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CONTROLLABLE, HIGH FORCE AMPLIFICATION USING ELASTIC CABLE CAPSTANS

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ABSTRACT

This paper presents the design and experimental characterization of a continuously variable linear force amplifier based on the theory of capstans. In contrast to traditional capstan amplifiers, the design presented here uses an elastic cable, enabling a control actuator to not only continuously clutch output to a rotating drum but also passively declutch by releasing tension. Our experimental results demonstrate successful declutching at all force amplification ratios up to the limit of our experimental apparatus, 21 - significantly higher than previously published values. A system of distributed capstan amplifiers driven by a central torque source with cable engagement switched by lightweight, low torque actuators has potential to reduce the mass of distal actuators and enable more dynamic performance in robotic applications.

INTRODUCTION

Cable-drum systems are used in many robotic applications to convert rotary motion from an actuator into translational motion in an end mover [1]. Their low backlash and high stiffness make them ideal for producing the linear motion observed in elevators, photocopy machines, printers, tape recorders, and paper feeders, for example [1, 2]. Some cable-drum systems act as friction drives – essentially mechanical amplifiers [3]. Traditionally, these systems, also known as capstan drive systems, have been used in rope rescue systems, vehicle clutches and brakes, and textile manufacturing [4, 5]. These systems have the potential to increase the dynamic performance of a robotic system by reducing the overall inertia of moving parts [6].

In capstan-based mechanical amplification systems, the tension of the cord wrapped around the continuously rotating drum, or capstan, is increased due to the friction between the cord and capstan. The relationship between the input and output tensions can be described in the idealized capstan equation:

$$T_{load} = T_{signal} e^{\mu\theta} \tag{1}$$

where T_{load} and T_{signal} are the respective output and input tensions, μ is the coefficient of dynamic friction between the capstan and cord, and θ is the wrap angle [4, 5, 7, 8]. This equation assumes ideal conditions and does not consider factors such as a nonlinear frictional behavior, the cord's Poisson's ratio, the extensibility of the cord, and the cord's second moment of area about the drum [4]. Nonetheless, this equation indicates that amplification can be increased by the addition of wraps to the capstan [9, 10]. However, the likelihood of binding also increases with additional wraps. When binding occurs, the increased tension in the cord causes the cord to effectively adhere to the drum, thus changing the kinetic friction coefficient to a greater static friction coefficient. Binding results in loss of control over the tensile loading of the output cable [9].

Several mechanical amplifier designs are based on the basic cable-drum actuation concept. In 1970, Harris patented a "Mechanical Amplifier" [11], where a rotating capstan-type drum is wrapped with two flexible elements. Each element has an end, emerging from the drum in the direction of rotation, which receives an input signal, while the other end, emerging from the drum opposite the direction of rotation, receives an output signal. The input ends are wrapped around one pulley, while the output ends are connected around a second pulley. In 1992, Smallridge patented a “Double Capstan Winch Drive” [9] designed to articulate many tensile members, like those of a human hand. His patent stressed the potential of using a single drive to control multiple members as well as the importance of responsive members that relax immediately with the input force. Smallridge recommended a limit of three wraps around the tracked drive drum to avoid the issue of binding. He referred to a generic solution of reversing the drive drum and relaxing the input tensile signal if binding did occur in the system. Perhaps the most recent development is Starkey’s “Mechanical Capstan Amplifier” [10], which involves cords wrapped loosely around a central actuating or drive rod. These cords engage the central actuating rod when tensioned by additional rods located around the drive rod. All these systems have the advantages inherent in an amplifier-based cable-drive power distribution system.

DESIGN OVERVIEW

Our design is similar to previous examples in that it addresses the need for a mechanism with minimal weight and volume, low power consumption, and the ability to massively amplify the tension in the cable.

However, our design allows for a greater number of wraps, and thus higher amplification ratios, without binding through the use of an elastic cable. As depicted in Figure 1, the system wraps a steel cable around a constantly rotating drum that acts as a capstan. Unlike Harris and Smallridge, there are no grooves on the drum. Instead, a casing encloses the capstan, preventing the elastic cable from escaping. In the current design iteration, the constraint has an internal helical track to prevent the cable from unwinding or crossing over itself, even with clearances between the capstan surface and the disengaged cable larger than the cable diameter.

As a result of the use of an elastic cable, the system can provide and control a continuously variable transmission. The un-tensioned cable is normally disengaged from the capstan drum due to the cable’s bending stiffness, which also discourages binding. Once engaged, any additional increase in the input tension will result in a similar increase in the output tension from the cable emerging from the capstan drum. This paper presents the initial experimental characterization of the system; our results indicate that the system is capable of producing higher amplification ratios than previously published in literature [10].

EXPERIMENTAL METHODS

To characterize the performance of capstan-based amplifiers as actuation mechanisms, we developed a test apparatus that measures the amplifier’s input and output forces.

As indicated in Figure 2 and detailed in Table 1, the test apparatus is composed of five main components and can be divided into two sides. The signal side, to the left of the capstan, consists of the signal load sensor and a servo-driven signal winch. The signal load sensor records the force on the signal winch, which tensions the steel cable feeding into the capstan drum. The load side, to the right of the capstan, consists

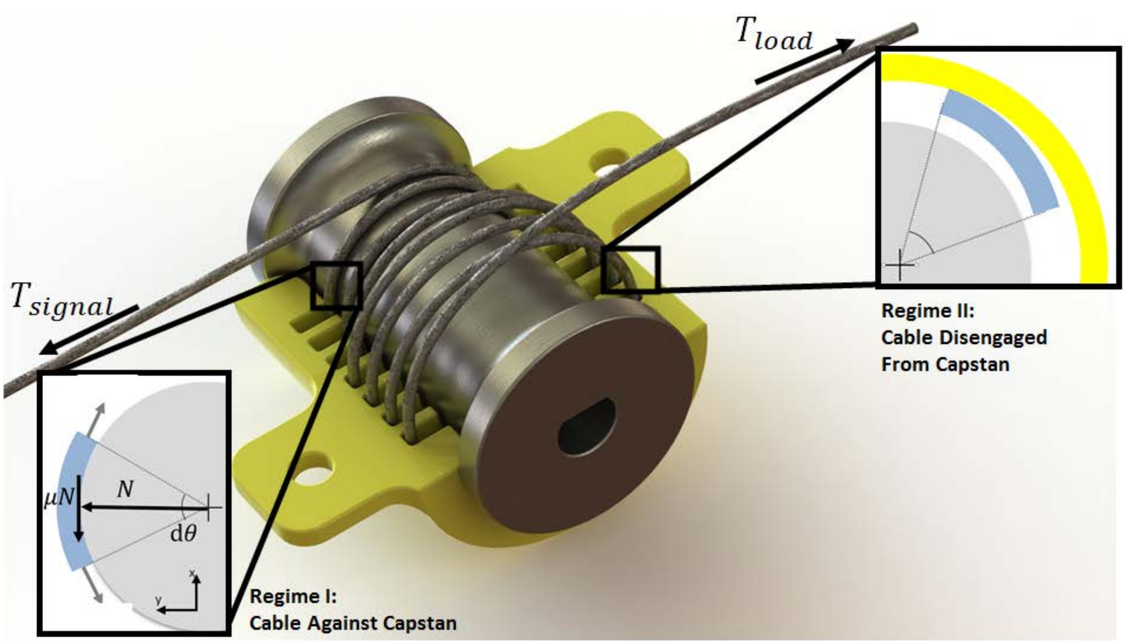

FIGURE 1. DIAGRAM OF ELASTIC CABLE CAPSTAN WITH THE TOP HALF OF THE CONSTRAINT HOUSING REMOVED. THE DIAGRAM ILLUSTRATES THE BEHAVIOR OF THE CABLE FOR TWO DISTINCT REGIMES.

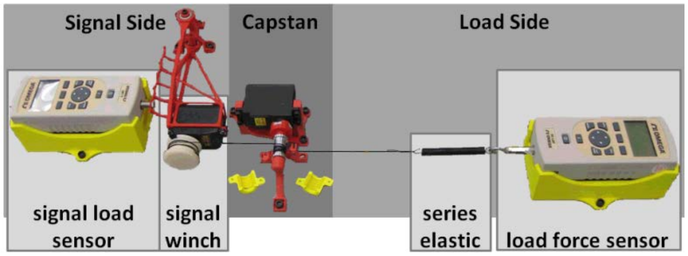

FIGURE 2. TEST APPARATUS USED TO MEASURE SIGNAL AND LOAD TENSIONS.

of a series elastic element and the load sensor which measures the force on the series elastic component. The series elastic component is used to protect the load sensor from unexpected effects or instantaneous force spikes. The test apparatus was also used with an uncoated diamond braided nylon cord in place of the steel cable, to compare our design to a traditional capstan amplifier. Analog voltages from both force sensors are recorded by the digital acquisition module and stored on a computer for recording and later analysis.

A LabVIEW program uses two distinct pulse-width modulation (PWM) signal channels to set the rotation of the signal winch and the capstan motor speed. The signal winch moves to an array of set positions for every predetermined capstan motor speed.

TABLE 1: PROPERTIES OF THE TEST APPARATUS

Cable Material	Type 304 stainless steel
Cable Diameter	0.79375 mm
Cable Ply	3x7
Capstan Material	Aluminum
Capstan Diameter	12.7 mm
Nylon Rope Diameter	2.778125 mm
Force Sensor	Omega DFG31 Series
Digital Acquisition Module	National Instruments DAQ USB-6211
Maximum Readable Load Force	222.4 Newtons
Maximum Readable Signal Force	44.5 Newtons

CALIBRATION

To calibrate the experimental setup, we removed the capstan, connecting the cable from the signal winch directly to the output series elastic element. Thus, the forces measured on the load force sensor were the same experienced by the signal winch. We experimentally determined the voltage to force calibration using the guaranteed calibrated screen display of the load force sensor. The DC offsets in the raw voltages were calibrated to tested unloaded means. After the scaling transform, the force sensors exhibited the following standard deviations over the duration of this experiment:

$$\sigma_{Load\ Sensor} = 4.3346 \times 10^{-2}\ N,$$
$$\sigma_{Signal\ Sensor} = 5.0451 \times 10^{-3} N$$

A 40ms delay between sending signals to the signal winch and any discernible change in the forces was experimentally determined and is due to the time-step of the data recording and the control system internal to the servo. To account for this, the data representing the extension in mm corresponds to the forces 40ms later.

To determine the coefficients of friction between the cable and the capstan and between the nylon rope and the capstan as detailed in Tables 2 and 3 respectively, we shifted the load force sensor out of plane, rotating it about the axis of the capstan to maintain alignment between the force sensor and capstan output cable. Wrap angles between zero and thirty-six degrees were possible in the setup. We removed the signal winch, connected the series elastic element between the signal force sensor and the capstan, and directly connected the load force sensor to the capstan. We rotated the capstan forwards and backwards, averaging the load side readings for each case over approximately one second. The signal load sensor showed negligible change; as a result, we computed the coefficient of friction using the following equation:

$$\mu = \frac{\ln\left(\frac{T_f}{T_r}\right)}{2\theta}$$

where T_f is the load side tension with the capstan rotating forward and T_r is the tension with the capstan rotating in reverse. In this case, the measurements show that the coefficient rises over time, which is due to the intense wear between the steel cable and the aluminum capstan over the course of a prolonged test.

TABLE 2: COEFFICIENT OF FRICTION MEASUREMENTS FOR STEEL CABLE AND ALUMINUM CAPSTAN

Angle ($\pm$.5°)	Tension, Forward (N)	Tension, Reverse (N)	Coefficient of Friction
9	3.21710	2.99346	0.229344
9	3.25539	2.95811	0.304818
9	3.30079	2.95592	0.351261
15	3.54805	3.14680	0.229206
15	3.65499	2.99591	0.379767
15	3.67366	3.01663	0.376334
36	2.05194	1.58348	0.206234
36	2.33049	1.54736	0.325892
36	2.36840	1.50576	0.360420
26	3.42292	2.57187	0.314973
26	3.42283	2.43084	0.377084
26	3.43316	2.35477	0.415436

TABLE 3: COEFFICIENT OF FRICTION MEASUREMENTS FOR NYLON ROPE AND ALUMINUM CAPSTAN

Angle ($\pm .5^{o}$)	Tension, Forward (N)	Tension, Reverse (N)	Coefficient of Friction
26	8.26511	7.35622	0.128361
26	8.21190	7.35479	0.121459
26	8.16467	7.26866	0.128083
36	5.70610	4.90818	0.119870
36	5.99050	4.90147	0.159664
36	5.70047	4.92279	0.116719
12	5.39501	5.15322	0.109465
12	5.38553	5.14999	0.106763
12	5.37026	5.13959	0.104811

RESULTS

The constrained elastic cable capstan amplifier produces close to the same load side forces when contracting as when releasing. The signal force on the other hand exhibits a near constant tension bias. These results are illustrated in Figure 3.

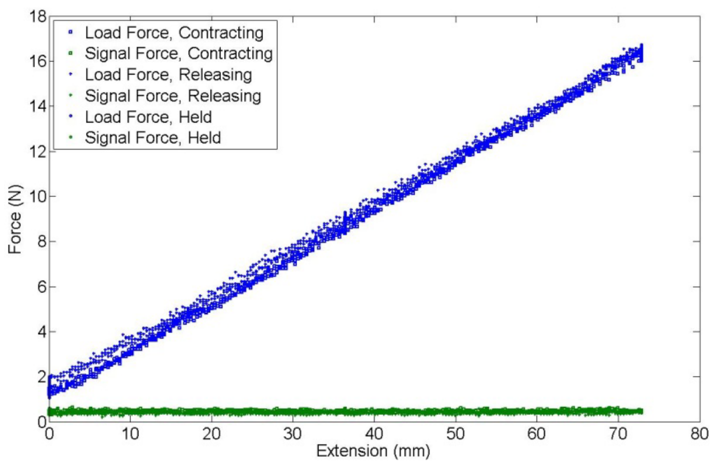

FIGURE 3. RESULTS OF A TEST USING THE ELASTIC CABLE HIGHLIGHTING THE VARIABLE AMPLIFICATION RATIO.

The controllable nature of using a cable capstan as opposed to a nylon capstan is highlighted in Figures 4 and 5. The unpredictable releasing behavior of the nylon cord capstan is the key difference between the two plots. The path taken by the signal winch was chosen to highlight this behavior. The winch contracts fully and then releases fully, testing the ability of the amplifiers to allow the load to physically release the cable or cord and thus lower the force due to the series elastic element. While the constrained cable capstan amplifier is clearly able to release in this manner, the cord capstan amplifier binds; the signal side is slack while the amplifier still maintained the load force. However, in the later part of the tests the signal winch contracted to its half-way point, dwelled there, and released. This portion of the signal winch's path

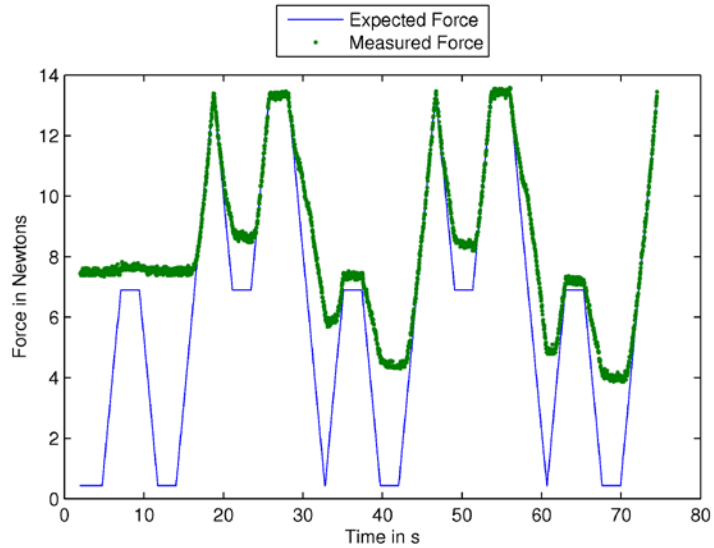

FIGURE 4. LOAD TENSION USING CORD: EXPECTED LOAD FORCE (BLUE), OBSERVED LOAD FORCE (GREEN)

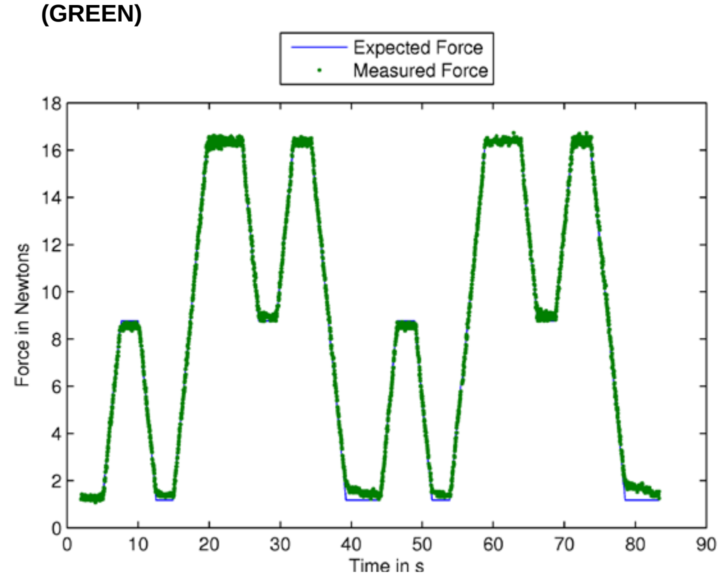

FIGURE 5. LOAD TENSION USING CABLE: EXPECTED LOAD FORCE (BLUE), OBSERVED LOAD FORCE (GREEN)

demonstrated the more extreme version of binding in which the releasing signal winch merely added slack to the signal side cord rather than enabling release on the load side. It was observed that the binding of the cord capstan was a delicate and easily disturbed event—the slightest disturbance could free the bound cord or trigger binding during release. On the other hand, the constrained cable capstan maintained a constant non-zero tension between the signal winch and the actuator regardless of minor disturbances. This experiment serves to illustrate how the constrained cable version of the amplifier improves the reliability of the releasing behavior.

DISCUSSION

The observed amplification ratios are an improvement over the largest values in the prior work [10], with peak values in current testing of nearly 21. Additionally, Figure 5 shows that the signal side cable tension is near-constant relative to the load side tension, the helically constrained elastic cable amplifier is more effective and controllable than the standard cord capstan amplifier thanks to its more predictable release behavior.

FUTURE WORK AND APPLICATIONS

Many aspects of the constrained inelastic cable capstan amplifier still require exploration and characterization. For example, the exact nature of the changes in the capstan's cable coils over time and the response of the system to higher speed signal changes are not yet understood. To this end, we intend to further characterize our actuator through modeling and simulation, experimental observation, and design variation. The design variations may include material selection for the cable and capstan or inclusions of tensioners or lubricants. Ideally, the variations will highlight optimal application methods and potential issues such the feasibility of scaling the design. After the system is adequately characterized, we intend to perform dynamic analyses of the motions achievable with the traditional approaches compared to approaches created with our mechanism in mind. For instance, in the case of robotic humanoid legs, traditional approaches for a precise and controlled system would require multiple high power electric motors. A system designed with our mechanism in mind could switch to a centralized engine running at a roughly constant speed. This strategy boasts that the maximum power requirement on the central motor is likely to be less than the sum of the maximum power requirements on the individual joints. As such, the constrained cable amplifier has potential to revolutionize design of robotic systems reliant on many actuated elements, only a few of which are powered simultaneously.

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