Investigating the Force Fidelity of a Series Elastic Actuator by Implementing a Feedback System

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***Abstract*—A Series Elastic Actuator can store energy in a compliant element such as a spring to facilitate locomotion and jumping abilities. Series Elastic Actuators (SEA) have unique features because of the elastic element, such as the capacity to store and release energy, tolerance to impact loads, and low mechanical output impedance. These advantages were tested using a feedback system consisting of a pulley system, belt, and an encoder to read deflection in the compliant element for series elastic actuator robotic legs. The Series Elastic Actuator (SEA), as a passive compliance actuator, was utilized to control the motion and force of a cheetah's robotic leg to provide a feedback system to compare the efficiency and stability. The feedback system was tested using a sinusoidal wave signal and PID force tracking was tested in simulations.**

***Index Terms*—Humaniod Robots, Elastic Robots, PID Control**

I. Introduction

SERIES Elastic Actuator (SEA) is a type of Variable Impedance Actuator (VIA) used to implement a high-performance torque control. Unlike traditional actuation, which uses stiff gears to send force/torque to the load that is proportionate to the motor torque and current flowing through it, the torque transferred to the end load by a SEA is meant to be proportionate to the spring deformation [1]. In other words, due to the existence of the spring, the SEA transforms the torque production problem from a motor current decision problem to a spring deformation choice problem. Aside from its force/torque producing capability, SEA is recognized for its complex mechanism, which consists of a motor, gears, and a compliant component, the structure of which varies depending on the SEA configuration.

Low-pass filtering shock loads are one of the results of series elasticity, which reduces peak gear forces significantly. Although the same low-pass filter that spreads out a shock impulse back driving the actuator also spreads out the actuator's output, being an engineering trade-off rather than a one-sided reduction. When the right amount of interface elasticity is used, shock tolerance may be significantly improved while yet keeping a modest motion bandwidth [2]. The use of series elastic actuators should improve the performance of robots performing human-like tasks. The robot structure will be less stiff, and the force control will be less noisy, more accurate, and stable [2].

II. SEA Control Background

The control architecture used by Pratt [2] contains both feedforward and feedback paths. The feed-forward terms attempt to fully compensate for all of the following three terms. The first is the force applied through the elasticity to the load. The second is the force required to accelerate the motor's mass in order to change the deformation of the elasticity. The third is the force required to accelerate the motor's mass so as to track the motion of the load. Feedback to compensate for modeling errors is accomplished by an ordinary PID loop, operating on force error [2].

Another approach was implemented by Paine [1] using a PID and a Disturbance Observer(DOB), which was designed using a model obtained from experimental system identification. The goal of force control is to make the measured actuator output force track the desired force profile using motor current as the plant input and spring deflection as the output. However, because the UT-SEA, the University of Texas Series Elastic Actuator, implemented is an RF-SEA, a type of Series Elastic Actuator which locates the spring between the stator of the motor and the ground and is called Reaction-Force SEA, style actuator output force cannot safely track the desired force for all frequencies. Instead, the force control approach regulates spring force which guarantees safe and oscillation-free force tracking at all frequencies. To improve the force tracking performance further and to remove steady-state error another control approach was required, a Disturbance Observer (DOB). A DOB may be used to:

1) measure and compensate for error from disturbances
2) reduces the effect of plant modeling error. To use a DOB, a nominal plant model is required

To obtain an accurate representation of the model, the actuator's output was fixed output to the ground to match the high output impedance model and perform system identification of the model using an exponential chirp signal for the input desired force. The frequency response of the magnitude and phase of the measured spring force to the desired force identified a second-order system, which was modeled as the mass-spring–damper [1].

The spring in the model by Brooks [3] was a beam with a cross-shaped cross-section. Deflection in the beam was measured using strain gauges. The motor was controlled using current control as the input to the motor, making the motor an effective torque source. The compensation scheme used both feedback from the strain gauges, and feedforward from the desired torque input to calculate a desired current for the motor. Backlash in the gearbox introduced some undesirable and unpredictable resonances in the closed loop response, and friction effects limited the effectiveness of providing large force bandwidth. In Robinson [3], the motor is to be controlled as a torque source. The effects of friction and backlash are better quantified, and some guidelines for spring selection are introduced.

Wyeth [3] used Williamson's [3] note the potential for improvement in the electronic design of the system. The motor was treated as a velocity source rather than as a torque source to overcome some of the undesirable effects of the motor and the gearbox. Velocity control is also more straightforward from an implementation perspective, unlike current control which is generally considered challenging. An encoder provides velocity feedback to the motor, creating a tight loop for controlling the motor and gearbox. The motor can be viewed as an effective velocity source with this tight velocity control loop in place, simplifying the torque control design. The need to eliminate steady-state error requires the introduction of two poles at the origin, and points to second-order PI compensation, using two cascaded PI compensates in the feedback path [3].

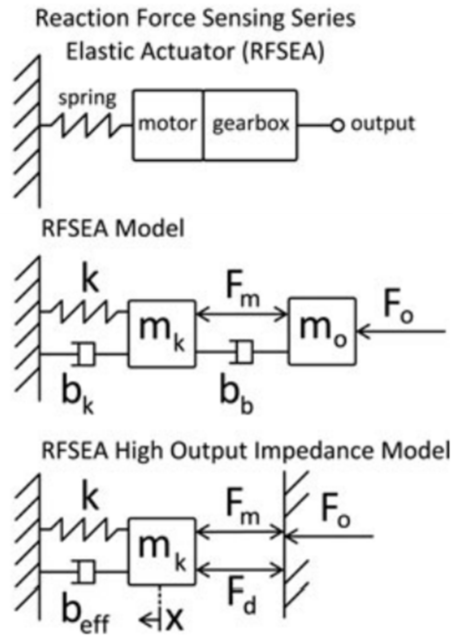

Fig. 1: Model for RFSEA style actuator. The notations represent: F_m : motor force, F_o : output force, b_b : viscous backdriving friction, b_k : viscous spring friction, k: spring constant, x: spring deflection, m_k : lumped sprung mass, m_o : output mass, b_{eff} : lumped damping which equals b_b + b_k , and F_d : disturbance forces and forces which are difficult to model [2].

III. Mathematical Model

Figure 1 shows a simple model for the UT-SEA. In the RFSEA model, generalized motor force (F_m) is generated between the output mass (m_o) and the lumped sprung mass (m_k) which includes the rotor inertia, the gearbox reduction, and transmission inertia. (m_k) includes the mass of the actuator housing and motor, including the rotor mass.

A high-output impedance model is useful for simplifying the force controller design problem. It assumes that the actuator output is rigidly connected to an infinite mass, which cannot be moved. For the high-output impedance models, the sprung mass feels a summation of forces from 1) the motor (F_m); 2) the spring (F_k); 3) lumped viscous friction $(F_{b_{eff}})$:

$$b_{eff} = b_b + b_k \tag{1}$$

and 4) from other disturbances that are difficult to model (F_d) such as the torque ripple from commutation, the torque ripple from the gearbox due to teeth engaging and disengaging, backlash, and various forms of friction such as stiction, and coulomb friction. In a RFSEAs, the spring acts as the force sensor.

According to the high output impedance model and Newton's 2nd law:

$$\begin{aligned} F_o &= F_m + F_d \\ &= F_{m_k} + F_{b_{eff}} + F_k \end{aligned} \tag{2}$$

It is known that:

$$F_{m_k} = m_k \ddot{x} \tag{3}$$

$$F_{b_{eff}} = b_{eff} \dot{x} \tag{4}$$

$$F_k = kx \tag{5}$$

Combining [3], [4], and [5] in [2] in time domain and applying Laplace Transform yields:

$$P_n = \frac{X_{meas}(s)}{F_{des}(s)} = \frac{1}{s^2 m_k + s b_{eff} + k} \tag{6}$$

Adding the tested hardware components of the Cheetah Robot, $m_k = 7.9kg$, $b_{eff} = 77.348N.s/m$, and $k = 10806N/m$ in [6] yields the transfer function:

$$P_n = \frac{1}{7.9s^2 + 77.348s + 10806} \tag{7}$$

For the UT-SEA, the speed reduction results from a pulley reduction (N_p) and a ball screw, which is parameterized by drive-train efficiency (η) and ball screw lead(l). The speed reduction defines the relation between actuator force (F) and motor torque (τ).

$$N_{bs} = \frac{F}{\tau} = \frac{2\pi N_p \eta}{l} = 1256.64 \tag{8}$$

IV. Force Control Hardware

The motor used is the SG775125000-20K DC Geared Motor which will be made and controlled to act as a servo drive. The motor has a no-load speed of 250rpm, rated current of 4A, and a torque of 1.03 N.m. The motor driver used was Cytron 10Amp 7V-30V DC Motor Driver. This motor driver was selected due to the motor's current requirements. This driver's advantages are: Bi-directional control for DC motor and allows a maximum current up to 10A continuous and 30A peak (10 second). 3.3V and 5V logic level input. The micro-controller used is Arduino UNO REV3. The Arduino UNO is an open-source micro-controller board based on the Microchip ATmega328P micro-controller and developed by Arduino.cc. The board is equipped with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards (shields) and other circuits. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header and a reset button [4]. A 12 Volts, 10 Ampere power supply was used according to the motor's requirement. In our robot, the KY-040 rotary encoder was used on a pulley system to measure the actuator's spring deflection for the force control loop.

A. Pulley System

To measure spring deflection, a timing belt and a pulley system were used. GT2 49.4cm Timing Belt was used, which has a 2mm pitch and a 6mm width. The pulley used is a 36 Teeth-5mm Inner Diameter-6mm width. The rotary encoder is placed on a 20 Teeth-8mm Inner Diameter-6mm width, as the shaft of the encoder is 6.35 mm. For the Cheetah robot, every 11 ticks represent 1.8cm deformation. So whenever the encoder outputs ticks, a spring deformation by this amount shown [9]. The system is shown in Figure [2].

$$deformation(cm) = \frac{1.8}{11} * ticks \tag{9}$$

V. Results

In order for a robotic manipulator, in our case the cheetah robotic leg, to be useful in the real world, it must be able to interact with it in a safe and controlled manner. The forces between the robot and the environment must be controlled so that neither the robot nor its end-effector is damaged as a result of normal operation or unexpected collisions. Some actions, such as walking, running and jumping, necessitate force control between the robotic end effector and its surroundings. The elasticity has the effect of making the force control easier, as larger deformations of the robot structure are needed to exert the same forces as a stiff robot [2].The control method used is a PID control and was implemented by a feedback system between the output measured force the the desired motor force.

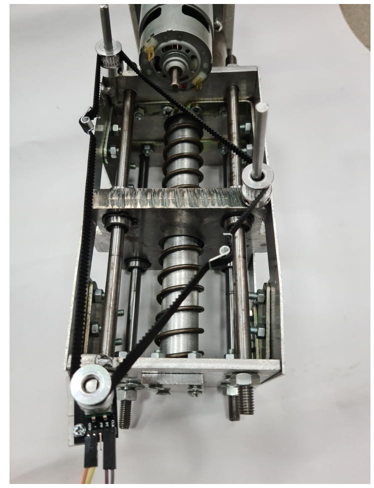

Fig. 2: Pulley system assembled with belt, motor, and encoder

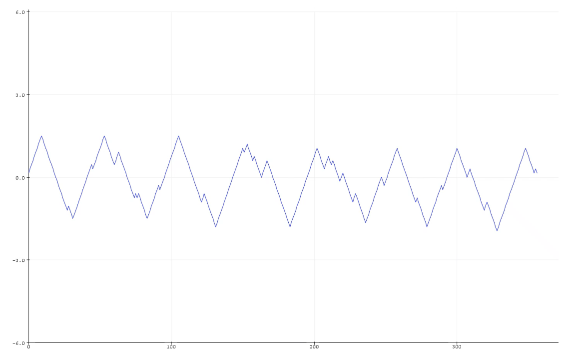

Fig. 3: The output generated from the encoder output pins reading as spring deflection.

A. Testing the Feedback System

The RF-SEA actuator was tested by using a sinusoidal sine signal with a high frequency of 50 Hz applied to the analog input of the motor. The goal is to test the encoder checking its ability to read very fast signals.

As shown in Figure 3, the output is satisfactory as it tracks the sinusoidal input. The output oscillates between 1.5cm and negative 1.5cm, the negative value represents the rotation of the encoder in the opposite direction.

B. Designing a PID Controller

Figure 4 shows the SIMULINK Block Diagram for force control of the Cheetah Robot Leg. The model includes a reference input as a step function, the output by the rotary encoder as a feedback, a scope to compare the input desired and output measured and the PID controller. In Figure 5, 2 plots are presented. The first is the step plot without any

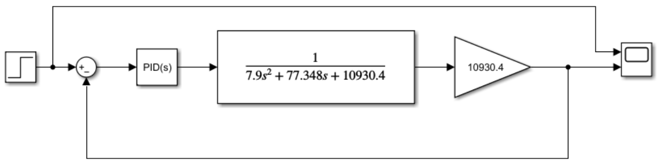

Fig. 4: Model for Cheetah leg with controller

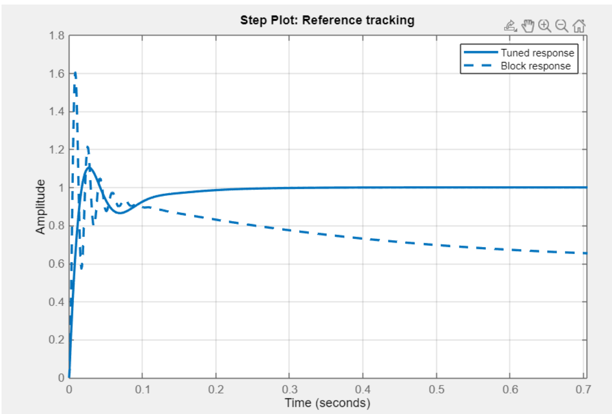

Fig. 5: Cheetah Robot when tuning Controller on Simulink

controller and the second is the tuned step response. As shown in the plot and in Table I, the PID controller improved the response by increasing the rise time, decreasing the settling time, and decreasing the overshoot. The tuned PID gains were adjusted to: $P = 4.2294, I = 65.5255, D = 0.068083$

C. Tuning Choice

When tuning the controller, 2 choices were given. Either choosing a faster response time or a more robust transient response. Faster Response means more overshoot, while slower response means zero overshoot. A more robust transient response means a slower response. When the controller is tested on hardware, a faster response was more favorable. Therefore the controllers were designed based on a faster response. Table shows a slower step response which has degraded most of the requirements but decreased the overshoot of the closed loop response. Table I compares the characteristics.

TABLE I: Table Type Styles

	Block	Tuned(Fast)	Slow
Rise Time	0.00314 sec	0.0128 sec	0.248 sec
Settling Time	5.63 sec	0.179 sec	0.471 sec
Overshoot	60.3%	10.4%	0%
Peak	1.6	1.1	1
Phase Margin	16.5^o @ 369 r/s	64.5^o @ 113 r/s	60^o @ 59.5 r/s
C-L Stability	Stable	Stable	Stable

D. Force Tracking

An exponential chirp signal is applied with a a frequency range of 0.1Hz to 100 Hz with an amplitude of 50 to test the controller designed for force tracking. Figure shows the open loop response for the cheetah robot leg and Figure shows the closed loop response. The results are satisfactory as the force input signal is accurately tracked.

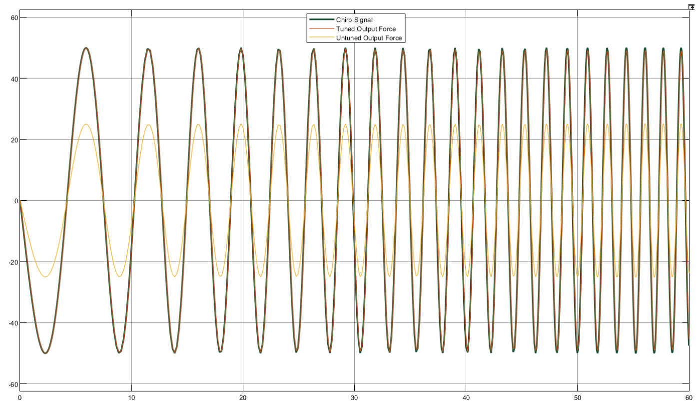

Fig. 6: Exponential Chirp Signal Test showing the black signal as the input chirp, the orange signal as the tuned output force, and the yellow as the untuned output force.

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