Design and Control of a Wearable Robot

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Abstract

The concept of wearability will be recognized very important in future robotics as in computer science. There is a strong possibility that wearable robots suggest a new direction for human-robot interaction. In this paper, we propose RoboWear, a wearable robot that a human operator wears on his arm for the purpose of human-robot interaction. The wearable robot can be used to amplify human power, to control a remote robot dexterously, to interact with humans in virtual environment. In this paper, the authors designed RoboWear that has active 7 DOF with suitable device to be worn by a human operator. Based on the anatomical analysis of a human arm and the distribution of multiple DOF over the space, authors designed a wearable robot with a hybrid structure consisting of two parallel manipulators and three separate joints. An operator wearing the robot arm can move around freely, because this robot is designed to have its base supported at the shoulder part of the operator. The total weight of the proposed robot arm is approximately 4 kg. Pneumatic actuators are used to reduce the total weight of the robot, to improve compliance with human motion and to generate high reactive forces. The feasibility of the wearable robot is demonstrated by examining the control performance and by incorporating the wearable robot with virtual environment.

1. Introduction

In modern technology, there has been persisting endeavor to facilitate interface between human being and machines and finally to coexist the both. Modern robots can communicate with humans more easily than their predecessors by being endowed with artificial intelligence and understanding human intention with many sensors. Another way of mutual communication and coexistence is to combine or to replace robotic mechanism with human body. This paper proposes a wearable robot, RoboWear to coexist a human with a robot in the same physical space. A human can wear a robot on his/her arm like a suit and communicate with the robot by operating his/her arm together. The advantage of wearing a robot is that a human can be supported or assisted by the robot with direct interaction. For this, a robot must be designed not only to have enough joint torque or joint range, but also to be proper to be worn. In the robot teleoperation area, master arm devices are successfully used to introduce dexterous human motions into the robot control [1, 2]. In one sense, these master arm devices can be described as primitive wearable robots. These researches on master arm devices, however, concentrate on the control performance of slave robots. As heavy actuators are used to provide sufficient joint torque, the devices are fixed at walls or poles that prevent operators from moving freely. EXOS Company developed a portable master arm in 1993, but the degrees of freedom of the master arm are 5 [3].

In this research, we try to expand the concept of master arm devices with wearability. For this, we consider a light-weight, large workspace, non-fixed type wearable robot. A wearable robot, RoboWear is designed based on this concept of wearability. Firstly, the exoskeletal mechanism of RoboWear based on the movement analysis of the human upper limb will be introduced. Next, the kinematics analysis and prototyping RoboWear will be described. Finally the feasibility of the wearable robot is demonstrated by examining the control performance and by incorporating the robot with virtual environment.

2. Design of RoboWear

2.1 Exoskeletal Mechanism

As human arms are very useful to manipulate and interact with objects, we design a wearable robot arm as the first step for the wearable robot. To design a wearable robot arm, it is necessary to analyses the degrees of freedom of human arm and to simplify the whole degree of freedom reasonably. It is also helpful to inspect the anatomical structure of the human arm before starting to design the robot arm. The human arm’s degrees of freedom are over 9 when it is analyzed based on movement anatomy [4]. The shoulder part has 2 translation degrees of freedom and 3 rotational degrees of freedom (flexion/extension, abduction/adduction and medial rotation/lateral rotation). The elbow joint has 2 degrees of freedom as rotational motions (flexion/extension and pronation/supination) and the wrist joint has also 2 degrees of freedom as rotational motions (flexion/extension and abduction/adduction)[4]. For the manipulation of near objects, 2 translation degrees of freedom at the shoulder part are negligible. So a wearable arm with 7 degrees of freedom is designed.

From the standpoint of the wearability, the structure of muscles gives many hints for the wearable robot. Muscles
around bones are actuators of our arms. Muscles are attached around bones and generate only the retraction forces but they can provide joint torque for each joint with the help of their parallel structure. Parallel structure is useful not only for the generation of joint torque from the retraction forces of muscles, but also the minimization of the required space for muscles. As a wearable robot should work like auxiliary muscles around a human arm, it is natural to imitate the configurations of human muscles. A parallel mechanism has useful configuration for a wearable robot because it has space inside prismatic joints. It is comparatively less weight to generate high power. The disadvantage of this structure lies in complex kinematics and singularity problems. A hybrid structure consisting of parallel manipulators and separate joints can be introduced for real application.

A 3RPS parallel mechanism consists of 3 Revolute-Prismatic-Sphere joints as shown in Fig. 1 and has two degrees of freedom in orientation and one degree of freedom in Cartesian position [5]. The two degrees of freedom in orientation can be used for the two rotational degrees of freedom at both the shoulder joint and the wrist joint. One translation degree of freedom in Cartesian position is useful for the reconfiguration of the robot arm for various operators with different dimensions.

![Fig. 1. Schematics of a 3RPS parallel mechanism](image)

A slip ring mechanism is a serial mechanism in which the ring shaped slider rotates along a guider. The slip ring mechanism has 1 degree of freedom in the rotation motion. As the slip ring mechanism has a space inside the ring shaped slider and guider, it is also an adequate structure for wearable robots. Fig. 2 shows the conceptual model of RoboWear using a hybrid structure consisting of two 3RPS parallel manipulators and 3 separate joints. For the shoulder part, one 3RPS parallel mechanism and one slip-ring mechanism are used. For the elbow joint, one 4 bar-linkage mechanism and one slip-ring mechanism are used. For the wrist joint, one 3RPS parallel mechanism is used. The translation degree of freedom of 3RPS parallel mechanism is used for the dimensional reconfiguration of the robot for different operators. The total active degrees of freedom of the proposed robot arm are seven. Pneumatic cylinders and pneumatic rotary actuators are used for the active prismatic joints of the parallel mechanism and the active rotational joint of the slip ring mechanism, respectively.

![Fig. 2. Concept of RoboWear](image)

### 2.2 Parameter Design of the 3RPS Parallel Mechanism

The joint range of a 3RPS parallel mechanism is dependent on positions of the revolute joints and the sphere joints, and the stroke of the prismatic joints shown in Fig.1. Parameters to be set for a 3RPS parallel mechanism can be summarized as table. 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>Size of the upper plate (position of the sphere joints)</td>
</tr>
<tr>
<td>$R$</td>
<td>Size of the lower plate (position of the revolute joints)</td>
</tr>
<tr>
<td>$L$</td>
<td>Stroke of prismatic joints</td>
</tr>
<tr>
<td>Minimum length</td>
<td>Minimum length of prismatic joints</td>
</tr>
</tbody>
</table>

As the links $B_1b_1$, $B_2b_2$, and $B_3b_3$ in Fig.1 are constrained by each revolute joint to move in the planes, three constraint equations are imposed by the three revolute joints [5]. If the degrees of freedom of the upper plate are defined as $\alpha, \beta, \delta, X_c, Y_c, Z_c$, the upper plate has only 3 degrees of freedom due to 3 constraint conditions. Three constraints can be described as equations (1).

\[
\delta = 0
\]

\[
X_c = -\frac{1}{2} \frac{r}{R} (1 - \cos(\beta)) \cdot \cos(2\alpha)
\]

\[
Y_c = \frac{1}{2} \frac{r}{R} (1 - \cos(\beta)) \cdot \sin(2\alpha)
\]
In this case, $\alpha$, $\beta$, $Z_c$ are unconstrained parameters. The distance parameter $Z_c$ is related to the dimension of the operator’s shoulder. The distance is adjusted as 170 mm and the size of the upper plate is set as 70mm based on the average diameter of the operators’ shoulder part. The minimum length of prismatic joints is determined by the diameter and stroke of the pneumatic cylinder. So, the independent parameters to be selected by the designer are the size (R) of the lower plate and the stroke (L) of prismatic joints. To design these parameters properly, a performance index was introduced as follows.

$$PI(\rho, L) = JR(\rho, L) \cdot W_1 + JT(\rho, L) \cdot W_2 + UF(\rho, L) \cdot W_3$$

(2)

where, PI is the performance index at given parameters, $tR(\rho)$ and stroke(L). JR and JT are the joint range and the joint torque, respectively. UF is a uniform factor of the joint torque. W1, W2, and W3 are weight factors for each item.

### Table 2. Joint ranges and joint torques for each joint

<table>
<thead>
<tr>
<th></th>
<th>Shoulder joint</th>
<th>Elbow joint</th>
<th>Wrist joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion/Extension</td>
<td>86 deg</td>
<td>17.7 Nm</td>
<td>97 deg</td>
</tr>
<tr>
<td>Adduction/Abduction</td>
<td>86 deg</td>
<td>17.7 Nm</td>
<td>-</td>
</tr>
<tr>
<td>Rotational Motion</td>
<td>90 deg</td>
<td>2.2 Nm</td>
<td>90 deg</td>
</tr>
</tbody>
</table>

### 3. Kinematics Analysis

To move a virtual robot using proposed wearable robot, it is necessary to solve the kinematics. Fig. 4 shows the forward kinematics model of the proposed wearable robot arm.

![Fig. 4. Forward kinematics model of the wearable Robot Arm.](image)

Fig. 5 shows the kinematics model for a 3RPS parallel mechanism. The vectors related to positions of 3 sphere joints of the upper plate are described as equations (3).

![Fig. 5. Kinematics model of a 3RPS parallel mechanism.](image)
where, $q_1$, $q_2$, $q_3$ are vectors from origin of the fixed base to three sphere joints of the moving plate. $g$ is the distance between the revolute joint and the origin in the fixed plate. $d_1$, $d_2$, $d_3$ are lengths of three prismatic joints and $\phi_i$ vectors are the angles between the fixed plate and three prismatic joints.

As three sphere joints construct an equilateral triangle, there exist one constraint condition between three sphere joints as equation (4).

$$|B_i-B_{i+1}| = \sqrt{3}h \quad \text{or} \quad [\bar{q}_i - \bar{q}_m] ^T[\bar{q}_i - \bar{q}_m] - 3h^2 = 0 \quad (4)$$

When $q$ vectors from equation (3) are combined with equation (4), another equation (5) composed of only $\phi_i$ vectors is derived. $\phi_i$ vectors are calculated from equation (5) by using Newton-Rhapson method [6]. From $\phi_i$ vectors, $q$ vectors and $P$ vector are calculated by using equation (3). The full forward kinematics can be calculated by multiplying all transformation matrixes calculated from each joint.

$$a_1 d_i d_{i+1} + b_1 s_i s_{i+1} + c_i c_i + d_i d_{i+1} + e_i = 0 \quad (5)$$

where,

$$a_i = d_i d_{i+1}$$
$$b_i = -2d_id_{i+1}$$
$$c_i = -3g_i$$
$$d_i = -3d_{i+1}$$
$$e_i = 3g_i^2 + d_i^2 + d_{i+1}^2 - 3h^2$$

4. Prototyping of the Wearable Robot

4.1 Body

All the detailed mechanisms were designed by using 3-D CAD software, Pro/Engineer. The proposed robotic arm is made of aluminum and engineering plastics and the total weight of the manufactured robotic arm is about 4 kg except a pneumatic power supply. The shoulder part was designed with the consideration of the chest shape of operators. As distances between the base platform and the moving platform of 3RPS parallel mechanisms can be changed, operators with different body dimension can wear RoboWear. For rotational motions for the shoulder joint and the elbow joint, slip ring mechanisms and rotary pneumatic actuators are used with a timing belt for torque transmission. The hand part of the robotic arm was designed like a glove so that a hand haptic device can be used with this robotic arm simultaneously. Fig. 6 shows a photo of an operator wearing RoboWear.

![Fig. 6. An operator wearing RoboWear.](image)

4.2 Pneumatic Control System

Pneumatic actuators are used to reduce the total weight of the robot, to improve compliance with human motion and to generate high reactive forces. A pneumatic control system with small-sized proportional control valves is developed to reduce the total weight of the robotic arm. The dimension of a pneumatic control valve is about 20*30*10 mm and the weight is very low. Two small-size pressure sensors (CPC100: Data Instruments) are attached in one control valve to detect the differential pressure between two output ports directly. These control valves are attached to the rear part of the robotic arm. As the tube length between the control valve and pneumatic cylinders becomes short by attaching control valves at the robotic arm, the time delay of pneumatic actuators can be reduced.

Two instrument amplifiers (AD620AN, Analog Device) are used to interface and amplify the signals from pressure sensors, and two dual OP amplifiers (LM358 by Motorola) are used to calculate the differential pressure and errors between the reference differential pressure and the actual differential pressure. A VI (Voltage to Current) converter circuit is used to drive the solenoid coil in the control valve. An analog PI controller is designed to control the proportional control valve to trace the reference pressure trajectories from the digital controller. Fig. 7 shows photos of the signal conditioning circuit for the pressure control valve and the digital controller (386 EX).
that generate the reference differential pressure for each pneumatic actuator after calculating the required joint torque. The digital controller has a wireless serial communication protocol with the external processors during operation.

5. Experiments

5.1 Pneumatic Control Performance

Fig. 10 shows an experimental result when the reference differential pressure is a step-wise form and operator moves his arm position. In this case, operator’s movement acts thrust force of pneumatic cylinder as disturbance. Even though operator moves as a sinusoidal form, the actual differential pressure of the cylinder is tracing the reference pressure with good performance. When reference differential pressure is set as zero, operator can move freely with least effort.

At motion following mode, the control system tries to keep differential pressure of pneumatic cylinders as zero value. This allows an operator to move freely during operation with low effort. At force reflecting mode, the control system calculates reference forces for each pneumatic cylinder and generates the reference signals for the sub-controller. Fig. 8 shows the schematic diagram of the total pneumatic control system and Fig. 9 shows the total pneumatic system attached at the rear side of the robot.

5.2 Incorporation with Virtual Environment

A virtual robot is designed by using OpenGL software. Fig. 11 shows a virtual human body model based on the virtual robot shown in Fig. 4. The distributed degrees of freedom of the proposed robot arm are reconstructed to be suitable for the human arm model. By the incorporation with the virtual robot, the full forward kinematics and sensory system of the wearable robot are validated. Fig. 12 shows a researcher wearing the proposed wearable robot arm.
For the incorporation with the interactive virtual environment, an interactive virtual reality system is installed as shown in Fig. 13. Users can move the wearable robot model in virtual environment and interact with the operator wearing the wearable robot. The interactive virtual reality system solves the full inverse kinematics of the robot arm and checks the contact of the robot arm with virtual object, and transmits the joint torque information to the wearable robot and the haptic device (Phantom 1.5a) simultaneously.

6. Conclusions

Based on the anatomy of movement of the human upper limb, a 7 DOF wearable robot, RoboWear is designed. RoboWear consists of two 3RPS parallel manipulators, two slip-ring serial mechanisms and one 4-bar linkage mechanism. To validate kinematics and its work a virtual robot and a virtual human arm is designed by using OpenGL S/W. In the future, researches on force interaction between the proposed wearable robot and a human being will be performed in deep. Especially a research on a robot that has the base of movement on a human body will be very interesting. To detect human intention to move, biological signals such as bio-impedance signal or EMG signal can be combined with the proposed wearable robot, RoboWear.

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References