A Simple and Scalable Force Actuator

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Abstract

One problem posed by robots that must perform in unstructured environments and interact with humans is that of achieving high fidelity force control as well as compliance in a compact form factor. Force control, as opposed to only position control, allows for safe, graceful contact behavior.

Having spring elements placed in series between an actuator and its output provides this desired compliance. It also provides low mechanical impedance, precise force sensing capability, and good control bandwidth, as demonstrated by Series Elastic Actuators (SEA). There have been both linear and rotary versions of SEA's, each with their own advantages and shortcomings. However, neither type of these actuators is easily miniaturized for joint mounting; linear SEA's require ball screws while conventional rotary ones require custom-made torsional springs.

The aim of this work was to integrate the positive features of an SEA into a compact, easy-to-build rotary actuator. This new actuator design involves two opposing linear springs coupled to a rotary shaft. A modified potentiometer relays position information linearly proportional to spring deflection and thus applied force. The mechanism is intentionally fabricated in layers to achieve precompression/extension of the springs while maintaining construction simplicity. The result is a completely encased and scalable module made of inexpensive off-the-shelf components.

Torque is provided by an electrical DC motor mechanically connected to the shaft of the module. This allows for easy mounting because there is no inherent constraint on the location of the motor. Ultimately any rotary shaft could be the shaft of the module, imparting the advantages of SEA's to any joint.

Controller performance has been validated by testing linearity and transient response. The module is currently being integrated into a manipulator at the lab. The scalability, precision, and ease of integration of the actuator make it particularly well-suited for robot manipulation research.

1. Introduction

Dextrous manipulation involves the coordination of many degrees of freedom with haptic information to act upon the environment. Such behavior is characterized by compliant performance that can initiate internal, and respond to external, force application. The human hand serves as a model for a robotic interface with the world.

However, achieving the prehension, perceptive, and manipulative capabilities of the human hand presents many technological challenges. For one, over twenty-five degrees of freedom are realized within the compact area of the hand. Each of these motions is enabled by a powerful actuator (muscle) that has inherent force feedback. Realization of a robotic analog of organic actuators provides motivation for our work.

One successful approach to this problem is the Series Elastic Actuator [1, 2]. SEA's comprise an elastic element, i.e., a spring, in series with a motor (see Figure 1). By measuring the deflection of the spring, one can determine the force being applied by the system. Given that the spring is the only connective element between the actuator and the output, SEA's effectively reduce the mechanical impedance of the system. This can be better explained with an example: Imagine a robotic link actuated by an SEA. Any external force applied to the link will only be resisted by the flexible spring as opposed to the high inertia projected by the gearhead reduction. Therefore, the mechanical impedance of the whole system is defined by that of the spring.

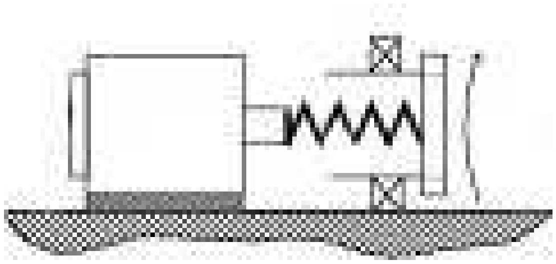

Figure 1: Conceptual depiction of an SEA, comprising a spring in series with a motor.

Although the spring also affects the reaction speed, or bandwidth, of the system, speeds still fall within an appropriate operational range for control applications. As a physical shock absorber, the spring also makes the robotic system less susceptible to and inherently reactive to unexpected impacts.

There are both linear and rotary SEA's. The linear version requires precision ball screws to control the spring deflection. Although allowing for good mechanical transmission reduction, this constraint makes the system expensive and puts a limit on how small it can be. Conventional rotary SEA's require custom-made torsional springs which are hard to fabricate and very stiff. This stiffness practically obviates the benefits of an elastic element. Furthermore, the torsional spring deflection is generally measured by strain-gauge sensors which are cumbersome to mount and maintain. Both of these linear and rotary SEA's present joint integration problems.

The actuator presented in this paper provides a solution to these problems in a scalable, compact, easily-mountable module.

2. Design

Figure 2 is a CAD rendering of the actuator. As will be explained, the module comprises: an actuated part, a transmission mechanism, and a mobile part. The actuated part is connected directly to the motor apparatus, while the mobile part is integrated into the moving output. The transmission mechanism transmits the motion from the actuated to the mobile part.

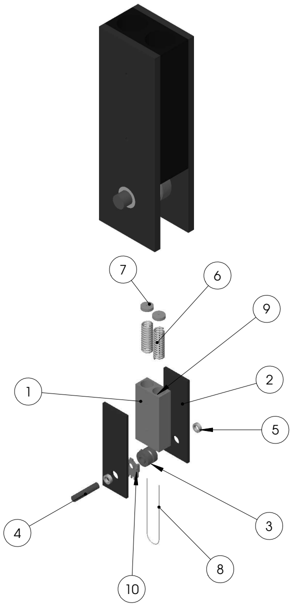

Figure 2: The force control actuator as a whole and an exploded, annotated view.

Description of the module functionality is easiest when we first consider the relationship between these subparts. The mobile part is composed of a spring box (1) sandwiched between two side plates (2). The actuated part consists of a wheel (3) fixed to a shaft (4) (which may be the motor shaft) and a potentiometer (10). The shaft/wheel assembly is mounted on bearings (5) in the two side plates. Therefore, the mobile part and the actuated part can rotate freely with respect to one another- at this point in the discussion, they are connected only by bearings. In other words, if a motor rotates the shaft, the wheel will move but the mobile part will not. The function of the pot will be described below.

The transmission mechanism consists of two compression springs (6), two lids (7), and a cable (8). Each spring sits within a cylindrical, close-fitting shaft (9) in the spring box. An opening at one end of the shaft allows for spring and lid insertion.

The other end of the shaft has a flat bottom (against which the spring compresses) with a hole for the cable to pass through (see Figure 3).Starting from its termination on one of the lids, the cable then runs through the center of one spring, out of the spring box, around the wheel and similarly back up through the other spring to terminate on its lid. The cable is fixed on the wheel to prevent it from slipping. Therefore, the springs can be effectively compressed between the bottom of their shafts and their respective lids through the tension in the transmission cable. Furthermore, both of the springs are initially compressed half way (described below). Due to this arrangement, any compression in one spring is reflected as an extension in the other. Because of this pre-compression of the springs, the routing of the cable may seem complicated; however, we present an elegant solution to this fabrication problem in Section 3.

In order to describe how the actuator works, we refer to the diagrams in Figure 4. In the first diagram, we have a depiction of the wheel (of radius R) mounted on an axel and the cable. The cable is fixed to the wheel at Point A. The torque of the motor T_m is applied directly to the wheel's axel such that

$$T_m = R(F_1 - F_2) \tag{1}$$

where F_1 and F_2 are the forces transmitted to the cable by the wheel .

The second diagram includes the springs. Each spring has rest length L and spring constant k, is capable of maximum compression C, and is initially pre-compressed to

$$L - x_i = C/2 \tag{2}$$

where x_i is the pre-compressed resting height of the springs. In order to keep the response of the actuator linear, its range must be maximally constrained to $\Pi/2$ radians on either side of Point A. Pre-compressing the springs to $C/2$ ensures that the springs will not escape their shafts over the operational forces of the module. In other words,

$$C/2 = \phi_{max}R | 0 < \phi_{max} \leq \Pi/2. \tag{3}$$

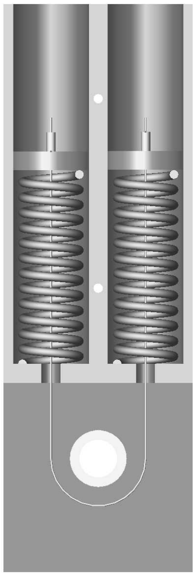

Figure 3: A cut-away view of the springbox showing the embedded springs (in their initial equally pre-compressed state) with their shafts and lids. As you can see, the cable terminates above each lid, runs down through the axis of each spring, and proceeds out the holes in the bottom of the shafts.

When the module (i.e., the mobile component) encounters a force such that it is held rigidly in place, we get a displacement of the springs (as shown in the Figure 5). That is, one of the springs is compressed a distance x and the other is extended by the same amount. Because the force on each spring is given by $F = k(x_i + x)$ and because this linear displacement is directly related to the rotation of the wheel by $x = \phi R$ (see Figure 5), we end up with an output torque T_o:

$$T_o = 2k\phi R^2. \tag{4}$$

The potentiometer measures the relative displacement between the wheel (essentially the motor shaft) and the mobile part (essentially the moving link) to give us ϕ. Thus the actuator provides an effective measurement of the applied torques by measuring linear displacement of springs.

In order to control the torque applied by the actuator, a proportional controller is used. The controller acts on the position of the wheel with respect to the mobile part. This position control is enough to control the torque because of Equation 4.

3. Mounting

One particularly important aspect of this module is its fabrication process. The whole actuator was designed to enable the pre-compression of the springs. Figure 6 depicts the assembly process which we describe in steps:

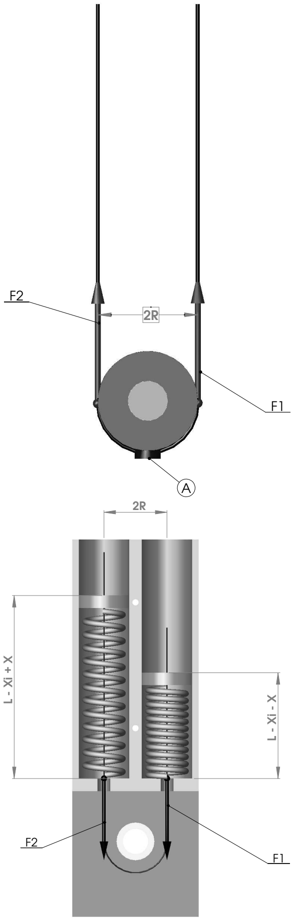

Figure 4: Free body diagrams of the actuator.

- The wheel is fixed to the shaft which is mounted into one of the side plate bearings.
- The springs are inserted into their shafts in the spring box and covered with their lids. The spring box is then temporarily placed tangent to the wheel (a distance of C/2 from its operational position).
- A cable is threaded through the hole in one of the spring lids, down through the center of that spring, out of the spring box, around the wheel and similarly up the other side. The cable is then fixed to the wheel directly across from the spring box to keep it from slipping.
- Next, cable terminators are crimped to the ends of the cable, flush with the outside of each lid. This is the configuration depicted in Figure 6.
- Pulling the spring box away from the wheel effectively compresses the springs. The distance between the wheel and the operational position of the spring

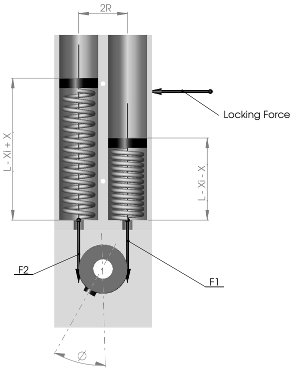

Figure 5: Actuator configuration with applied force holding it in place.

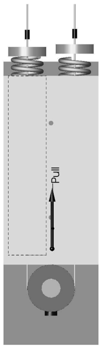

Figure 6: Mounting of the actuator.

box was intentionally designed to be half the total compression of the springs. Thus by then fixing the spring box to the side plates, in its operational position, we have equally compressed both springs half way (see Figure 3).

- The modified potentiometer (or an encoder) is then attached to the wheel and the other side plate, which is finally mounted to the assembly.

4. Characterization

The linearity of the actuator was determined by measuring the actual torque applied to the load and recording both the desired and actual displacement angles. The ratio between the torque and the angle yields the spring-constant of the actuator. The results of this test, shown in Figure 8, demonstrate that the ratio between the actual displacement and the applied torque is fairly linear and confirm the expectations of the design. The actuator constant determined was 0.008 Nm/degree.

In order to determine the time-response of the actuator, we lock the mobile part and then apply a step function to the input of the actuator. The step function is applied by sending a desired force to the actuator at time 0. The controller of the actuator will move the motor until the desired angle is achieved. Given the current conditions, the motor will deform the springs and by measuring the displacement of the shaft with respect to the mobile part of the actuator, we determine the applied torque. In Figure 9 we can observe the time it takes for the actuator to apply the desired torque to the load. We also observe that the damping of the system introduced by the springs is quite considerable. The rising time, defined as the time it takes the actuator to go from the 10% to 90% of the desired output, is around 270 ms.

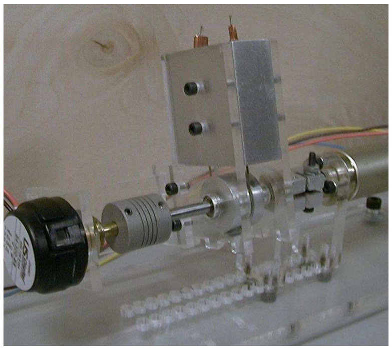

Figure 7: A testing prototype of the actuator made of acrylic and aluminum. The motor is off to the right.

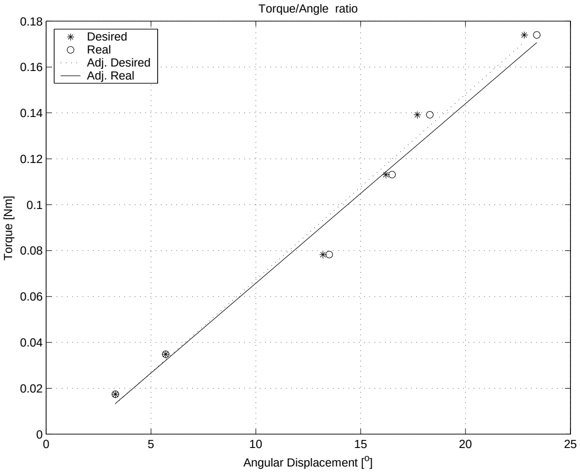

Figure 8: Data exhibiting the linearity of the actuator.

5. Conclusion

The actuator can be used for force control on any robot joint that incorporates rotary motors. Because the module is scalable, it can be applied to large industrial robotic applications as well as miniature research platforms.

Furthermore, the actuator comprises off-the-shelf com-

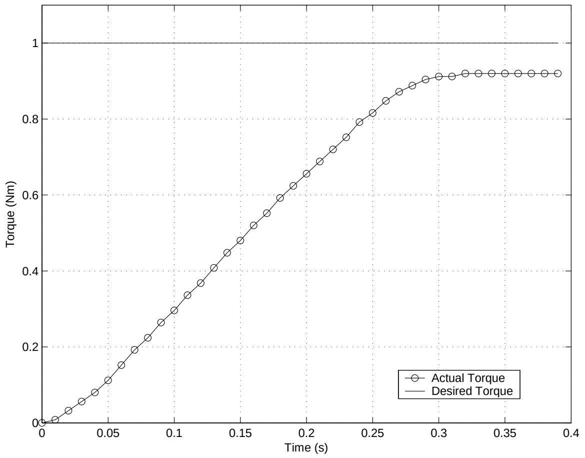

Figure 9: Time-response test data.

ponents, making it an inexpensive alternative for robots with many degrees of freedom. This factor, along with its consequently low repair/maintenance costs and short fabrication time, contribute to the great economic potential of the technology. The toy industry in particular, offers a rich market for these actuators.

The module has been incorporated into multiple robot hands being designed at our lab. It proves to be an important factor in manipulation research which calls for a wide range of grasp forces and configurations.

References

[1] D. Robinson and J. Pratt and D. Paluska and G. Pratt. *Series Elastic Actuator Development for a Biomimetic Walking Robot*. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Sept 1999.

[2] M. Williamson. *Series Elastic Actuators*. Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, Feb 1995.