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Experimental Evaluation of Guided Twisted Actuation

G. Palli * **M. Hosseini** * **C. Melchiorri** *

* *DEI, University of Bologna, Italy,*
(e-mail: {gianluca.palli, mohssen.hosseni,
claudio.melchiorri}@unibo.it)

Abstract: In this paper, an ongoing work for verifying the behavior of a twisted string actuator in contact with a sliding surface or guided through a sheath is presented. After the presentation of the basic properties of the twisted string actuation system, the model of the twisted string in contact with a sliding surface is discussed. The behavior of the system has been then experimentally verified and discussed. A preliminary evaluation of control strategies for compensating the side effects generated by the contact of the twisted string with the sliding surface is also presented.

Keywords: Twisted String Actuation, Tendon-Sheaths Transmission Systems, Guided Tendons, Friction Compensation.

1. INTRODUCTION

The Twisted String Actuation (TSA) concept described in Moshe (2004); Palli et al. (2013) represents a very interesting design solution for the implementation of very compact and low cost linear transmission systems. Indeed, with an proper choice of the strings parameters (in particular the radius and length), it is possible to easily satisfy the usually tight requirements for the implementation of miniaturized and highly-integrated mechatronic devices. As a proof of its benefits and advantages, the TSA has been already successfully used for the implementation of different robotic devices like robotic hands, see Sonoda and Godler (2010); Palli et al. (2014), exoskeletons, as reported in Popov et al. (2013), and tensegrity robots for space applications, see Park and SunSpiral (2014). The mathematical model of the TSA and, in particular, the analysis of its force/position characteristic and of the resulting transmission stiffness has been investigated in Palli et al. (2013). Recently, the TSA model has also been improved taking into account the characteristics of different type of strings and a non constant string radius in Gaponov et al. (2014).

Even if in literature, some variants of the TSA exploiting environmental constraints to change or adjust the characteristics of the TSA have been proposed, such as in Jee-Hwan Ryu (2013), one of the major disadvantages of TSA is related to the fact that, by now, the transmission system should be not in contact with other structures because the generated friction will introduce deviations from the ideal behavior of the system. This fact limits in some way the applicability of the TSA concept or increases the space need for the actuators, in particular in case of robotic hands. Indeed, in the DEXMART Hand described in Palli et al. (2014), the whole forearm length is exploited to host the TSAs driving the wrist and the fingers, and the TSAs are connected to a conventional tendon-based transmission system just before the wrist to avoid any TSA contact with the hand structure. The possibility of using the TSA even if the string is in contact with structural elements may introduce significant improvements in the design of such a robotic hand, reducing the space needed for hosting the actuation and allowing the optimization of the actuator arrangement.

In this paper, an ongoing work for evaluating the TSA in contact with a sliding surface or guided by means of a Teflon sheath is reported. Particular attention is posed in both the modeling and the experimental verification of the hysteresis introduced in the transmission system by the friction. The paper reports also the preliminary activity for the experimental evaluation of the system behavior and related control strategies.

2. MODELING OF THE GUIDED TSA

2.1 TSA: general properties and modeling

For the modeling of the TSA, we assume that the two strings form an ideal helix of constant radius r along the whole range of the motor angular position θ. The kinematic relationship between the motor angle and the load position can be easily derived from the geometry of the helix formed by the strings, see in particular Fig. 1, which implies the following straightforward relations:

$$L = \sqrt{\theta^2 r^2 + p^2}, \tag{1}$$

$$\sin\alpha = \frac{\theta r}{L}, \quad \cos\alpha = \frac{p}{L}, \quad \tan\alpha = \frac{\theta r}{p}, \tag{2}$$

where α is the helix slope, L is the strand length and p is the length of the transmission system or, in other words, the load relative position wrt the motor. Note that eq. (1) can be easily obtained by “unwrapping” the helix of total length L and radius r and applying Pythagoras' theorem to the resulting triangle in Fig. 1(b). From eqs. (1) and (2) it follows that:

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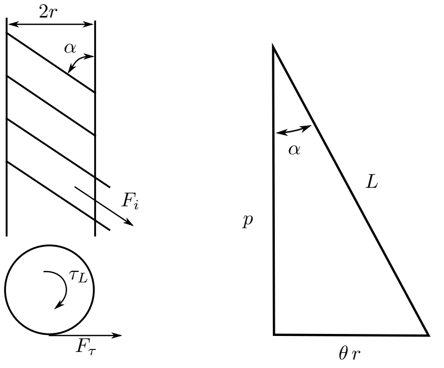

(a) Lateral and axial view. (b) Unwrapped helix.

Fig. 1. Schematic representation of the helix formed by the strings that compose the TSA.

$$\dot{L} = \dot{p}\cos\alpha + \dot{\theta}\, r \sin\alpha. \tag{3}$$

In this analysis, the strings are assumed to act as linear springs, with the capability of resisting tensile (positive) forces only. With respect to the unloaded length L_0, the total length of a string L changes according to the fiber tension F_i and the string stiffness K (normalized with respect to the length unit), i.e.

$$F_i = \frac{K}{L_0}(L - L_0) = \frac{K}{L_0}\left(\sqrt{p^2 + r^2\theta^2} - L_0\right) \tag{4}$$

where r is the string radius, θ is the motor angle and p is the resulting length of the transmission system. It is worth noticing from (4) that the string acts as a spring whose deformation is defined as $\sqrt{p^2 + r^2\theta^2} - L_0$ and, therefore, can be modulated through the motor angular position θ. It follows that the transmission length p is given by

$$p = \sqrt{L_0^2\left(1 + \frac{F_i}{K}\right)^2 - \theta^2 r^2} \tag{5}$$

The external torque τ_L provided by the motor and the load force F_L can be derived from (4) and by the geometrical considerations on the system:

$$\tau_L(\theta, p) = 2\frac{\theta\, r^2\, K}{L_0}\left(1 - \frac{L_0}{\sqrt{p^2 + r^2\theta^2}}\right) \tag{6}$$

$$F_L(\theta, p) = 2\frac{Kp}{L_0}\left(1 - \frac{L_0}{\sqrt{p^2 + r^2\theta^2}}\right) \tag{7}$$

The previous relations show that the motor torque and the force along the string depend on the twist angle θ and actuation length p.

2.2 TSA in contact with external elements

In Fig. 2 an overview of the setup used for the evaluation of the TSA in contact with external elements is reported. The experimental setup is composed by a rotative motor used to twist the string on one end and a linear motor (LinMot-37160) attached to the opposite string end acting as a load for the TSA. The linear motor is equipped with a load cell for measuring the load-side force and with a integrated high-resolution encoder (1μm) for load position measurement and it can be controlled to act as a modulable inertia or to apply a constant force compensating for the slider friction, the details about the linear motor controller can be found in Palli and Melchiorri (2008). The rotative motor is hosted in a suitably developed motor module described in Palli and Pirozzi (2013, 2014) with integrated force sensor, position sensor and motor power electronics.

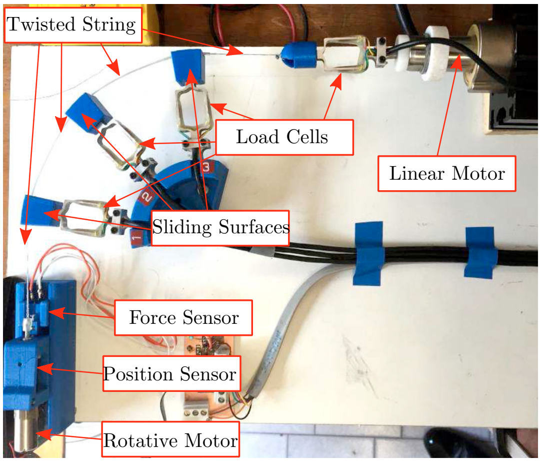

Fig. 2. Experimental setup of the TSA guided by the teflon tube and environmental constraints.

As can be seen in the detailed view of the experimental setup reported in Fig. 2, the twisted string is not straight from the rotative motor to the linear load, but it is deviated by three external elements, i.e. the sliding surfaces, emulating the environmental constraints or the structural parts of the robot, to form an arc of 90 degrees from the rotative motor to the load. In the investigation reported in this paper, both the cases in which the string is directly in contact with the environmental constraints and the case in which the twisted string is passed through a Teflon tube to reduce the friction between the string and the environment are considered. The environmental constraints guiding the TSA are also equipped with load cells for measuring the resultant constraint force: this information allows to estimate the friction acting on the string, but these data are not reported here for brevity and will be subject to future investigation. This particular structure of the experimental setup allows a deeper investigation of both the friction effects and the TSA behavior, since the state of the system can be evaluated in some intermediate points along the curvature from the rotative motor to the load. In particular, it is here assumed that the string parts not in contact with the obstacles behaves as ideal TSA according to the model described in Sec. 2.1 (see Palli et al. (2013) for further details). On the other hand, the contact of the TSA with a sliding surface will be modeled adopting the same assumptions regarding the distribution of the load along the string typical of tendon-based transmission systems, and the effect of the string twisting will be included for completing the system model. According to what reported by Palli et al. (2012) about the modeling of tendon-based transmission systems, the string path can be represented as an arc connecting the input and the output string directions, as schematically represented in Fig. 3(a). In this picture, the force f_{f_i} represents the overall friction effect along the string on the i-th sliding surface characterized by a curvature angle $\beta_i = 30\,\mathrm{deg}$ and by a radius $r_{s_i} = 100\,\mathrm{mm}$, whereas f_{n_i} represents the normal force