全方向物体搬送テーブルと共に物理的に人間を補助するための軽量ワイヤ駆動ロボットアームの研究
Study on a Lightweight Robotic Arm for Physical Assist of Human with Omnidirectional Table

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1. Introduction
There has been a long-standing interest in the implementation of robotic manipulators to assist humans in everyday tasks. Safety is an issue of primary importance in applications that require interaction with humans, since a collision or forceful contact with the robot can result in serious injury. In addition to the safety measures provided by its control system based on sensory data, the mechanical design characteristics of the robotic manipulator have to be taken into consideration in order to provide inherent safety for human-robot interaction (HRI). A robotic manipulator that operates in close proximity with humans is desired to be as lightweight as possible in order to reduce the impact force it has in case of a collision.

A serial-link wire driven robotic arm has been proposed in [1], [2], [3] in which the motors are removed from the arm's moving structure and placed on its nonmoving base, having the joints remotely actuated by flexible wires. This approach results in a significant reduction in weight and inertia in comparison with conventional manipulators, and also offers the benefit of miniaturization as reported in [4]. However the serial distribution of six or seven joints in a long cantilever structure limits the robotic arm's payload capacity and increases the complexity of joint control due to the mechanical interference of the wires as they pass through each articulation.

To tackle this problem, we study the design of a lightweight wire driven robotic arm with 4-DOF implementing a serial-parallel architecture and a method for independent joint control using a spiral pulley mechanism. The 4-DOF lightweight wire driven robotic arm can be further integrated with an independent 2-DOF planar omnidirectional table to form a complete 6-DOF robotic manipulation system to assist humans.

2. Wire Driven Robotic Arm Overview
The wire driven robotic arm consists of a 1-DOF revolute elbow joint connected serially through a forearm link to a 3-DOF spherical wrist. The spherical wrist is composed of a five-bar parallel link mechanism and an end-effector link. The combination of serial and parallel architectures takes advantage of the large workspace of a serial-link manipulator and the compactness and structural stiffness of a parallel-link manipulator. The joints of the robotic arm are actuated by low mass Kevlar wires that are routed from the motors located at the nonmoving base to each joint through a system of pulleys.

Fig. 1 Overview of the wire driven robotic arm.

Fig. 2 Prototype of the wire driven robotic arm.

3. Spiral Pulley Mechanism and Joint Control
As a result of the wires passing through the articulation on the forearm link, yaw rotation causes a certain length of wire on the wrist roll and pitch pulleys to be displaced, inducing undesired motion on those joint axes. To overcome this mechanical interference, a spiral pulley mechanism is deployed for the wrist pitch and roll joints. We use the relationship between the yaw, roll and pitch rotation angles and the radii of the spiral pulleys and driving pulleys to derive a control equation that compensates the undesired displacement of the wires by winding and unwinding that displacement on the clockwise and counterclockwise grooves of the spiral pulleys accordingly.
Fig. 3 View of the spiral pulley mechanism on the prototype.

The length of wire winding onto and unwinding from the roll/pitch spiral pulley is the same as the length of wire displaced by the roll/pitch driving pulley. The roll/pitch spiral pulley rotation angle $\theta_d$ as a function of the roll/pitch driving pulley rotation angle $\theta_d$ is:

$$\theta_d = \frac{r_s \cdot \theta_d}{r_y}$$

Where $r_s$ is the radius of the roll/pitch spiral pulley and $r_y$ is the radius of the roll/pitch driving pulley.

The yaw axis pulley rotation angle $\theta_d$ as a function of the yaw driving pulley rotation angle $\theta_d$ is:

$$\theta_d = \frac{r_y \cdot \theta_d}{r_y}$$

Where $r_y$ is the radius of the yaw driving pulley and $r_y$ is the radius of the yaw axis pulley. The rotation angle of the roll/pitch spiral pulley $\theta_d$ (equation 1) has to be equal to the rotation angle of the yaw axis pulley $\theta_d$ (equation 2). Therefore:

$$\frac{r_s}{r_y} \cdot \theta_d = \frac{r_y}{r_y} \cdot \theta_d$$

Using this relationship we solve for the roll/pitch driving pulley rotation angle $\theta_d$:

$$\theta_d = \frac{r_s}{r_y} \cdot \theta_d$$

According to the control equation (equation 4), for a given rotation angle of the yaw driving pulley $\theta_d$, the roll and pitch driving pulleys must rotate by and angle $\theta_d$ to compensate the influence of the yaw motion and cancel the mechanical interference to allow independent joint control.

4. Fundamental Experiment

A fundamental experiment was conducted to test the accuracy of the iterative motion of the wrist roll, pitch and yaw joints in a motion rage of $\pm 25^\circ$. For this experiment the elbow joint was fixed to a horizontal position to measure only the wrist angles.

Table 1 Specifications of the wire driven robotic arm prototype

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tbody>
<tr>
<td>Mass</td>
<td>1.6 kg</td>
</tr>
<tr>
<td>Length from elbow to wrist</td>
<td>177 mm</td>
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<tr>
<td>Length from wrist to end-effector</td>
<td>353 mm</td>
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<tr>
<td>Total arm length</td>
<td>530 mm</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>Wrist roll, wrist pitch, wrist yaw, elbow pitch</td>
</tr>
<tr>
<td>Wrist motion range [deg]</td>
<td>Roll: $\pm 56$ Pitch: $\pm 62$ Yaw: $\pm 90$</td>
</tr>
</tbody>
</table>

5. Conclusions

A prototype was developed to test the mechanical characteristics of the wire driven robotic arm. An arm mass of 1.6 kg and arm length of 530 mm was achieved, 2.6 kg and 19.2 mm less than the average mass and length of a human arm, respectively. The interference of the yaw rotation on the wrist roll and pitch is eliminated with the spiral pulley mechanism.

6. References