. Series elastic actuators have been previously demonstrated but further research, development and understanding are required.

The research focus for this proposal has been divided into three areas: construction of actuators, study of spring effects, and study of actuator control and operation. Each of these areas have been explained and specific tasks have been outlined. A timeline for completion of this thesis work by the end of spring term 2000 has also been proposed. The research in this thesis has many potential contributions which will aid in applying series elastic actuators in manufacturing, biomimetic robotics, and other areas in robotics. While there exist potential difficulties, there is incentive to examine and develop the actuators more fully.

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