Twisted String Actuation - History, principle and performance

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Robotic hand application

- Five-fingered robotic hand under development at DEIS, University of Bologna within the European funded project DEXMART
The principle

- **two or more strings or strands are connected in parallel**

- **twisting of strings reduces their length, generating linear motion**

- **low transmission ratio permits use of very small and lightweight electric motors**

- **interesting in applications where size and weight are of crucial importance**
Demonstration units

- Presentations at Schunk Expert Days, Hannover Fair 2010 and AUTOMATICA 2010

Compact high-strength motor module
Dual-arm twisted string 16 kg case lifter
Uses of Twisted String

- For starting fires
- For drilling holes

(Source: The coming of the Maori)

(Source: karenswhimsy.com)

(Source: thegardengoblin.com)
Uses of Twisted String

Balista / Catapults

- From ancient Greek and Roman warfare ...

- ... to modern hobbies

(Source: www.imperiumromanum.com)

(Source: www.siege-engine.com)
Uses of Twisted String

- **Spanish windlass**
  - Thomas splint
  - Drawing heavy loads
  - Structural fixation, e.g. in boot construction

(Source: www.jbjs.org)

(Source: www.bigstones.com)

(Source: www.finehomebuilding.com)

(Source: picasaweb.google.com)
Uses of Twisted String

**Button Spinner**
- For recreation
- For training

(Sources include bild der wissenschaft shop)
Previous Technical Developments

UNITED STATES PATENT OFFICE

2,027,386
SYSTEM FOR MOVING BODIES TOWARDS AND AWAY FROM EACH OTHER
Adolf Krümmern, Berlin, Germany
Application December 1, 1933, Serial No. 700,631
In Germany December 3, 1932

(Source: ip.com)
Previous Technical Developments

United States Patent [19]

Jacobsen

[54] ROTARY-TO-LINEAR AND LINEAR-TO-ROTARY MOTION CONVERTERS

[76] Inventor: Stephen C. Jacobsen, 12 Burton St., Arlington, Mass. 02174

[22] Filed: May 8, 1974


(Source: ip.com)
Previous Technical Developments

United States Patent

Kremer

[54] TWISTED CORD ACTUATOR

[76] Inventor: Stephen R. Kremer, 3283 Yelton La., Amelia, Ohio 45102

[21] Appl. No.: 182,880

[22] Filed: Apr. 18, 1988
Previous Technical Developments

KeJun Ning

- Crane building hobby as child
- Use of twisted cloth ca. 1989
- Post-Doc at Göttingen University

(Source: KeJun Ning)
Previous Technical Developments

Toward Springy Robot Walk Using Strand-Muscle Actuators

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M. Suyuki, H. Akiba, A. Ishiyaka:
Previous Technical Developments

(12) **United States Patent**

**Soham**

(54) **TWISTING WIRE ACTUATOR**

(76) **Inventor:** Moshe Soham, Hoshaya, M.P. Hamovil, Hoshaya (IL) 17915

( * ) **Notice:** Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 364 days.

(21) **Appl. No.** 10/595,530

(22) **PCT Filed:** Oct. 24, 2004

(Source: ip.com)
Previous Technical Developments

(19) United States
(12) Patent Application Publication

Godler

(54) MOTION CONVERSION DEVICE

(75) Inventor: Ivan Godler, Kitakyushu (JP)

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(73) Assignee: Ivan Godler, Kitakyushu (JP)

(21) Appl. No.: 12/397,361

(22)Filed: Mar. 4, 2009

Fig. 1

also www.twistdrive.com)
Actuator modeling

- **Kinetostatic model**
  - load equally distributed over $n$ strands
    \[ F_i \sin \alpha = \frac{F_\tau}{n} = \frac{\tau_L}{n} \]
  - the total axial force is related to the motor torque as
    \[ F_z = n F_i \cos \alpha = \frac{\tau_L}{r \tan \alpha} \]
  - transmission ratio
    \[ h(\theta) \equiv \frac{\tau_L}{F_z} = r \tan \alpha = \frac{\theta r^2}{p} \]
  - note that
    \[ h(0) = 0 \]
- Strands with finite dimensions and stiffness
  - string transmits forces and deforms (spring-like system)
  - length of a strand $L$ can be computed as the unloaded length $L_0$ plus the elongation due to the fiber tension $F_i$ and the stiffness $K$ of the strand

\[ L = F_i \frac{L_0}{K} + L_0 = \sqrt{\theta^2 r^2 + p^2} \]

- the actuation displacement is

\[ \Delta p = L_0 - p = L_0 - \sqrt{L_0^2 - \theta^2 r^2} = L_0 (1 - \cos \alpha) \equiv k(\theta) \]
Actuator testing

- Experimental setup
  - DC motor with encoder
  - Twisted string
  - Load cell
  - Linear motor acts as load for the transmission
  - Real time acquisition and control system
Evaluation of the kinematics and stiffness

- The system kinematics has been evaluated with very low load
- The transmission stiffness has been evaluated for different values of motor angle and different loads
Duration tests

- both single and multiple string solutions have been tested
- experiments involving full displacement cycling under constant load have reached up to 40,000 cycles for low load
- cycling of the load force between 0 N and 50 N with nearly zero displacement has reached over 400,000 cycles (grasping case)
- the string typically breaks at the fixing points
Actuator dynamics and control

- Simplifying assumptions
  - negligible inductance of the DC motor
  - negligible compliance of the string
  - purely elastic load

- State-space model

  \[ \dot{x}_1 = x_2 \]
  \[ \dot{x}_2 = -a_1 h(x_1)k(x_1) - a_2 x_2 + bu \]
  \[ y = ck(x_1) \]

  \( x_1 \) motor angle
  \( x_2 \) motor angular velocity

- A sliding manifold control algorithm has been defined for:
  - tracking the transmission force
  - robustness against parameter uncertainty and variability
  - disturbance rejection

- The controller can be described as

  \[ C(s) = \frac{n_2 s^2 + n_1 s + n_0}{\epsilon^\nu s^\nu + \epsilon^{\nu-1} d_{\nu-1} s^{\nu-1} + \ldots + \epsilon d_1 s} = \frac{N(s)}{D(s)} \]
Control design procedure

- Select the $\nu$ poles $\delta_i$ of the boundary layer system then compute the coefficients $d_i$ of the following polynomial as
  \[ s^\nu + d_{\nu-1}s^{\nu-1} + \ldots + d_1s + d_0 = \prod_{i=1}^{\nu}(s - \delta_i) \]

- Compute the coefficient $n_2$ as
  \[ n_2 = d_0/(c b h(\bar{x}_1)) \]
  by selecting $\bar{x}_1$ to ensure uniform stability of the polynomial
  \[ s^\nu + d_{\nu-1}s^{\nu-1} + \ldots + d_1s + d_0 h(x_1)/h(\bar{x}_1) \]
  using a root-locus method with parameter $x_1 \in [x'_1, x''_1]$.

- Select the two poles $\lambda_1$ and $\lambda_2$ of the reduced order system then compute the coefficients of the polynomial as
  \[ s^2 + \bar{n}_1s + \bar{n}_0 = (s - \lambda_1)(s - \lambda_2) \]

- Compute the numerator of the controller as
  \[ N(s) = n_2(s^2 + \bar{n}_1s + \bar{n}_0) \]

- Choose $\epsilon$ as small as possible, compatible with sensor noise and desired closed-loop bandwidth, and compute the denominator of the controller as
  \[ D(s) = \epsilon^\nu s^\nu + \epsilon^{\nu-1}d_{\nu-1}s^{\nu-1} + \ldots + \epsilon d_1s \]
Control remarks

- The computational load is very low and the controller does not require any feedforward action unless a mismatch of initial conditions exists.
- As an output feedback control algorithm, state measurement is not required; a load cell measures the output force at one end of the twisted string.
- A low-noise sensor signal is required, even though high frequency amplification is mitigated by the strictly proper controller achieved by selecting $\nu \geq 3$.
- It can be shown that for $\epsilon = 0$ the control signal is exactly the same as the classical feedback linearization algorithm.
- The zeros can be selected by taking into account the closed-loop bandwidth.
- The system is stable for any value of $\bar{\epsilon}_1$. 

![Graph showing stability region](image)
Simulations have been performed to evaluate the control performance.

Parameter uncertainties and sensor noise have been introduced to evaluate the robustness of the controller.

Experimental results were compared with those of simulations.
Actuator design and manufacturing

- **Actuator module design**
  - A twisted string actuation module scaled to the robotic hand application has been designed and built by USAAR
  - Experience from string characterisation, string fixation, motor selection and detailed mechanical design have contributed to the module design
    - The module lifts 7 kg by 25 mm using a compact DC motor of Ø12.4 mm
Finger actuation design

- A module for the actuation of a single finger has been designed
- Multiple modules are used for the actuation of the whole hand
- A single actuation module for the entire hand can be evaluated
Actuator design and manufacturing

- Development of a robotic finger actuation module
  - Investigation on the string fixation is still going on
  - Prototype of the finger + actuation system

Finger Actuation Module (4 tendons)

Weight \( \sim 0.2 \) kg
Power Consumption = 16 W max
Summary

Twisted String Actuation

- Compact, yet powerful system for actuating robotic devices such as robotic hands

- Kinetostatic model describes nonlinear transmission, shows design parameters

- Experiments validate model and demonstrate actuation under various loading conditions

- Sliding manifold controller designed and achieves good force reference tracking
Conclusions

- **Summary of significant results**
  - Simplified kinetostatic model has been developed
  - The model has been experimentally validated
  - The developed models fit very well with experimental data
  - The transmission stiffness is not negligible
  - A model of the stiffness must be developed (polynomial approximation?)
  - Comparative analysis of the materials and string fixation continues
  - A preliminary prototype for actuating a single robotic finger was successfully developed

- **Future activities**
  - Design of control system for robotic finger with twisted string actuation
  - Development of the actuation system for the whole robotic hand
For more information about twisted string actuation

go to www.dexmart.eu

or contact

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