Extended Abstract: Twisted String Actuators for Exosuits

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Abstract - SUPERFLEX is a wearable robotic undergarment that incorporates active motor elements and quasi-passive elements that act in parallel with the wearer's musculoskeletal system to augment physical performance. SRI International has developed several innovative components that offer benefits (compared to traditional linear actuators) because they are light weight, provide high force output, and are composed of commodity materials and components that are consistent with an all-electric solution.

Index Terms – Exosuits, FlexDrive, Twisted String Actuator (TSA)

Introduction

The Warrior Web program, a DARPA initiative, was a multi-year effort to create an undergarment for augmenting a soldier's movement to lessen fatigue and reduce the potential for injury. The main goal of the program was to have a system capable of reducing metabolic cost to a soldier carrying a load of 100 lb while consuming 100 Watts or less of battery power. SRI International's (SRI's) technology, dubbed SuperFlex, is a form-fitting undergarment capable of augmenting the muscles and tendons of the wearer for enhanced strength and performance. The suit differs from exoskeleton methods by providing muscle-like actuation, conformable skin attachment, and adaptive state-based control, and uses the wearer's skeletal anatomy to carry compressive loads.

A low-cost, lightweight, high-power density actuator was necessary to achieve these program goals. SRI met this challenge by developing an integrated dual-twisted string actuator (TSA) with commercial off-the-shelf (COTS) robotic components. The actuator, weighing less than 0.4 kg, can deliver a peak force of 1000 Newtons (N) to the heel of the user. The development of SRI's TSA technology has benefited from numerous evolutionary development cycles, and is now implemented in a "heavy" version for a private client. Furthermore, the SuperFlex technology is now the basis for a recent SRI spin-out company.

Material Selection

SRI's development of TSA has resulted in significant improvements to twisted-pair actuators, with efficiency reaching as high as 92% and extended operational lifetime. Compared with metal linear transmissions, such as ball screws, TSAs typically exhibit reduced continuous power capacity and reduced lifetime in the synthetic fiber elements. Reduction in power is mainly due to the low melting point of the materials used. To address this shortcoming, SRI has focused its research on the goal of reducing the heat generated by friction. We have also been able to increase lifetime through material and lubricant selection.

When under load, twisted pairs are known to "creep," or get longer with time. This poses challenges for traditional robot design and control where actuator position repeatability is an important consideration. Twisting the string pair results in a scissoring motion between the two primary twisted-pair bundles, and eventually leads to fiber breakdown and actuator failure.

Kevlar and Vectran aramid fibers exhibit virtually no creep. The use of such fibers in TSA actuators may seem appealing if the system design requires precise open-loop position control. In experiments, SRI has observed steady elongation of Vectran TSA's in cycle testing as the fibers fray, and it is likely that the broken fibers no longer contribute to the effective diameter of the twisted braid. As the effective diameter decreases, the remaining fibers appear to elongate, but they are just wrapped in tighter helixes.

Dyneema, on the other hand, is known to exhibit a considerable amount of creep, which seems to benefit string lifetime. Fibers under the greatest load elongate, shedding load to adjacent fibers in a natural load-balancing process. The heat generated from friction possibly encourages this process. Dyneema strings also get shorter when run at sufficiently high power and under cyclic load. So while Dyneema may be an excellent candidate for force control, position control can only be realized with an adequate position sensor on the output. The specific transmission ratio varies over the actuator's lifetime in a manner that is not reliably modeled.

The extreme strength of Dyneema fibers enables the use of thinner strings, which increases the transmission ratio within a string. As a result, it is more often feasible to directly attach a twisted string to a motor without an intermediate transmission. This increases efficiency and lowers inertia, all of which improve response time.

Additional research is needed to identify a fiber material or blend with sufficiently low creep to enable open-loop position control, such as a Dyneema-like fiber with a significantly higher melting point. Vectran offers a much higher melting temperature, but breaks down rapidly.

DESIGN APPROACH

Twisted pair transmissions have been developed independently by several groups; however, they have all suffered from relatively short lifetimes and unremarkable efficiency. SRI's years of developing TSA's have led to the design of key common components shown in Figure 1 that address these issues, such as

- Synthetic fiber and termination blocks
- Out-runner brushless DC motors
- Load cell for closed-loop control
- Bearings for linear output and thrust loads

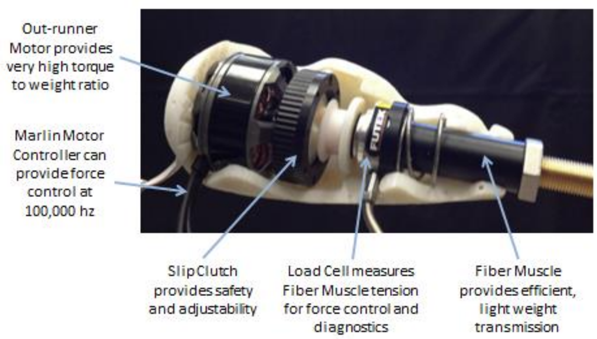

FIGURE 1. FLEXDRIVE 1.0: SINGLE MOTOR TSA DESIGN WITH SLIP CLUTCH, FORCE SENSOR, AND RETURN SPRING

Out-runner brushless DC motors provide high torque-to-weight ratios. They are an excellent choice for a single-stage twisted-pair system. The hobby radio-contol industry has reduced the cost of these motors to consumer level prices, driven by the demand from the consumer drone industry. However, the very low inductance of these motors makes torque and current control unstable for most COTS motor controllers. SRI has developed a custom high-frequency, high-current motor controller that addresses this problem.

For proper force control, a donut-style load cell compressed between the out-runner motor and a thrust bearing provides outstanding results. Other solutions that incorporate load cells at the actuation stage require bearing assemblies to help mitigate side loads imparted on the overall system that add additional weight. Single-stage TSAs provide excellent force control. Commercially available precision load cells can be quite costly compared to the rest of the components in the system.

A bearing solution is required to capture the TSA output from spinning freely as the system retracts relative to a fixed ground frame. SRI has investigated numerous bearing designs, such as radial bearings located in a slot and fluoropolymer bushings, to address the torque loads placed on the system. Though functional, these bearing solutions have not achieved acceptable cycle life. The best solution we have identified indicate that a miniature linear rail provides the most dynamic load capacity for the cost and size. However, these systems are relatively costly due to the assembly required.

Balanced torque from the two twisted pairs eliminates the need for a linear bearing and usually results in a reduced overall system weight. The design, shown in Figure 2, controls two smaller motors in parallel. Each individual twisted string is attached to a brushless DC motor. SRI has successfully run this setup off one motor controller, and has shown that, when running the motors in opposite directions, the angular momentum created by one spinning motor is canceled by the other. The design also allows for a lower profile, since the equivalent power of two motors have smaller diameters can effectively replace a single large motor.

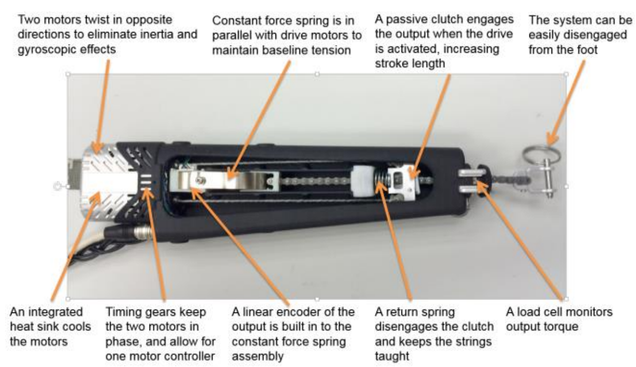

FIGURE 2. FLEXDRIVE 2.0: DUAL MOTOR SETUP

AUXILIARY DESIGN FEATURES

Another method to make the system more compact is to place the motor along an offset parallel axis with the twisted string. This requires a secondary transmission to connect the motor and twisted string, but the overall height is reduced by 25% (Figure 3). This method of offsetting the motor is rather attractive when system length is a concern but the design penalty is increased system components, cost, and weight which need to be evaluated based on the system's requirements. We were able to maintain a high efficiency and lower inertia by using a miniature timing belt to transfer the work done by the motor to the twisted pair.

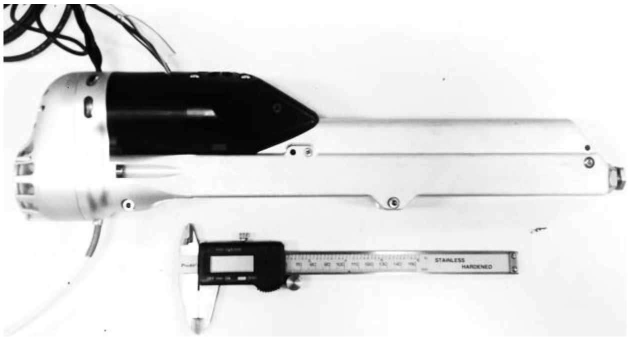

FIGURE 3. FLEXDRIVE 1.H: TSA WITH PARALLEL MOTOR FOR REDUCED OVERALL LENGTH

When attaching powerful actuators to the human body, safety is a primary concern. As a precaution, the design includes mechanisms to decouple the actuator from the user. Hard stops on all actuators limit the overall travel of the system. Figure 4 illustrates the evolution of the TSA drive system, called the FlexDrive. Clutching mechanisms were added to FlexDrive 1.0 and 2.0 for safety. To couple two twisted strings simultaneously, a passive clutch engages the TSA when actuation occurs. When the operator extends beyond the stroke length during the heel strike, the system disengages from the chain output. The return spring between the clutch and the chain driven output provides a constant return force on the assembly.

FIGURE 4. FLEXDRIVE EVOLUTION: FROM LEFT TO RIGHT V1.0, V2.0, AND V1.H

SYSTEM RESULTS

SRI's approach has shown excellent lifetime properties (over one million cycles) and very high mechanical efficiencies (over 90%), both areas where past implementations have struggled. In addition, SRI's custom motor controllers can operate out-runner style hobby motors under very accurate force or position control. One of the key advantages of such a light-weight, powerful actuator is that it can be placed directly at the location of actuation resulting in higher gate efficiency without the additional weight of a typical linear actuator.

The result is a linear actuator that is lighter than a conventional ball screw actuator at less than 0.4 kg, yet can produce 1000 Newtons of force and withstand 300 mechanical Watts of peak work for the FlexDrive v2.0. The continuous work consumed by the system averages 65 Watts per actuator, which is ample for the application of human augmentation. Nonetheless, the same fiber drive can run at very low power levels and maintain high efficiency, making it ideal for reducing metabolic cost while walking under a heavy load. For more dynamic situations in heavier load cases, FlexDrive V1.H was designed for use on exosuits capable of running and jumping. These requirements pushed the design of a new TSA capable of handling over 2000 W of peak power and producing 2900 N of force for less than 1 kg in weight. The TSA technology evolution for exosuits can be seen in Table 1. SRI's history of designing TSA has shown promise as a suitable alternative in conventional linear actuator technology due to advancements in synthetic materials, utilization of low-cost COTS components, and highly efficient mechanical and electrical systems.

TABLE 1: FLEXDRIVE METRICS

	FlexDrive Evolution		
	V 1.0	**V 2.0**	**V 1.H**
Peak Force	740 N	1000 N	2900 N
Peak Power	200 W	300 W	2000 W
Active Stroke Length	50 mm	80 mm	100 mm
Total Length	350mm	300 mm	350 mm
Total Actuator Weight	375 g	300 g	950 g
Peak Efficiency	90%	92%	92%