Twisted Strings Based Robotic Hand and Eyes

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Abstract— **In this paper we summarize basic findings in modeling of twisted strings actuation. The kinematic relation between motor angle and driving distance is derived, and a suggestion to improve nonlinearity in a robotic joint is presented. Various materials of strings were tested for durability, showing UHMWPE having the longest life span. Applications of twisted strings actuation to a robotic hand, to a fast moving stereo camera, and in a high precision angular positioning device are presented. In conclusion we discuss some unsolved problems and suggest possible future research topics.**

I. Introduction

Principle of force or motion generation by using twisted strings has been known to humans for a long time. Applications in actuators were proposed rather recently. For example, related patent applications in Japan and USA can be found in 1984 [1] and 1988 [2] respectively. Initial presentations in RSJ conferences can be found as early as in 1997 [3]. However, these patents and presentations mostly describe the idea and present practical applications without going deeper into the topic to develop mathematical models, computer simulations, or control algorithms.

In 2010 we can find first published papers which deal with the mathematical modeling of twisted strings actuation [4], [5]. Transmission characteristics presented in mathematical and geometrical form for a pair of nonstretchable strings are presented in [4], while [5] deals with a model of multiple stretchable strings. The researchers in this field continued work on applications of twisted strings actuators in robot arms, hands, and similar. It was found out that the practical limitation of actuation is not strength of the strings, but durability of the strings [6]. Most of the materials with high tensile strengths (various metals, carbon fibers, etc.) tend to break very soon in the operation. On the other hand, synthetic fibers (Kevlar, Zylon, Spectra/Dyneema, etc.) show good durability, but even these strings fail under repetitive use especially under load.

In section II of this paper we present the basic knowledge regarding mathematical modeling of the twisted strings actuation including linearization technique when driving a robotic joint. In section III we report on results of various strings' materials durability test, and in section IV we present applications to robotic hand, fast moving stereo camera, and in precise angular positioning of a video camera pointing towards a distant mobile robot. In conclusion we give remarks regarding some unsolved problems and propose possible future research topics.

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II. Basics of Twisted Strings Actuation

A. Mathematical Model of Transmission Characteristics

For easier understanding and imagining of what happens when two strings of length L twist on each other we assume that the strings have circular cross sections S with radius R, are both nonstreachable, and pose no resistance against twisting and bending, while friction between the strings is neglected. With these conditions in mind we can assume that the strings ideally twist on each other without changing their respective lengths and pose no resistance against twisting and bending. As a result, when we untwist the twisted part of the strings, we can see that the strings are perfectly straight, as shown in Fig. 1. Here A is half of a distance between the two attachment points of the strings' ends (note that A can be equal to R in a case when the strings are attached in parallel to each other), and β is the twist pitch angle, which changes with the twisting.

From the presented geometry of the twisted strings we can derive transmission equations for actuation distance x and motor shaft's rotation angle α, and for actuation speed $\dot{x}$ and motor speed $\dot{\alpha}$, which also describes the relation between actuation force F and motor torque T in inverse.

$$x = \sqrt{L^2 - A^2} - \sqrt{L^2 - (A + R\alpha)^2} \tag{1}$$

$$\frac{\dot{x}}{\dot{\alpha}} = \frac{T}{F} = \frac{R(A + R\alpha)^2}{\sqrt{L^2 - (A + R\alpha)^2}} = \frac{R}{\tan\beta} \tag{2}$$

In reality the strings are multifilaments composed of many thin fibers, thus a cross section does not have a defined circular shape, however, experience shows that from measurement of the actual transmission characteristic we can derive an equivalent strings cross section radius R, so that it can be used for estimation of kinematic relations used in design and in simulations of the twisted strings actuation [7].

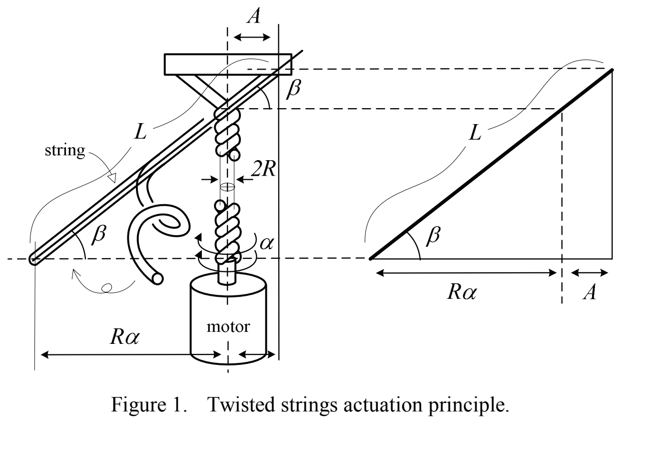


Figure 1. Twisted strings actuation principle.

B. Equivalent Geometrical Representation

A simple way to represent the twisted strings actuation with a geometrical model is to imagine two straight strings (or links) that are pulled apart on one side so that they cross with each other as shown in Fig. 2. Pulling apart the ends of the strings for a distance $R\alpha$ causes the other ends to travel for a distance x. The transmission equations (1) and (2) can be derived from this model as well, and the actuation principle including its nonlinear characteristic are easier to imagine and understand by using this model.

C. Reducing Nonlinearity in a Robotic Joint

Fig. 3(a) shows geometry of a twisted strings actuator assembled in a robotic joint. The twisted strings are in this configuration directly attached to the link. Fig. 3(b) shows comparison of transmission characteristics for different configurations, namely, for the case when twisted strings are attached to a pulley in comparison to different attachment points defined by the distances ratio a/b. Here the radius of the pulley is assumed to be $\sqrt{a^2+b^2}$.

We can see that by changing the ratio a/b we can reduce initial high gear ratio of the twisted strings and thus reduce the overall nonlinearity in the transmission from motor rotation to joint rotation.

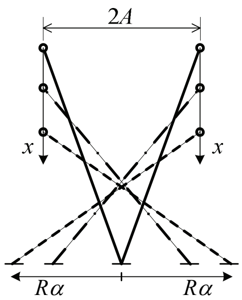
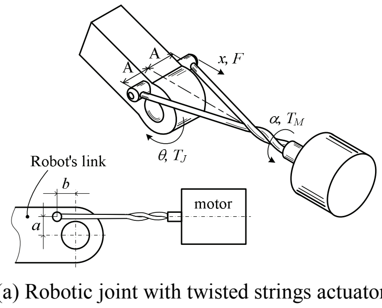
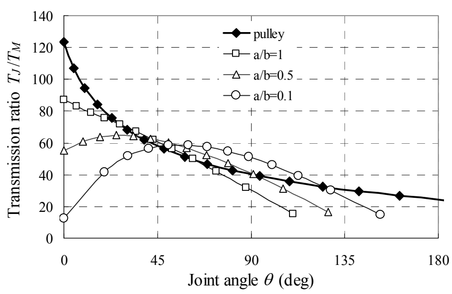


Figure 2. Geometrical representation of twisted strings actuation.



(a) Robotic joint with twisted strings actuator.



(b) Transmission characteristic for different configurations.

Figure 3. Twisted strings actuator transmission characteristic in robot joint.

III. Strings Materials' Durability Comparison

In practical use of twisted strings actuation we have found out that more than tensile strength of the strings durability of the strings is a limiting factor. In a repetitive motion especially under load, strings are getting gradually damaged. Various metal strings, carbon fiber and similar immediately break due to the stress caused by bending and twisting of the strings on each other. On the contrary, some synthetic fibers e.g. Kevlar, Zylon, Spectra/Dyneema show much higher durability. The best performance was confirmed for Spectra/Dyneema, which are product names for UHMWPE (Ultra High Molecular Weight Polyethylene) strings. Experimental results of durability test with repetitive motion under equivalent conditions for selected materials are shown in Fig. 4(a). It is apparent that the best durability is confirmed for Dyneema; that is for UHMWPE strings. Fig. 4(b) shows photographs of UHMWPE string at different stages of wear.

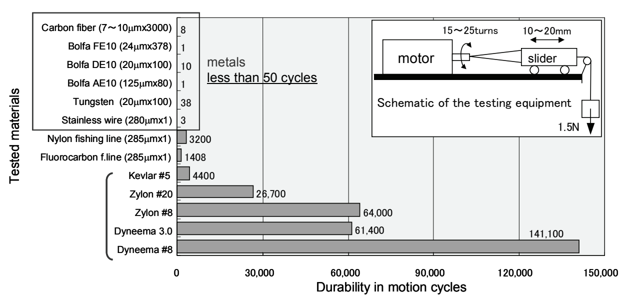
IV. Application Examples

In this section we present three applications of twisted strings actuation, namely, to a robotic hand, in a fast moving stereo camera, and in precise angular positioning of a video camera.

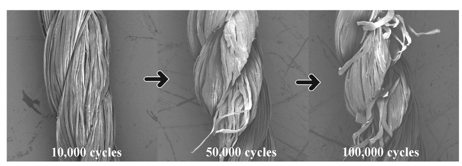
A. Robotic Hand

In the research at University of Kitakyushu we developed a robotic hand with 18 degrees-of-freedom of which 14 were actively actuated by twisted strings, and 4 were passively coupled with other joints.

The goal of the design was to put all actuators in the hand, thus achieving small size and modular design. We used motors and strings that were placed into a palm and into fingers as shown in Fig. 5. As a result, we could not achieve very strong grasping force as the maximum force per finger was about 10 N, which is much less than a human hand's ability, but the size and the weight was similar to a human hand. The used strings were UHMWPE threads with equivalent thickness of $R = 0.2$ mm, length $L = 25$ mm, and attachment distance $A = 7$ mm. (More information can be found in [4], [7]-[10].)



(a) Relative durability of tested materials.



(b) UHMWPE string at different stages of wear.

Figure 4. Durability test results for various strings' materials.

B. *High Speed Stereo Camera*

One of possible applications for twisted strings actuation is to drive a camera with a goal to create a robotic eye. We have developed a stereo camera with capability similar to a human eye, that is, maximum angular speed of 900 deg/s. A picture of the device is shown in Fig. 6(a), and a typical angle and speed profile for fast motion is shown in Fig. 6(b). The device is named “sacada900” and is available for ordering from Twist Drive Technologies, Inc., Nogata, Japan.

C. *High Precision Angular Positioning of Video Camera*

In the application of a mobile robot for drawing lines on a baseball field or on a soccer pitch, there was a need to orient an observing video camera with a high positioning resolution towards the mobile robot. The requirement was to achieve 1 mm positioning resolution at the distance of 100 m from the mobile robot, that is an angular resolution of 10^{-5} rad or 628,319 divisions per revolution. We solved the task by using a pair of Kevlar thin strings ($R = 0.1$ mm), length $L = 240$ mm, attached to a link of length 100 mm. By using a two-phase stepping motor with 200 pulses/revolution we were able to achieve the required positioning resolution with hysteresis as small as ± 5 pulses, which is about 10-times better than with a typical worm gear mechanism.

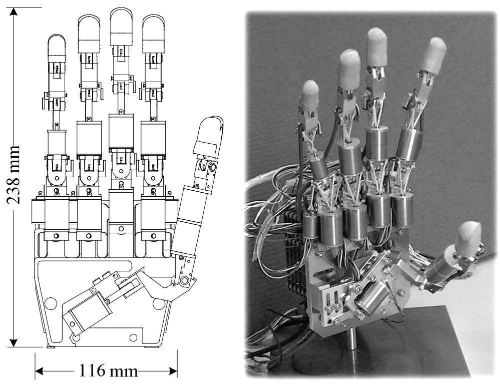
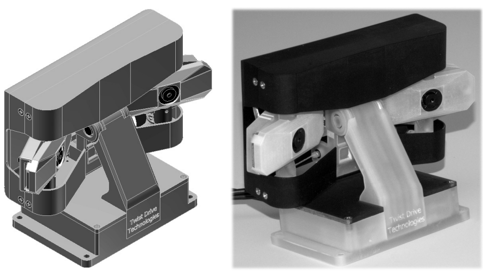
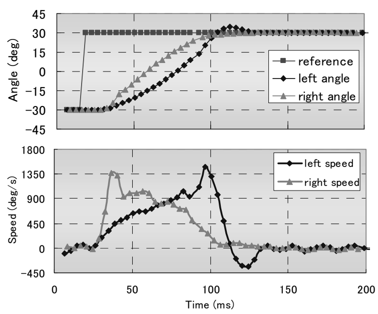


Figure 5. Developed robotic hand.



(a) Stereo camera “sacada900”.



(b) Example of angle and speed profile.

Figure 6. High speed stereo camera.

V. Conclusion

In this paper we described some basic characteristics of twisted strings actuation principle and presented a few application examples. From the authors’ perspective we can conclude that the twisted strings actuation has great benefits in low cost, quiet operation, and muscle-like characteristics. The unsolved problems mainly pertain to durability of the strings, and to the fact that the needed production technology for the twisted strings actuators is significantly different from the traditional ones. Used materials and mechanical components are quite different from typical mechanical engineering components, thus the production technologies of today are not suited to deal with assembling strings and motors into twisted strings actuators.

As a needed future development we would first require more durable strings, and then methods to standardize and make possible easy production and assembly of twisted strings actuators.

A possible topic for future research is development of force sensors to detect tension in the strings, which would significantly be beneficial to wider the range of possible applications.

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