"Twisted Strings Based Robotic Hand and Eyes"

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Twisted strings mechanism: Twist Drive

- Twisted strings principle = Twist Drive

\[ \alpha \ldots \text{motor rotational angle} \]
\[ T \ldots \text{motor rotational torque} \]
\[ x \ldots \text{linear motion distance} \]
\[ F \ldots \text{pulling force} \]
\[ R \ldots \text{wire crosssection radius} \]
\[ L \ldots \text{wire length} \]
\[ A \ldots \text{fixture distance} \]

**Benefits:**
1. Muscle-like function
2. Low-cost, simple structure
3. Light weight
4. Silent operation

**Assumptions:**
- Length \( L \) is constant
- Crosssection radius \( R \) is constant
- No friction, bend or twist resistance

**Design parameters**

\[ x = \sqrt{L^2 - A^2} - \sqrt{L^2 - (A + R \alpha)^2} \] (1)
Transmission characteristics of Twist Drive

\[ x = \sqrt{L^2 - A^2} - \sqrt{L^2 - (A + Ra)^2} \]

Pulling force and torque relation (with energy loss neglected):

\[ \dot{x} = \frac{R(A + Ra)}{\sqrt{L^2 - (A + Ra)^2}} \tan \beta = \frac{R}{\tan \beta} \]

\[ F = \frac{\sqrt{L^2 - (A + Ra)^2}}{R(A + Ra)} = \tan \beta \]

**Example**

- \( R = 0.2 \text{mm} \) … radius of wire's crosssection
- \( L = 25 \text{mm} \) … length of wire
- \( A = 7 \text{mm} \) … fixture distance

An example

\[ \alpha_{\text{max}} = \frac{\pi L - A\sqrt{\pi^2 + 4}}{R\sqrt{\pi^2 + 4}} \]

\[ x_{\text{max}} = \sqrt{L^2 - A^2} - \frac{2L}{\sqrt{\pi^2 + 4}} \]

Could still be twisted further, but that we call an "over-twist".

\[ \alpha_{\text{max}} = 70.45 \text{rad} = 11.2 \text{turn} \]

\[ x_{\text{max}} = 10.57 \text{mm} \]
Design parameters

Known:
- longer strings → larger stroke
- thinner strings → larger reduction ratio (shorter life span)

**Influence of parameter $A$?**

When $\alpha = 0$:

Dimensionless representation

Parallel strings

Measurements and comparison to the model

Wire: nylon filament (a fishing line)

- $R = 0.14\text{mm}$…wire's crosssection radius
- $L = 60\text{mm}$…wire length
- $A = 15\text{mm}$…fixture distance

Solution: Use "equivalent thickness radius" to describe measured characteristic
Measured characteristics

Motor 150W Maxon RE39
Encoder 2000p/rev
Torque sensor HBM T20WN/0.5
Linear scale Renishaw RGS40-S/RGH34 10μm res.
External load 29N

String (thread)

\[ R = 0.2\,\text{mm}, \quad L = 35\,\text{mm}, \quad F = 15\,\text{mm}, \quad x_{\text{max}} = 23.4\,\text{mm} \]

Distance vs. motor angle 

Motor torque vs. motor angle

Twist/twist (grease) vs. motor angle

Motor torque vs. rotational angle

We tested commercially available wires, threads, sutures...etc.

Engineering problem — string’s thickness

A thin string has high transmission ratio: a small torque produces a strong pulling force.

A thin string is soon worn-out and tears → short life span.
**Engineering problem — string’s durability**

Durability testing equipment

One test cycle is a motion from un-twisted state to twisted state and back to un-twisted state.

<table>
<thead>
<tr>
<th>Tested materials</th>
<th>Durability in motion cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon fiber (7~10µm/3000)</td>
<td>61,400</td>
</tr>
<tr>
<td>Bolfa FE10 (5µm/316)</td>
<td>64,000</td>
</tr>
<tr>
<td>Bolfa SE10 (3µm/1059)</td>
<td>26,700</td>
</tr>
<tr>
<td>Bolfa AE10 (12µm/959)</td>
<td>4400</td>
</tr>
<tr>
<td>Tungsten (25µm/1000)</td>
<td>3200</td>
</tr>
<tr>
<td>Stainless wire (28µm/grey)</td>
<td>11</td>
</tr>
<tr>
<td>Fluorocarbon fishing line (30µm/grey)</td>
<td>6400</td>
</tr>
<tr>
<td>Kevlar #5</td>
<td>38,700</td>
</tr>
<tr>
<td>Zylon #25</td>
<td>141,100</td>
</tr>
<tr>
<td>Zylon #8</td>
<td>11</td>
</tr>
<tr>
<td>Dyneema 3.0</td>
<td>10</td>
</tr>
<tr>
<td>Dyneema #8</td>
<td>10</td>
</tr>
</tbody>
</table>

Tested materials less than 50 cycles:

- Carbon fiber
- Bolfa FE10
- Bolfa SE10
- Bolfa AE10
- Tungsten
- Stainless wire
- Fluorocarbon fishing line
- Zylon #25
- Zylon #8
- Dyneema 3.0
- Dyneema #8

**The best performing material**

(Ultra High Molecular Weight Polyethylene (UHMWPE) or High-Modulus Polyethylene (HMPE) or High-Performance Polyethylene (HPPE)

Brands:
- **Dyneema** = Royal DSM N.V. (Netherlands) → Toyobo
- **Spectra** = Honeywell
- **TIVAR** = Quadrant EPP Inc.
- **Polystone-M** = Röchling Engineering Plastics
- **Tensylon** = Integrated Textile Systems
- **GARDUR** = Garland Manufacturing

**Electron microscope photo**

- Single crystal
- X-ray diffraction
**Five fingered robotic hand prototype**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>238 x 116 x 72 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>Approx. 720 grams</td>
</tr>
<tr>
<td>D-O-F</td>
<td>18 of which 14 independent</td>
</tr>
<tr>
<td>Max. grasp force</td>
<td>10 N per finger</td>
</tr>
<tr>
<td>Motors</td>
<td>brushless DC x 15</td>
</tr>
<tr>
<td>Sensors</td>
<td>joint’s angle (12 bit) x 14</td>
</tr>
</tbody>
</table>

**Robotic finger**

Twist Drive is used to flex the finger; extension is achieved by springs.

**Benefits from Twist Drive use:**
- Finger can be easily flexed by external force, which results in increased safety during unwanted contacts.
- Small objects cannot be squeezed with large force (higher safety).
Application to a robot joint

Example

\[ R = 0.22 \text{mm} \ldots \text{wire's crosssection radius} \]
\[ L = 60 \text{mm} \ldots \text{wire length} \]
\[ A = 15 \text{mm} \ldots \text{fixture distance} \]
\[ \sqrt{a^2 + b^2} = 7 \text{mm} \ldots \text{pulley radius} \]

Control of antagonistic pair of actuators

Problem: Faster pulling side can cause interlock.

Detection of strings' tension would be preferable, but is practically difficult in the hand, thus disturbance observer.
Experimental results

without unwinding torque compensation

with unwinding torque compensation

Robotic hand prototypes

- 5 fingered robotic hand with force sensor and force control

- 3 fingered lower cost robotic hand with force detection in joints
Robotic eyes

- Uncanny valley

- Robotic eyes with human eye’s capability
  - motion range ±45deg
  - maximum speed 900deg/s
  - “sacada900”

Robotic eyes – “sacada900”

- 3 DOF, Twist Drive actuation
- motion range
  - horizontal ±45deg
  - vertical ±25deg
- maximum speed
  - horizontal 900deg/s
  - vertical 500deg/s
- angular positioning resolution
  - horizontal and vertical 0.1deg
- USB camera
  - Logitech HD Webcam C615

Typical response
More human like robotic eyes – “sacada130”

- Roller shape body (possible to rotate)
- External housing (left-right symmetrical)

Built in camera FCB-MA130

Typical response (sacada130)

- 0 to 22.5 deg
Concluding remarks

- Twisted strings actuation has interesting potentials due to its light weight, low cost, muscle-like and quiet operation.

- Applications to robot hands, eyes, and high precision positioning were presented.

- Unsolved engineering problems:
  - durability of strings
  - production technology of actuators

- Possible future topics:
  - strings materials
  - standardized components and production methods
  - force/tension detection from strings

- Thank you for your attention.