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A compact two-phase twisted string actuation system: Modeling and validation

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ABSTRACT

In this paper, we propose a compact twisted string actuation system that achieves a high contraction percentage (81%) on two phases: multi string twist and overtwist. This type of system can be used in many robotic applications, such as robotic hands and exoskeletons. The overtwist phase enables the development of more compact actuators based on the twisted string systems. Furthermore, by analyzing the previously developed mathematical models, we found out that a constant radius model should be applied for the overtwisting phase. Moreover, we propose an improvement of an existing model for prediction of the radius of the multi string system after they twist around each other. This model helps to better estimate the bundle diameter which results in a more precise mathematical model for multi string systems. The model was validated by performing experiments with 2, 4, 6 and 8 string systems. Finally, we performed extensive life cycle tests with different loads and contractions to find out the expected life of the system.

1. Introduction

A twisted string actuation system converts the rotation from a motor's shaft into a linear motion. It offers some advantages over conventional systems, like a rack and pinion, or a lead screw and nut system, such as being lighter, simpler and less expensive. The actuator is also not completely rigid due to the strings elastic behavior. This can make it harder to control but it should be safer to operate around humans, due to the natural compliance of the entire system.

Some of the earliest applications of the twisted string systems in robotics was reported by M. Suzuki et. al., where they were used to drive a six-legged robot [1] and also an articulated arm that includes an anthropomorphic robotic hand [2,3]. As reported in [3], actuators of the anthropomorphic hand are placed in the forearm of the system outside the hand itself. The same concept was applied in the DEXMART hand [4], where several actuators with twisted string systems are placed outside the palm and in a relatively large forearm. While placing the actuators at a remote distance from the driven object is advantageous for some applications, it is not desired in many others. Godler et. al. presented a five fingered robotic hand, that uses 15 twist drives to control the fingers [5]. In this case the actuators are placed in the fingers. To do so and in order to increase the joints motion range with a limited stroke of the twisted string system, the coupling point of the tendon was shifted from the joint at the cost of making the fingers larger.

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All above examples demonstrate a common problem in the twisted string systems. That is, twisted string systems suffer from a low contraction to length ratio (the ratio of the actuator stroke to the total string length). If neglecting the dead zone (actuators and coupling zone), this ratio for a lead screw and nut system can reach to almost 100 %, which is the same for a rack and pinion system. Previous works on twisted string systems,[6–9], show a contraction percentage of less than 25%. This is problematic for systems that demand for compactness. For instance, one application of the twisted string system, which was considered by several research teams, is in robotic hands. For this application, it is desirable to develop light weight self-contained hands with all actuators integrated inside the palm.

1.1. The two phase twisted string system

In this paper, we propose a two phase twisted string concept which could achieve a much higher contraction compared to the previous systems. In this concept, in the first phase of the contraction, multiple strings twist around each other to the maximum possible amount. At the end of this phase, a single twisted string is formed, in which the individual strings cannot twist around each other anymore. Afterwards, in the second phase, the single string twists around itself. We call this stage “overtwisting phase”. In this way, we could achieve a significant contraction percentage of 81% which was never reported before.

Fig. 1 shows the schematic of our proposed twisted string system. It is composed by the actuator, a connection between the actuator shaft and the strings. Similar to the mechanism presented by Popov et. al. [10], we also used a separator. The role of the separator is to limit the zone where the strings can twist. In this way, beyond the separator there is only linear motion. The zone between the shaft and the separator (Fig. 1) is called the twisting zone.

In all the above articles, the authors either did not specify the reason for their limited contraction range or mentioned that the tensile strength and fast wearing of the strings are their limiting factor. For instance in [8], the authors stated that most strings suitable to be used in twisted string can only carry relative small loads. Furthermore, the overtwisting stage was not considered in any of the previous works, while our proposed system was tested for the overtwisting phase for hundred of cycles and performed a life cycle experiment that demonstrated that the strings can endure overtwisting without a reduction in the strings life (Section 4).

1.2. Mathematical model

In this article we suggest a mathematical model for controlling the system linear displacement over the whole range of the contraction. Even though previous mathematical models could predict the contraction in the initial twisting zone, none of them could correctly fit our experimental results after 15% of the contraction. In the twisted string system presented in [8], authors mentioned that their mathematical model provides high correlation with the practical data only up to 15% contraction.

After studying the previous models and our experiments, we performed some corrections to the model presented in [10], which applies to systems with a separator. First, we developed an improved theory for prediction of the radius of the multi string system after they twist around each other. Second, we showed that a constant radius model performs significantly better over the variable radius model for the long stroke range. Integrating these two contributions, this paper suggests a mathematical model that can precisely predict the contraction of the system over a large range of contraction.

2. Experimental setup

In order to test the two phase twisting string system a prototype was built (Fig. 2). A Micro Metal Gearmotor from Pololu with 100:1 gear ratio, 320 r.p.m. and 0.22 Nm stall torque was employed. The string which was used for this experiment, was a

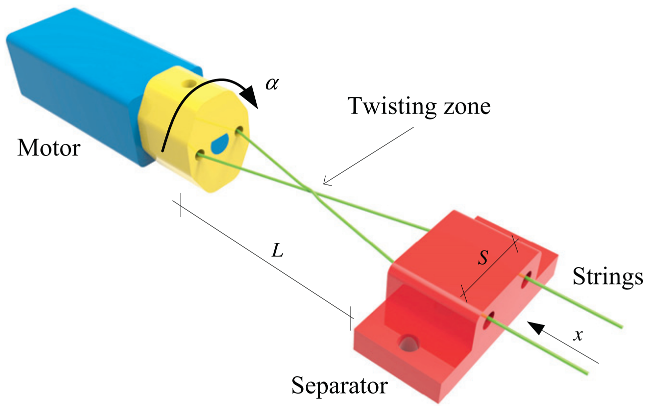

Fig. 1. Twisted string system: electric motor, strings, connection between motor shaft and strings and separator. L is twisting zone length, α is the rotational angle of the motor shaft, x is the linear displacement of the strings and S is the distance between the holes of the separator.