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Twisted string actuation with position feedback for robotic endoscopy

Abstract: A twisted string actuator (TSA) is a small, strong, lightweight, and low-cost gear, transforming rotation into a linear pulling movement. The TSA consists of two or more strings that are twisted along their common longitudinal axis. The helix formed in this process becomes shorter the further the bundle is twisted. A possible application is a tendon-based endoscopic robot. To control the movement of the endoscope, a precise contraction of the tendon is necessary. Since the strings of the TSA show an elastic behaviour, position feedback is needed to determine the exact movement of the TSA. In this paper, a TSA with a closed-loop position control by a low-cost displacement sensor is presented.

Keywords: TSA, twisted string actuator, robotic endoscopy, position control

<https://doi.org/10.1515/cdbme-2021-2087>

1 Introduction

Minimally invasive surgery (MIS) provides crucial advantages in comparison to open surgery, especially for patients, who experience great benefit in terms of reduced surgical trauma resulting in faster recovery [1]. However, compared to open surgery, MIS is much more demanding in terms of instrument handling. To compensate for the disadvantages of handling, robotic support is proposed. The instrument is no longer operated directly by the surgeon but maneuvered by a robot and controlled by the surgeon via a console [2]. Robot-assisted endoscopy will also enable increasingly complex operations to be performed in MIS that are otherwise only possible in open surgery. However, to access hard-to-reach areas of the body and to follow the natural pathway automatically, particularly robot-aided flexible endoscopes are being developed.

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1.1 State of the Art: Robotic endoscopy

In principle, robot-assisted flexible endoscopes are designed similarly to conventional flexible endoscopes. They consist of a light source, a camera, an instrument channel, a proximal passive section, and an active distal tip. Conventionally, the active distal tip is actuated by pulling tendons through manual actuated wheels on the handle of the endoscope. In robot-aided flexible endoscopy, manual actuation is replaced by a motorized drive unit. The pulling of the tendons is achieved by the rotation of a motor in combination with a pulley. Further, the endoscope is kept in position to the patient by a robotic arm or frame and does not need to be actively controlled by a surgeon. To enable more complex operations in single port surgery as well as in Natural Orifice Transluminal Endoscopic Surgery (NOTES), the robotic systems are designed with multiple instrument channels. The instruments are still manually operated in some systems. Table 1 gives a short overview of robot-aided flexible endoscope systems.

Table 1: Overview of robot-aided flexible endoscope systems

System	Description
FLEX	Hybrid procedure for total laryngectomy with a flexible robot-assisted surgical system [3]
K-FLEX	Flexible robotic platform with strong continuum manipulator and max resistance to distortion [4]
MASTER	Dexterous and flexible master-slave device used with conventional flexible endoscope [5]
STRAS	Modular robotic system compatible with medical environment based on Anubis ® platform (by Karl Storz) [6]
ViaCath	Teleoperated robot consisting of a master console and slave drive mechanisms running alongside a standard gastroscope or colonoscope [7]

1.2 Aim of this work

Advantages such as its low weight and low cost, propose twisted string actuation (TSA) to drive a flexible endoscope. Due to the unknown internal forces (friction) and external forces, the tensile force to adequately actuate the endoscope

tip is unknown. The TSA strings that actuate the endoscope tendons are elastic, so the contraction depends on the tensile force. Therefore, it is not possible to calculate the contraction under load using the theoretical kinematic equations, since they do not consider the elastic behaviour of the strings. To improve the performance of a TSA-driven endoscope under load, this work aims on realizing a closed-loop-control using a low-cost position sensor.

2 System Design

A TSA achieves high tractive forces in a compact design. This consists of two or more strings that are twisted along their common longitudinal axis. Due to the twisting by an electric motor along the TSA main axis, the string bundle creates a helix and reduces its initial length [8]. Thus, the rotation of the motor is converted into a linear movement. This type of actuator shows multiple advantages, such as a compact and lightweight setup with only few components, low costs, and low noise [9].

The actuators are located at the back end of the endoscope to transfer the tensile force to the tip of the endoscope using tendons. Two actuators are used to antagonistically control the movement of the endoscope in one plane. Therefore, a precise contraction of the string array is necessary. A schematic drawing of the TSA with the position feedback is depicted in figure 1.

2.1 Design of the TSA

The TSA should be able to perform a translational movement of 20 mm with an applied axial load of 50 N and an positioning accuracy of 0.1 mm. A theoretical maximum contraction of 29 % follows from the geometric consideration [10]. A safety factor of ~ 3 is applied to the theoretically required untwisted initial length of 69 mm due to the predicted elastic behavior of

the Dyneema® strings and the associated reduced shortening of the TSA. An initial length of $x_0 = 200$ mm is used. The contraction of a non-elastic TSA

$$\Delta x = x_0 - \sqrt{x_0^2 - (\theta \cdot R_H)^2} \quad (1)$$

depends on the angle of rotation θ , the radius of the resulting helix R_H , and the initial length x_0 . The radius of the resulting helix R_H is equal to the diameter ($\varnothing 0.4$ mm) of the used Dyneema® strings [10].

The motor was selected based on the required torque T . To apply the necessary pulling force $F = 50$ N at a maximum angle of rotation $\theta_M = 112\pi$, the motor must apply a torque

$$T = F \frac{R_H^2 \cdot \theta_M}{\sqrt{x_0^2 - (R_H \cdot \theta_M)^2}} \quad (2)$$

of 19,8 Nmm. Therefore, a NEMA8-stepper motor (SCA2018M0804, Nanotec Electronic GmbH & Co. KG, Feldkirchen, DE) is selected. Since the shaft of the motor can only handle an axial load of 4 N, an F6-12M-M axial bearing (Kugellager-Express GmbH, Schloss Holte-Stukenbrock, DE) is used.

2.2 Position feedback

To achieve position feedback, the linear displacement of the slider is measured by a reflex coupler (OPB606A, OPTEK Technology Inc., Carolton, USA) and a greyscale progression [11]. A printed 80 mm long greyscale progression is glued on a linear guide (NS-01-17, igus GmbH, Cologne, DE) and a reflex coupler is integrated into a slider (NW-02-17, igus GmbH, Cologne, DE). Depending on the grey value, more or less light is reflected and detected by the phototransistor. The distance to the greyscale must be kept constant at 1.3 mm as recommended in the datasheet. The measured signal is proportional to the position of the phototransistor (see figure 2). For calibration, the actual linear displacement of the reflex coupler on the greyscale is measured with an electronic calliper (3472BPN, TOOLLAND Inc., San Carlos, USA).

Figure 1: Schema of the two TSAs with the greyscale and axial bearings. The actuators work antagonistically to each other. If one TSA is fully shortened and the strings of the second TSA are in parallel position, the endoscope tip is angled.

Figure 2: Principle of reflex coupler and grey scale. The signal depends on the reflected and measured light that is emitted by the IR-LED of the reflex coupler.

Six different loads (0.3 kg, 1 kg, 2 kg, 3 kg, 4 kg, 5 kg) were applied to the TSA with both, open-loop and closed-loop control. To communicate with the TSAs the motors are connected to an Arduino UNO (Arduino LLC, MA, USA) through a motor driver shield. On the Arduino, an EtherCAT Shield (EasyCAT, AB&T Srl, Ivrea, IT) is mounted, which receives the desired position from a host PC and sends the measured position back to the host, acting together as Master and Slave. Depending on the configuration of the hard- and software, the position control can be done either on the Arduino Uno or the host PC.

3 Results

A prototype of a TSA with position feedback has been set up. The assembly of the TSA is shown in figure 3. Two TSAs were installed, which work antagonistically. The motor mount was manufactured from laser-cut acrylic plates attached to an aluminum construction profile. Further, the additional axial bearing was fixed in the motor mount. The slider and linear guide were positioned so that the strings were aligned with the motor axis. The reflex coupler was implemented into the slider

Figure 3: Prototype consisting of two parallel working TSAs controlled by an Arduino UNO microcontroller

Figure 4: Linear slider with mounted reflex coupler and greyscale

Figure 5: Voltage over displacement of the reflex coupler on an 80mm long greyscale progression.

Figure 6: Actual contraction Δx over target contraction Δx with the closed loop control.

to integrate closed-loop position feedback as shown in figure 4. The greyscale is embedded in the linear guide.

Figure 5 shows the measured values of the reflex coupler on an 80 mm long greyscale progression. In the range of 30 mm to 60 mm the greyscale progression shows a linear behaviour ($U = -1.73 \text{ V} + 0.11 \text{ mm/V} \cdot x$; $R^2 = 0.99$). In this range, positioning with a closed-loop control with a root-mean-square error (RMSE) of 0.13 mm regardless of the applied force was achieved (see figure 6).

From lowest (0.3 kg) to highest (5 kg) applied load, the experimentally achieved contraction of open-loop control of the TSA varies between 40 mm (with 0.3 kg) and 29 mm (with

Figure 7: Rotations vs. Contraction of the TSA with different applied axial loads compared to the theoretical value, starting from untwisted to maximally twisted.

Figure 8: Rotations vs. Contraction of the TSA with different applied axial weights compared to the theoretical value, starting from maximally twisted to untwisted

5 kg) at 120π (see figure 7 & 8), 41,7 % to 56,9 % less than the analytic model predicts. The theoretical contraction of the TSA reveals a maximum contraction of 69 mm, assuming a non-elastic behavior of the strings.

4 Discussion

A closed-loop position feedback TSA has been implemented that can be used to actuate a robotic endoscope. The chosen actuation is more lightweight and less expensive than other established solutions for generating precise linear motion, such as a linear spindle drive. The TSA can perform a stroke of 30 mm under a load of up to 5 kg with a RMSE of 0.13 mm. With the low-cost position sensor developed, the elastic behavior of the TSA can be compensated and the contraction under load can be accurately determined.

Figure 5 shows that there is a linear relationship between 30 mm and 60 mm of greyscale to the output signal of the reflex coupler. Beyond that, no linear relationship can be seen. It is, therefore, crucial to place the shortening of the TSA in this range to obtain sufficient position feedback. Since a shortening of 20 mm was required, the greyscale used is adequate. However, the greyscale progression should be adjusted so that the reflex coupler outputs a linear signal over the entire range. This will save space in the setup and no limited range in the greyscale progression has to be taken into account. Alternatively, a lookup table could be used.

If a load is applied to the TSA, the contraction deviates according to the theoretical model (Eq. 1). The greater the load, the smaller the contraction of the TSA (see figure 7 & 8), caused by the elastic behavior of the Dyneema® string. Depending on the load, the initial length x_0 changes. In addition, the radius of the helix cannot be considered constant, since it also changes under load and no perfect helix structure is formed during twisting. The selected safety factor of the chosen initial length proved to be necessary and sufficient for

the given load. Therefore, accurate contraction of the TSA is not sufficient with an open-loop control when the load is unknown. With the developed position sensor, a closed-loop control could be realized and the deviation due to elastic string behaviour is compensated.

Author Statement

Research funding: This work was supported by the Federal Ministry of Education and Research of Germany (Grant: 01DR19002A). Conflict of interest: Authors state no conflict of interest.

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