Novel 6-DOF Wearable Exoskeleton Arm with Pneumatic Force-Feedback for Bilateral Teleoperation

ZHANG Jialan 1, FU Hailun 2, DONG Yiming 1, ZHANG Yu 1, YANG Canjun 1, and CHEN Ying 1

1 State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China
2 Zhejiang Province Institute of Metrology, Hangzhou 310027, China
3 National Die & Mold CAD Engineering Research Center, Shanghai Jiao Tong University

Received April 25, 2014; revised June 26, 2014; accepted August 26, 2014

Abstract: Magnetic drive pump has gotten great achievement and has been widely used in many fields. Currently, the researches on magnetic drive pump have focused on hydraulic design, bearing, axial force and high head have been developed overseas. However, low efficiency and large size are the common disadvantages for the magnetic drive pump. In order to study the performance of high-speed magnetic drive pump, FLUENT is used to simulate the inner flow field of magnetic drive pumps with different rotate speeds, and get velocity and pressure distributions of inner flow field. According to analysis, the changes of velocity and pressure to ensure the stable operation of pump and avoid cavitation. Based on the analysis of velocity and pressure, this paper presents the pump efficiency of magnetic drive pumps with different rotated speeds by calculating the power loss in impeller and volute, hydraulic loss, volumetric loss, mechanical loss and discussing the different reasons of power loss between the magnetic drive pumps with different rotated speeds. In addition, the magnetic drive pumps are tested in a closed test system. Pressure sensors are set in inlet and outlet of magnetic drive pumps to get the head and efficiency. Based on this, the simulation and test results show that the method of simulation is feasible. The proposed research provides the instruction to design high-speed magnetic drive pump.

Key words: exoskeleton arm, teleoperation, pneumatic force-feedback, hybrid fuzzy control

1 Introduction

At first look at modern society, more and more robots and automated devices are coming into our life and serve for human. But on even further look, we will find that the levels as just the term human operator which is coined by SHI[1]. The master-slave teleoperation system for the safe manipulation of radioactive materials in a contaminated area in 1955[2] was the typical example of this concept. Hereafter, exoskeleton arms with force-feedback have been widely developed in the fields of robotic teleoperation, haptic interface to enhance the performance of human operator, also in the exciting applications in surgery planning, personnel training, and physical rehabilitation. DUBEY, et al[3] developed a methodology to incorporate sensor and force-feedback into human controlled teleoperation systems. In their approach, the human operator was retained at all phases of the operation, and was assisted by adjusting system parameters which were not under direct control by the operator, specifically, the controlling of positions and velocities between the master and slave and their impedance parameters. The ESA human exoskeleton with redundantly robotic arms[4] has been used to control the robot. New concepts were applied in a joint research project between researchers from Korea University and the Korea Institute of Industrial Technology(KIST) introduced a 3RPS parallel mechanism as a new type of master-slave tele-operation system for the safe manipulation of radioactive materials in a contaminated area in 1955. The electric brakes with the torque sensor beams were used for force feedback[5]. Likewise, the authors gave out a 2-port network model to describe the bilateral control performance of the control system[6]. In this research, a wearable exoskeleton arm, ZJUESA, based on man-machine system is designed and a bilateral teleoperation control system is proposed, which includes three main levels: 1. 

* Corresponding author. E-mail: caffeezhang@hotmail.com

DOI: 10.3901/CJME.2014.0425.100
supervisor giving the command through the exoskeleton arm in safe zone with assistant operator interface; ② slave manipulator more comfortably and intuitively than the system with the joystick or the keyboard input.

2 Configuration of the Exoskeleton Arm System

The master-slave control is widely employed in the robot manipulation system. In our system, the joystick is the routine interface for the master-slave control system. The configuration of the exoskeleton arm system is shown in Fig. 1.

![Fig. 1. Configuration of the exoskeleton arm system](image)

In the system, the joystick as the input interface and can transfer the motions of human upper-limb to the slave manipulator position-control-commands through the Internet or Ethernet between the master and slave computers. With this information, the slave manipulator mimics the motion of the operator. At the same time, the force-feedback signals, detected by the 6-axis force/torque sensor on the slave robot arm end effector, are sent back to indicate the pneumatic actuators for the force-feedback on ZJUESA to realize the bilateral teleoperation.

Since ZJUESA is designed by following the physiological parameters of the human upper-limb, with such a device the human operator can control the manipulator more comfortably and intuitively than the system with the joystick or the keyboard input.

3 Design of the Exoskeleton Arm

What we desire is an arm exoskeleton which is capable of following motions of the human upper-limb accurately and supplying the human upper-limb with proper force feedback if needed. In order to achieve an ideal controlling performance, we have to examine the structure of the human upper-limb.

3.1 Anatomy of human upper-limb

3.1.1 Upper-limb

Recently, various models of the human upper-limb anatomy have been published in Refs. [18]. The muscles of the arm that start from the corresponding muscles, tendons and bones are too complex to be utilized in mechanical design of an anthropomorphic robot arm. From the view of the mechanism, we should set up a more practicable model for easy and effective realization.

Fig. 2 introduces the configuration of human upper-limb and its equivalent mechanical model, which is a 7-DOF structure, including 3 degrees of freedom for shoulder (flexion/extension, abduction/adduction and rotation), 1 degree of freedom for elbow (flexion/extension) and 3 degrees of freedom for wrist (flexion/extension, abduction/adduction and rotation) (flexion/extension, abduction/adduction and rotation). The details about the main joints can be obtained from Refs. [18]. The mechanical model is considered as the equivalent model for the human upper-limb, and the base is for the design and construction of exoskeleton arm-ZJUESA.

![Fig. 2. Configuration of human upper limb and its equivalent mechanical model](image)

### Table: Requirements of figure and table

<table>
<thead>
<tr>
<th>Image</th>
<th>resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grayscale</td>
<td>&lt; 150</td>
</tr>
<tr>
<td>Color</td>
<td>&lt; 150</td>
</tr>
<tr>
<td>Bitmap</td>
<td>&lt; 600</td>
</tr>
</tbody>
</table>

3.2 Mechanism of the exoskeleton arm

Because the goal of this exoskeleton arm is to make the best of motion scope of the human upper-limb and limit it as little as possible. A flexible structure with the same or similar configuration of human upper-limb is an ideal choice. Based on the anatomy of human upper-limb, the joint motion originates from extension or flexion of the muscle and ligament with each other to generate torque around the bones. Compared with the serial mechanism, the movements of the parallel mechanism are driven by the
prisms, which act analogically to the human muscles and ligament. Besides, using the parallel mechanism not only influences the workspace of ZJUESA, but also the third translation degree of freedom for flexion/extension, abduction/adduction at shoulder. Its revolution degrees of freedom embodies the displacement of the prismatic (factor A), circumradius ratio of the upper and lower platforms (factor B), initial length of the prismatic (factor C), and their coupling parameters (factor A*B, A*C and B*C) (Table 1) and, namely, its workspace, weight, size. So, we use the orthogonal experiment design method with the foregoing 6 key factors[21] and Eq. (1) gives the expression of the optimal target function of this problem:

\[ Q = F\left( L_0, \theta - \theta_r, \frac{r}{R}\right). \]  

where \( L_0 \) is the initial length of the prismatic, \( R \) is the circumradius of the lower base in 3RPS mechanism, \( r \) is the circumradius of the upper base in 3RPS mechanism, \( \theta \) is the reachable angle around axis. The optimal target function is advantageous in that it can reduce the number of experiments performed with only slightly less accuracy than full factor testing. The orthogonal experiment design concept can be used for any complicated system being investigated, regardless of the nature of the system. During the optimization, all variables, even continuous ones, are thought of discrete “levels”. In an orthogonal experiment design, the levels of each factors are allocated by using an orthogonal array[22]. By discretizing variables in this way, a design of experiments is advantageous in that it can reduce the number of combinations and is resistant to noise and conclusions valid over the entire region spanned by the control factors and their setting.

Table 2 describes an orthogonal experiment design array for 6 key factors[23]. In this array the first column implies the number of the experiments and factors A, B, C, A*B, A*C, B*C.

<table>
<thead>
<tr>
<th>Table 1. Factors and their levels</th>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
<th>( A*B )</th>
<th>( A*C )</th>
<th>( B*C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>0.5</td>
<td>150</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0.438</td>
<td>160</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>0.389</td>
<td>170</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>–</td>
<td>180</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

The orthogonal experiment design array was chosen for the ease with which levels were set and for the efficiency. The concept of orthogonal experiment design is discussed in Ref. [21] to obtain parameters optimization, finding the setting for each of a number of input parameters that optimizes the output(s) of the design. Orthogonal experiment design allows a decrease in the number of experiments performed with only slightly less accuracy than full factor testing. The orthogonal experiment design concept can be used for any complicated system being investigated, regardless of the nature of the system. During the optimization, all variables, even continuous ones, are thought of discrete “levels”. In an orthogonal experiment design, the levels of each factors are allocated by using an orthogonal array[22]. By discretizing variables in this way, a design of experiments is advantageous in that it can reduce the number of combinations and is resistant to noise and conclusions valid over the entire region spanned by the control factors and their setting.

Table 2 describes an orthogonal experiment design array for 6 key factors[23]. In this array the first column implies the number of the experiments and factors A, B, C, A*B, A*C, B*C.
A*B and B*C are arbitrarily assigned to columns respectively. On Table 2, 36 trials of experiments are needed, factor for each trial-run number. The frame around a page indicates horizontal position 1.8 cm Relative to a page. The levels of the columns represent the experimental factors to be studied using that array. Each of the columns contains several assignments at each level for the corresponding factors. The levels of the other three factors are dependent on those of the former three factors. The elements of the column IV, namely factor A*B, are determined by the elements in the columns I, II, and elements of column V, factor A*C, has the relationship with the elements of columns I, III, and the column VI, factor B*C, lies on the columns II, III.

Table 2. Orthogonal experiment design array L36 for 6 key factors

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>A*B</th>
<th>A*C</th>
<th>B*C</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Y₁</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td>Y₂</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td>Y₃</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td>Y₄</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td></td>
<td>Y₅</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td></td>
<td>Y₆</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td></td>
<td>Y₇</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td></td>
<td>Y₈</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>Y₉</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>10</td>
<td>Y₁₀</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>11</td>
<td>11</td>
<td>Y₁₁</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td>Y₁₂</td>
</tr>
</tbody>
</table>

The relation between column IV and columns I, II is that: if level of A is n and level of B is m, the level of A*B is 3(n–1)+m, where n=1, 2, 3 and m=1, 2, 3.

All the cases can be expressed as follows:

(1, 1) → 1 (1, 2) → 2 (1, 3) → 3;
(2, 1) → 4 (2, 2) → 5 (2, 3) → 6;
(3, 1) → 7 (3, 2) → 8 (3, 3) → 9.

The first element in the bracket represents the corresponding level of factor A in Table 1 and the latter means the corresponding level of the factor B. Factor A*B has totally 9 levels, as factor A and factor B have 3 levels, respectively.

Likewise, the relation between column V and columns I, III is

(1, 1) → 1 (1, 2) → 2 (1, 3) → 3 (1, 4) → 4;
(2, 1) → 5 (2, 2) → 6 (2, 3) → 7 (2, 4) → 8;
(3, 1) → 9 (3, 2) → 10 (3, 3) → 11 (3, 4) → 12;

Also the relation between column VI and columns II, III is

(1, 1) → 1 (1, 2) → 2 (1, 3) → 3 (1, 4) → 4;
(2, 1) → 5 (2, 2) → 6 (2, 3) → 7 (2, 4) → 8;
(3, 1) → 9 (3, 2) → 10 (3, 3) → 11 (3, 4) → 12.

The optimal design is carried out according to the first three columns:

\[
\begin{align*}
I_A &= \left\{ \frac{1}{3}, \frac{1}{3}, \frac{1}{3}, 0, 0, 0, 0, 0, 0 \right\} \text{ for } \{ Y_1 \} \\
I_B &= \left\{ 0, 0, 0, 0, 0, 0, 0, 0, 0 \right\} \text{ for } \{ Y_2 \} \\
I_{A*B} &= \left\{ \frac{1}{3}, 0, 0, 0, 0, 0, 0, 0, 0 \right\} \text{ for } \{ Y_{35} \}
\end{align*}
\]

\[
K_i = \max \{ I_y \} - \min \{ I_y \}, \quad (3)
\]

where \(i = A, B, C, A*B, A*C, B*C\). If the number of factor \(j\) is much bigger than \(K_{B*C}\) and \(K_C\), the relationship between the target \(Q\) and each factor can be described, as shown in Fig. 5.

According to the plots in Fig., the superiority and the degree of the influence of each design factor. The factor with bigger extreme difference \(K_i\), as expressed in Eq. (3) has more influence on \(Q\). In this case, it can be concluded that the sensitivity of the factors \(A*B\) and \(A*C\) are high and factors \(B*C\) and \(C\) have weak influence, since \(K_{A*B}\) and \(K_{A*C}\) are much bigger than \(K_{B*C}\) and \(K_C\). And the set \(A_B, A_2C_1, A_3, B_1, C_1, B_1C_1\) are the best combination of each factor levels. But there is a conflict with former 3 items in such a set. As their \(K_i\) have little differences between each other, the middle course is chosen. After compromising, we take the level 2 of factor \(A\), the level 1 of factor \(B\) and the level 1 of factor \(C\), namely \(d = 80\) mm, \(r/R = 0.5\), \(L_0 = 150\) mm[32].

It is interesting to know how good the results derived from the above 36 trials are, when compared with all other possible combinations. Because of its mutual balance of orthogonal arrays, this performance ratio can be guaranteed.
by the theorem in non-parametric statistics\(^{[13]}\). It predicts that this optimization is better than 97.29\% of alternatives.

Combined with the kinematics and dynamics simulation of the 3RPS parallel mechanism and ZJUESA with chosen design parameters by ADAMS, we perform the optimal design. Table 3 indicates the joint range and joint torque of each joint on ZJUESA. It is apparent that ZJUESA can almost cover the workspace of human upper-limb well so that it can follow the motion of human operation upper-limb with little constrain, as shown in Fig. 6.

Table 3. Joint ranges and joint torques for each joint on ZJUESA

<table>
<thead>
<tr>
<th>Joint on ZJUESA</th>
<th>Joint range</th>
<th>Joint torque</th>
<th>Joint density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion/extension(shoulder)</td>
<td>-60–60</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>Abduction/adduction</td>
<td>-50–60</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>Rotation(shoulder)</td>
<td>-20–90</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>Flexion/extension(elbow)</td>
<td>0–90</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>Rotation(wrist)</td>
<td>-20–90</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>Flexion/extension(wrist)</td>
<td>0–60</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>Abduction/ addition(wrist)</td>
<td>□ □ □ □ □ □</td>
<td>□ □ □ □ □ □</td>
<td>□ □ □ □ □ □</td>
</tr>
</tbody>
</table>

Fig. 6. Motion of exoskeleton arm following the operator

4 Hybrid Fuzzy-Controller for the Force Feedback On Zjuesa

In master-slave manipulation, besides the visual feedback and man-machine soft interface, the force feedback is another good choice to enhance the control performance. If the slave faithfully reproduces the master motions and the master accurately feels the slave forces, the operator can experience the same interaction with the teleoperated tasks, as would the slave. In this way the teleoperation becomes more intuitive.

In our bilateral teleoperation system with ZJUESA, a 6 axis force/torque sensor is mounted on the end effector of the slave manipulator and detects the force and torque acting on the end effector during performing the work. This information is transferred to the master site in real time. With dynamic calculation, the references of the generating force on actuators of ZJUESA are obtained. Hereafter, the feeling can be reproduced by means of the pneumatic system.

Eq. (4) expresses the relation between the force and torque on the end effector and the torques generating on the joints:

\[
\tau = f^T f ,
\]

where \(F\) — Force and torque on the end effector,

\[
F = \begin{bmatrix} f_1 & f_2 & f_3 \end{bmatrix}^T ,
\]

\(\tau\) — Torque on each joint,

\[
\tau = \begin{bmatrix} \tau_1 \tau_2 \cdots \tau_7 \end{bmatrix}^T ,
\]

\(J\) — Jacobian matrix of ZJUESA.

By dividing the force arm, it is easy to get to the generating force on the joints, such as shoulder ring, elbow, wrist ring and wrist, as explained by Eq. (5):

\[
f = \begin{bmatrix} f_4 & f_5 & f_6 & f_7 \end{bmatrix}^T = \begin{bmatrix} \tau_1 / a_1 & \tau_2 / a_2 & \tau_3 / a_3 & \tau_4 / a_4 \end{bmatrix}^T ,
\]

where \(a_i (i=3, 4, 5, 6)\) is the force arm of the shoulder ring, elbow, elbow ring and wrist joints, respectively.

As for the generating force of the prismatic on the 3RPS parallel mechanism, it can be calculated as follows\(^{[35]}\):

\[
\begin{bmatrix} f_4 \\ f_5 \\ f_6 \end{bmatrix} = G_i^f \begin{bmatrix} \tau_{\text{3RPS}} \end{bmatrix} ,
\]

where \(G_i^f\) — Jacobian matrix of 3RPS parallel mechanism,

\(\tau_{\text{3RPS}}\) — Torques on 3RPS parallel mechanism,

\(f_{\text{3RPS}}\) — Force on 3RPS parallel mechanism.

Therefore, with Eqs. (5), (6), the total seven force references are obtained for the pneumatic system on ZJUESA. Fig. 7 explains the scheme of the pneumatic cylinder-valve system for the force feedback.

Therefore, with Eqs. (5), (6), the total seven force references are obtained for the pneumatic system on ZJUESA. Fig. 7 explains the scheme of the pneumatic cylinder-valve system for the force feedback. Therefore, with Eqs. (5), (6), the total seven force references are obtained for the pneumatic system on ZJUESA. Fig. 7 explains the scheme of the pneumatic cylinder-valve system for the force feedback. Therefore, with Eqs. (5), (6), the total seven force references are obtained for the pneumatic system on
ZJUESA. Fig. 7 explains the scheme of the pneumatic cylinder-valve system for the force feedback. Therefore, with Eqs. (5), (6), the total seven force references are obtained for the pneumatic system on ZJUESA.

![Diagram of pneumatic cylinder-valve system](image)

Fig. 7. Scheme of the pneumatic cylinder-valve system

The high-speed on-off valve components in the system, are controlled by the pulse width modification (PWM) signals from the control units, respectively. Rather than the proportional or servo valve, this is an inexpensive and widely used method in the application of position and force control in the pneumatic system [23–28]. To simplify the control algorithm, there is just one valve on work at any moment. For instance, when a leftward force is wanted, the valve V₁ works and valve V₂ is out of work. Under this case, we can control the pressure \( p_1 \) in chamber 1 by modifying the PWM signals. Chamber 2 connects to the atmosphere at that time and the pressure \( p_2 \) inside the chamber 2 of cylinder is absolutely ambient pressure, and vice versa. At each port of the cylinder, there is a pressure sensor to detect the pressure value inside the chamber for the close-loop control. And the throttle valves are equipped for limiting the flow out of the chamber to reduce piston vibrations. In our previous work, we gave out the specific mathematic models of the system, including pneumatic cylinder, high-speed on-off valve and connecting tube [23].

However, the pneumatic system is not usually a well linear control system, because of the air compressibility and its effect on the flow line. Also the highly nonlinear flow brings troubles into the control. The conventional controllers are often developed via simple models of the plant behavior that satisfy the necessary assumptions, via the specially tuning of relatively simple linear or nonlinear controllers. As a result, for pressure or force control in such a nonlinear system, especially in which the chamber pressure vibrates rapidly, the conventional control method can hardly have a good performance.

Fortunately, the introduction of the hybrid control method mentioned, gives out a solution to this problem. But the traditional design of the hybrid controller is always complicated and only available to the proportion or servo valve system. In our system, we figured out a kind of novel hybrid fuzzy control strategy for the high-speed on-off valves, which is much simpler and can be realized by micro control units (MCUs) in the contributed architecture. This strategy is composed of two main parts: a fuzzy controller and a bang-bang controller. The fuzzy controller provides a formal methodology for representing, manipulating, and implementing a person’s heuristic knowledge about how to control a system. It can be regarded as an artificial decision maker that operates in a closed-loop system in real time and can help the system to get the control information either from a human decision maker who performs the control activity, while the bang-bang controller is added to drive the response of the system much more quickly.

Fig. 8 shows the concept of the proposed hybrid fuzzy controller. The concept of multimode switching is applied to activate either the bang-bang controller or the fuzzy controller mode.

![Diagram of hybrid fuzzy controller](image)

Fig. 8. Concept of the hybrid fuzzy controller

Bang-bang control is applied when the actual output is far away from reference value. In this mode, fast tracking of the output is implemented. The fuzzy controller is activated when the output is near the set point, which needs accuracy control.

In the fuzzy-control mode, we use pressure error \( e(t) = P_{ref}(t) - P_{实际}(t) \) and its change \( \dot{e}(t) \) as the input variables on which to make decisions. On the other hand, the width of the high voltage in one PWM period is denoted as the output of the controller.

As mentioned above, the PC on master site works as the supervisor for real-time displaying, kinematics calculation and exchanges the control data with the slave computer and so on. For the sake of reducing the burden of the master PC, the distributed control system is introduced. Each control unit contains a Mega8 MCU of ATMEL Inc., working as a hybrid fuzzy-controller for each cylinder respectively, and forms a pressure closed-loop control. The controller samples the pressure in chamber with 20 kHz sampling rate.
by the in-built analog-digital converters. These controllers keep in contact or get the differential pressure signals from the master PC through RS232, as depicted in Fig. 9. In this mode, fast tracking of the output is implemented.

Fig. 9. Distributed control system of the master arm

5 Force Feedback Experiments

Fig. 10 gives out the set up of the force feedback experiments. The system includes the soft interface, data acquisition, Mega8 MCU experiment board, on-off valves, sensors of displacement and pressure, and the oscilloscope. We chose the cylinder DSNU-10-40-P produced by FESTO Inc. The soft signal generator and data acquisition are both designed in the LabVIEW, with which users may take advantage of its powerful graphical programming capability. The most obvious difference is that LabVIEW is a graphical compiler that uses icons instead of lines of text. Additionally, LabVIEW has a large set of built-in mathematical functions and graphical data visualization and data input objects typically found in data acquisition and analysis applications.

The plots in Fig. 11 give out experimental results of the chamber pressure outputs with step input signals on one joint. While at frequencies higher than 80 Hz, force is sensed through the operator’s joint, muscle and tendon receptors, and the operator is unable to respond to, and low amplitude disturbances at these frequencies. We remove reflected force signals above 80 Hz band by fast Fourier transfer (FFT) and get the smoothed curve in the plots. One is obtained by using hybrid control strategy and another is obtained by using traditional fuzzy controller without bang-bang controller. Although these two curves both track the reference well with very good amplitude match (less than 5% error) and a few milliseconds misalignment in the time profile, by comparing these two curves, it can be found that the adjust time of the curve with hybrid control strategy is less than 0.03 s, which is much less than 0.05 s of other with traditional fuzzy controller.

Fig. 11. Experimental results with a step signal

Fig. 12 shows the results of tracking a sinusoidal commander. This experiment is implemented to test the dynamic nature of the system. Although there is a little error and delay between the reference curve and the experiment curve, the system has good performance.

Fig. 12. Experiment results for sinusoidal pressure commands

realize the bilateral teleoperation with simple motion, in which the slave manipulator is controlled for the shoulder abduction/adduction (the movement of a bone away/toward the midline in the frontal plane) and extension/flexion of elbow (the movement in the sagittal plane) by the teleoperation with ZJUESA.

In the first experiment, the operator performs the shoulder abduction/adduction movement with ZJUESA, when the slave robot follows and holds up the load. With the force feedback on ZJUESA, the operator has feeling as if he holds the load directly without the mechanical structure, as shown in Fig. 13. Plots in Figs. 14, 15 show the torque and force on each joint on ZJUESA during the shoulder abduction/adduction movement from 45° to 90° (in the frontal plane) with 5 kg load. There are some remarks. In plots of Fig. 14 shoulder 3RPS-x means the torque around x-axis of 3RPS mechanism at shoulder and the same to shoulder 3RPS-y. Shoulder ring, elbow, wrist ring and wrist represent the torques on these joints, respectively. The characters shoulder 3RPS-1, shoulder 3RPS-2 and shoulder 3RPS-3 in Fig. 15 represent corresponding force on the cylinders on 3RPS parallel mechanism (referring to Fig. 3) with length $L_1$, $L_2$ and $L_3$, respectively.

The operator teleoperates the slave manipulator with force feedback as if he performs for lifting a dumbbell or raising package in daily life (Fig. 16). Fig. 17 shows the moment on each joint during the process for producing the feeling of lifting a 10 kg dumbbell. Fig. 18 depicts the force output of every pneumatic cylinder on ZJUESA.

All these results of experiments demonstrate the effect of ZJUESA system. ZJUESA performs well by following the motions of human upper-limb with little constrain and the pneumatic force feedback system supplies a proper force feedback tracking the reference well.
6 Conclusions

(1) According to the anatomy of human upper-limb, the structure of ZJUESA is presented, which has 6 DOFs totally. 3RPS parallel mechanism analogy to the motion of muscle and ligament of human joint is employed to realize the shoulder structure with 3 degrees of freedom.

(2) The orthogonal experiment design method is employed for the optimal design. As a result a larger workspace of ZJUESA is obtained.

(3) In the interest of much more intuitive feelings in master-slave control process, the force feedback is realized simultaneously on ZJUESA by the pneumatic cylinders. And a novel hybrid fuzzy-controller is introduced in the Mega8 MCU as a unit of the distributed control system due to the non-linearity of the pneumatic system. The bang-bang control is utilized to drive the response of the system much more quickly and the fuzzy controller is activated when the output is near the set point, which needs accurate control.

(4) With sets of experiments, step, slope and sinusoidal commands are taken and the system shows a good transparency and experimental curves as well.

(5) The experiments of shoulder abduction/adduction and elbow extension/flexion teleoperation with force feedback are implemented. The results verify the feasibility of ZJUESA master-slave control system and the effect of the hybrid fuzzy controller is much more quickly and the fuzzy controller is utilized to drive the response of the system much more quickly.

References

Biographical notes
ZHANG Jiafan, born in 1977, is currently an engineer at Zhejiang Province Institute of Metrology, China. He received his master degree on mechatronics in Zhejiang University, China, in 2006.

DONG Yiming, born in 1983, is currently a master candidate at State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, China. E-mail: tim830528@163.com

ZHANG Yu, born in 1985, is currently a master candidate at State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, China. E-mail: zhangyu_mm@hotmail.com

YANG Canjun, born in 1969, is currently an professor at Zhejiang University, China. He received his PhD degree from Zhejiang University, China, in 1997. His research interests include mechatronics engineering, man-machine system, robotics and ocean engineering. Tel: +86-571-87953759; E-mail: ycj@sfp.zju.edu.cn

HEN Ying, born in 1962, is currently a professor and a PhD candidate supervisor at State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, China. His main research interests include mechatronics engineering, fluid power transmission and control ocean engineering. E-mail: ychen@zju.edu.cn

Appendix
Appendix and supplement both mean material added at the end of a book. An appendix gives useful additional information, but even without it the rest of the book is complete: In the appendix are forty detailed charts. A supplement, bound in the book or published separately, is given for comparison, as an enhancement, to provide corrections, to present later information, and the like: A yearly supplement is issue.