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Novel 6-DOF Wearable ...ith Pneumatic Force-Feedback for Bilateral Teleoperation

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Abstract: A particular emphasis is put on a novel wearable exoskeleton ar... f freedom, which is used for the robot teleoperation with the force-feedback in the unknown en... al structure mechanism, the 3-revolution-prismatic-spherical (3RPS) parallel mechanism is devised from the concept of the human upper-limb anatomy and applied for the shoulder 3-DOF joint. Meanwhile, the orthogonal experiment design method is introduced for its optimal design. Aiming at enhancing the performance of teleoperation, the force feedback is employed by the pneumatic system on ZJUESA to produce the vivid feeling in addition to the soft control interface. Due to the compressibility and nonlinearity of the pneumatic force feedback system, a novel hybrid fuzzy controller for the precise force control is proposed and realiz... of the distributed control system on ZJUESA. With the results of several experiments ... control with force feedback, the feasibility of ZJUESA system and the effect of its hybrid fuzzy controller are verified.

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

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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 ... mechatronic devices replace h... lower levels, essentially provi... routine tasks. Human control i... levels just as the term human ... which is coined by SH... master-slave teleoperation syst... of radioactive materials in a c... GOERTZ, et al[2], was the typi... Hereafter, exoskeleton arms with force-feedback hav... widely developed in the fields of robot teleoperatio... haptic interface to enhance the performance of the h... 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 model based computer assistance into human controlled teleoperation systems. In their approach, the human operator was retained at all phases of the ... and was assisted by adjusting system paramet...

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were not und... ator, specifically, the mapping of positions and velocities between the master and slave and their impedance parameters. The ESA human arm exoskele- ton was developed to enable force-feedback tele-manipulation on the exterior of the international space ...ith redundant robotic arms[4]. In recent work[5–6], ...omuscular signal has been used to control the ...ton arm and many new concepts were applied in ...bilitation[7–10]. Several researchers from Korea ... Technology (KIST) introduced ...o the exoskeleton and designed a ... 3RPS parallel mechanism[11–12]. ...koskeleton-type master arm, in ... with the torque sensor beams ...llection[14]. Likewise, the authors ... model to describe the bilateral ... the view of the control theory [15–17].

In this research, a wearable exoskeleton arm, ZJUESA, based on man-machine system is designed and a hierarchically distributed teleoperation control system is explained. This system includes three main levels: ① supervisor giving the command through the exoskeleton ... with the operator interface; ② slave-robot working in hazardous zone; ③ data transmission between supervisor-master and master-slave through the Internet or Ethernet. In section 2, by using the orthogonal experiment design method, the design foundation of ZJUESA and its optimal design are presented. Then in section 3, we describe a novel hybrid fuzzy control

system for the force feedback on ZJUESA. Consequently, the force feedback control simulations and experiment results analysis are presented in section 4, followed by discussions and conclusions.

2 Configuration of the Exoskeleton Arm System

The master-slave control is widely employed in the robot manipula r the keyboard is the routi ster-slave control system. tem presented in this paper is shown in Fig. 1.

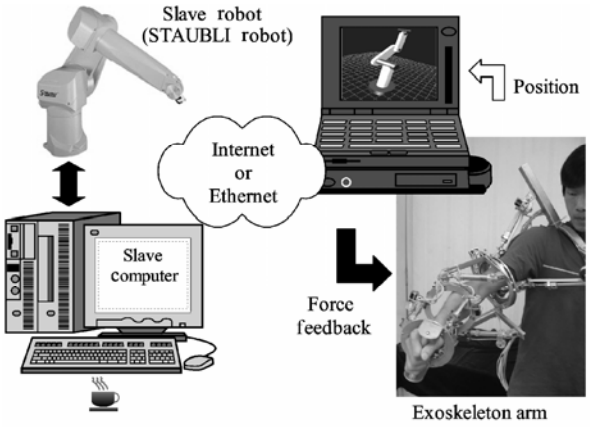

Fig. 1. Configuration of the exoskeleton arm system

In the syste the joystick as structure mecha and can transfer the motions of human upper arm 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 of the human upper-limb anatomy have s of the arm that sta ding 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) [18]. The details about the motion characteristics of these skeletal joints can be obtained in Refs. [18−20]. Compared to the mechanical model, the shoulder and wrist can be considered as spherical joints and the elbow as a revolution joint. It is a good approximate model for the human arm, and the base for the design and construction of exoskeleton arm-ZJUESA.

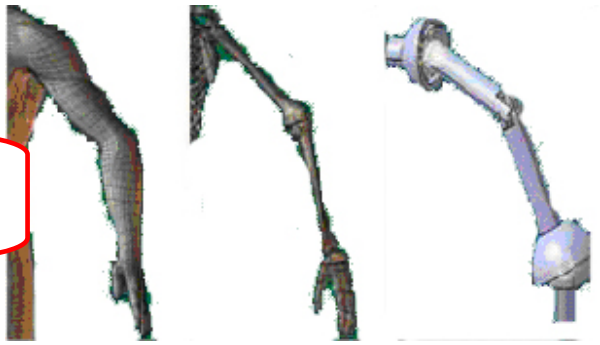

Fig. 2. Configuration of human upper limband its equivalent mechanical model

3.2 Mechanism of the exo

Because the goal of this of the human arm accurately fo ght 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 prismatics, which act analogically to the human muscles and ligament. Besides, using the parallel mechanism not prismatics, which act analogically to the human muscles and ligament. Besides, using the parallel mechanism not prismatic joints in the parallel mechanism lie on the surface of human upper-limb.

The 3RPS parallel mechanism is one of the simplest

mechanisms. Fig. 3 explains the principle of the 3RPS parallel mechanism. KIM, et al[11], introduced it into the KIST design. Here we follow this concept. The two revolution degrees of freedom embodied in the 3RPS are for flexion/extension, abduction/adduction at shoulder. Its third translation degree of freedom along z axis can be used for the dimension adjustment of ZJUESA for different operators. The prismatic joints are embodied by pneumatic actuators, which are deployed to supply force reflective capability. Also displacement sensors are located along with the pneumatic actuators and the ring-shaped joints to measure their linear and angular displacements. At elbow, a crank-slide mechanism composed of a cylinder and links is utilized for flexion/extension. At wrist, since the abduction/adduction movement is so limited and can be indirectly reached by combination of the other joints, we simplify the configuration by ignoring the effect of this movement. As shown in Fig. 4, the additional ring is the same as that at shoulder for the elbow rotation. Thus our exoskeleton arm-ZJUESA has 6 degrees of freedom totally.

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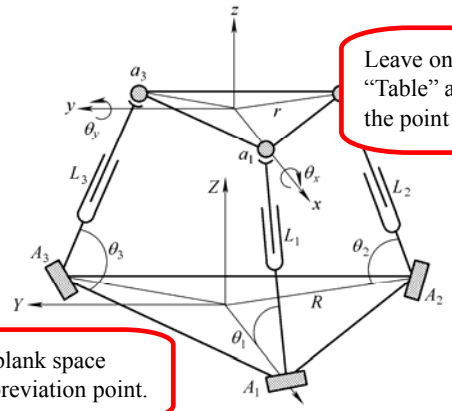

Fig. 3. 3RPS parallel mechanism

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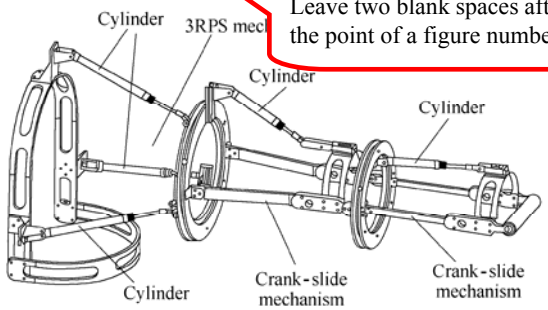

Fig. 4. Prototype of the exoskeleton arm-ZJUESA

3.3 Optimization design of ZJUESA

As nentioned above, the best design is to make the workspace of ZJUESA as fully cover the scope of the human upper-limb motion as possible. We employ the 3RPS parallel mechanism for the shoulder, whose workspace mainly influences the workspace of ZJUESA. The optimal design of 3RPS parallel mechanism for the shoulder is the [illegible]ign. However, it is [illegible]ors, saying the displ[illegible] A), circumradius ratio [illegible]ctor B), initial length[illegible]heir coupling parameters (factor $A*B$, $A*C$ and $B*C$) (Table 1) and multi-targets, namely, its workspace, weight, size. So we use the orthogonal experiment d[illegible] foregoing 6 key factors[21] and Eq. (1) g[illegible] of the optimal target function of this pro[illegible]

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$$Q = F\left(L_0,\ \theta - \theta_x,\ \frac{r}{R}\right) \tag{1}$$

where L_0 is the initial length of the prismatics, R is the circumradius of the lower base in 3RPS mechanism, r is the circumradius of the upper base in 3RPS mechanism, θ is the expected reachable angle ar[illegible] reachable angle around axis.

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Table 1. Factors and their levels mm

	A	B	C	A*B	A*C	B*C
	60	0.5	150	—	—	—
	80	0.438	160	—	—	—
	00	0.389	170	—	—	—
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The orthogonal experiment [illegible] the ease with which levels [illegible] its 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, $A*B$, $A*B$ and $B*C$ are arbitrarily assigned to columns respectively. From Table 2, 36 trials of experiments are needed, with the level of each factor for each trial-run indicated in the array. The elements represent the levels of each factors. The vertical columns represent the experimental factors to be studied using that array. Each of the columns contains several assignments at each level for

the corr… factors. The levels of the latter three facto… the former three factors. The … namely factor $A*B$, are dete… 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.

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

Experiment number	A	B	C	$A*B$	$A*C$	$B*C$	Result Q
1	1	1	1	1	1	1	Y_1
2	1	1	2	1	2	2	Y_2
3	1	1	3	1	3	3	Y_3
4	1	1	4	1	4	4	Y_4
5	1	2	1	2	1	5	Y_5
6	1	2	2	2	2	6	Y_6
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
33	3	3	1	9	9	9	Y_{33}
34	3	3	2	9	10	10	Y_{34}
35	3	3	3	9	11	11	Y_{35}
36	3	3	4	9	12	12	Y_{36}

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:

$$(1,1)\to 1 \quad (1,2)\to 2 \quad (1,3)\to 3;$$
$$(2,1)\to 4 \quad (2,2)\to 5 \quad (2,3)\to 6;$$
$$(3,1)\to 7 \quad (3,2)\to 8 \quad (3,3)\to 9.$$

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

$$(1,1)\to 1 \quad (1,2)\to 2 \quad (1,3)\to 3 \quad (1,4)\to 4;$$
$$(2,1)\to 5 \quad (2,2)\to 6 \quad (2,3)\to 7 \quad (2,4)\to 8;$$
$$(3,1)\to 9 \quad (3,2)\to 10 \quad (3,3)\to 11 \quad (3,4)\to 12.$$

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

$$(1,1)\to 1 \quad (1,2)\to 2 \quad (1,3)\to 3 \quad (1,4)\to 4;$$
$$(2,1)\to 5 \quad (2,2)\to 6 \quad (2,3)\to 7 \quad (2,4)\to 8;$$
$$(3,1)\to 9 \quad (3,2)\to 10 \quad (3,3)\to 11 \quad (3,4)\to 12.$$

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

$$\begin{pmatrix} I_{A_1} \\ I_{A_2} \\ \vdots \\ I_{B*C_{11}} \\ I_{B*C_{12}} \end{pmatrix} = \begin{pmatrix} 1/9 & 1/9 & 1/9 & \cdots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 1/3 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 1/3 \end{pmatrix} \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_{35} \\ Y_{36} \end{pmatrix}, \tag{2}$$

$$K_i = \max\{I_{ij}\} - \min\{I_{ij}\}, \tag{3}$$

where i= A, B, C, $A*B$, $A*C$, $B*C$; j is the number of i rank.

By Eqs. (2), (3) and the kinematics calculation of the 3RPS parallel m… nism [35], the relationship between the target Q and … d, as shown in Fig. 5.

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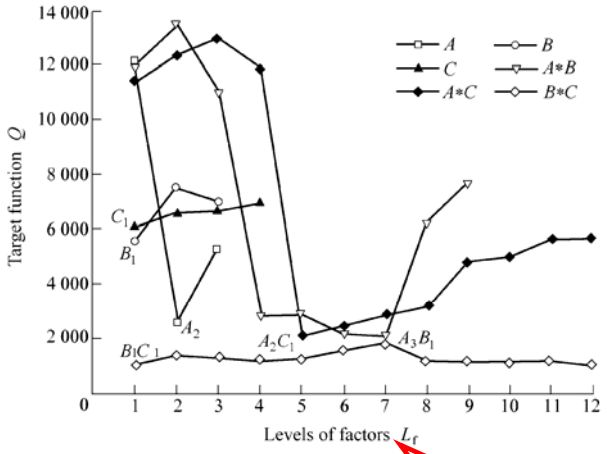

Fig. 5. Relation between levels of f… …

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According to the plots in Fig. … superiority and the degree of the infl… 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_3B_1, A_2C_1, A_2, 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

Joint on ZJUESA	Joint range $\theta/(°)$	Joint torque $T/(\mathrm{N\cdot m})$
Flexion/extension (shoulder)	–60–60	36
Abduction/adduction (shoulder)	–50–60	36
Rotation (shoulder)	–20–90	18
Flexion/extension (elbow)	0–90	28
Rotation (wrist)	–20–90	13
Flexion/extension (wrist)	0–60	28
Abduction/ adduction (wrist)	—	—

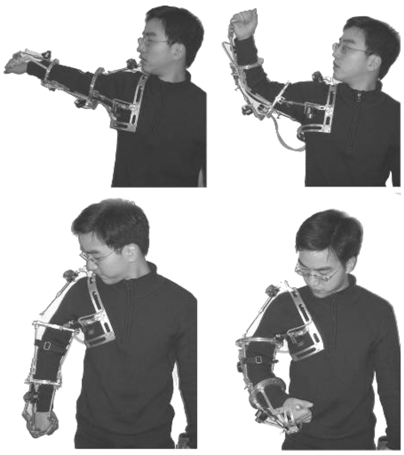

Fig. 6. Motion of exoskeleton arm following the operator

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:

$$\boldsymbol{\tau} = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{F} \tag{4}$$

where $\boldsymbol{F}$—Force and torque on the

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$\boldsymbol{F} = \begin{pmatrix} \boldsymbol{f} \\ \boldsymbol{n} \end{pmatrix}$,

$\boldsymbol{\tau}$—Torque on each joint,

$\boldsymbol{\tau} = (\tau_1 \quad \tau_2 \quad \cdots \quad \tau_6)^{\mathrm{T}}$,

$\boldsymbol{J}$—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):

$$\boldsymbol{f} = (f_4 \quad f_5 \quad f_6 \quad f_7)^{\mathrm{T}} = \left(\frac{\tau_3}{a_3} \quad \frac{\tau_4}{a_4} \quad \frac{\tau_5}{a_5} \quad \frac{\tau_6}{a_6}\right)^{\mathrm{T}} \tag{5}$$

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 prismatics on the 3RPS parallel mechanism, it can be calculated as follows[35]:

$$\begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} = \boldsymbol{G}_F^f \begin{pmatrix} \boldsymbol{\tau}_{\mathrm{3RPS}} \\ \boldsymbol{f}_{\mathrm{3RPS}} \end{pmatrix} \tag{6}$$

where $\boldsymbol{G}_F^f$—Jacobian matrix of 3RPS parallel mechanism,

$\boldsymbol{\tau}_{\mathrm{3RPS}}$—Torques on 3RPS parallel mechanism,

$\boldsymbol{\tau}_{\mathrm{3RPS}} = (\tau_1 \quad \tau_2)^{\mathrm{T}}$,

$\boldsymbol{f}_{\mathrm{3RPS}}$—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.

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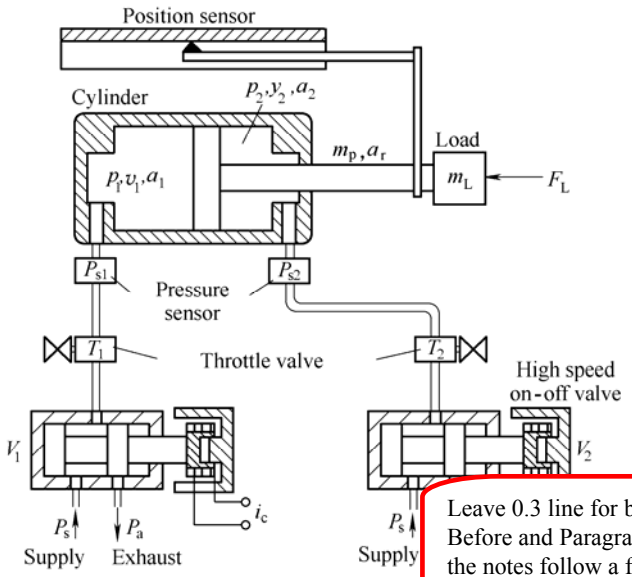

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Fig. 7.　Scheme of the pneumatic cylinder-valve system

p_1, v_1, a_1—Pressure, volume and section area of cylinder chamber 1
p_2, v_2, a_2—Pressure, volume and section area of cylinder chamber 2
m_p—Mass of the piston
a_r—Section area of rod
m_L—Mass of load

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The high-speed on-off valves, as the actuating 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 V_1 works and valve V_2 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[33].

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 [illegible]s in a closed-loop system in real time and [illegible]n to get the control information either [illegible]sion maker who performs the control [illegible]dy, 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.

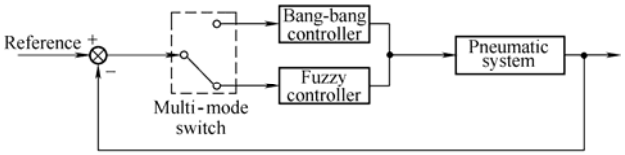

Fig. 8.　Concept of the hybrid fuzzy controller

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 $e(t) = P_{\text{ref}}(t) - P_{\text{actual}}(t)$ 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.

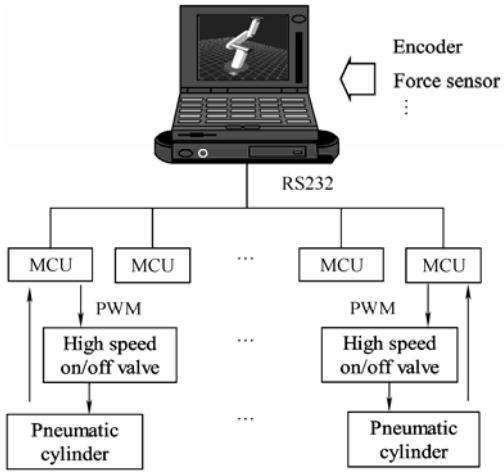

Fig. 9. Distributed control system of the master arm

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. Compared with other conventional programming environments, 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.

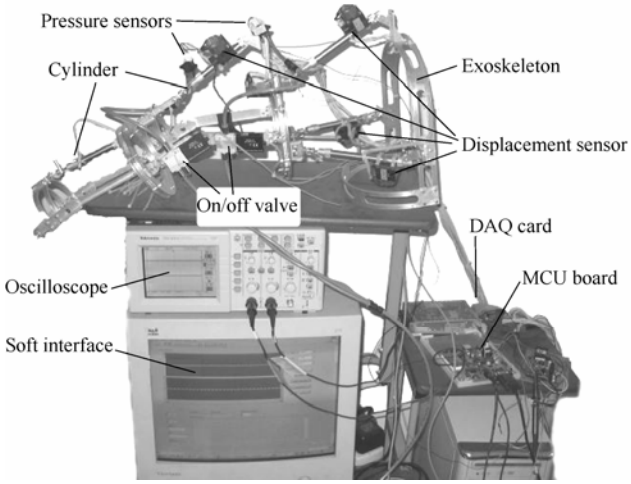

Fig. 10. Set-up of force feedback experiment

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. It proves effect of the hybrid control strategy.

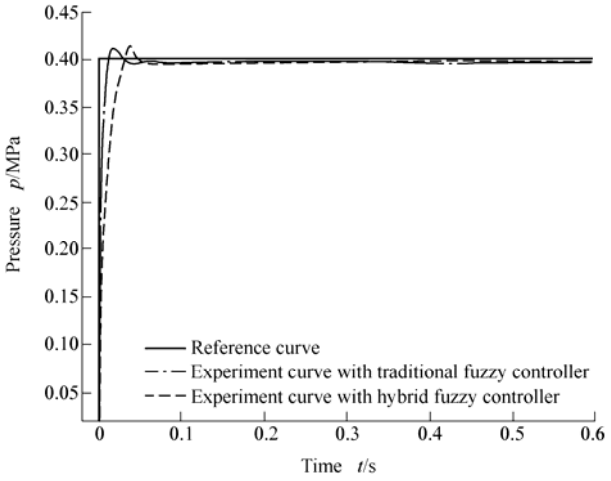

Fig. 11. Experimental results with a step signal

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. According to the experiments, the system with the help of hybrid fuzzy control strategy can track an up to 5 Hz frequency sinusoidal command well.

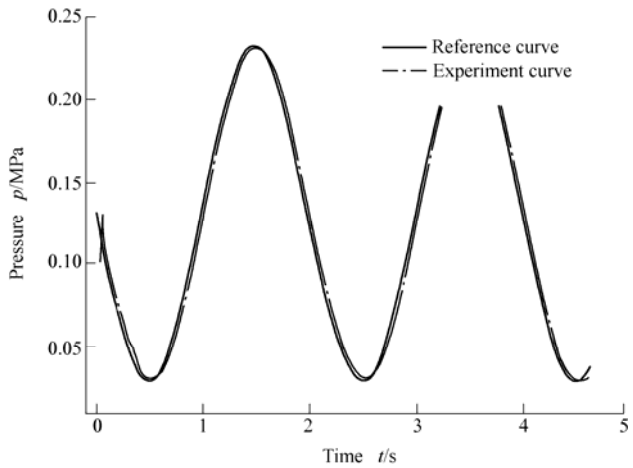

Fig. 12. Experiment results for sinusoidal pressure commands

After then, another two experiments are carried out to 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.

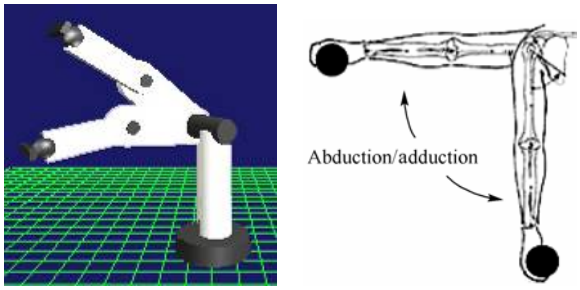

Fig. 13.　Shoulder abduction/adduction teleoperation

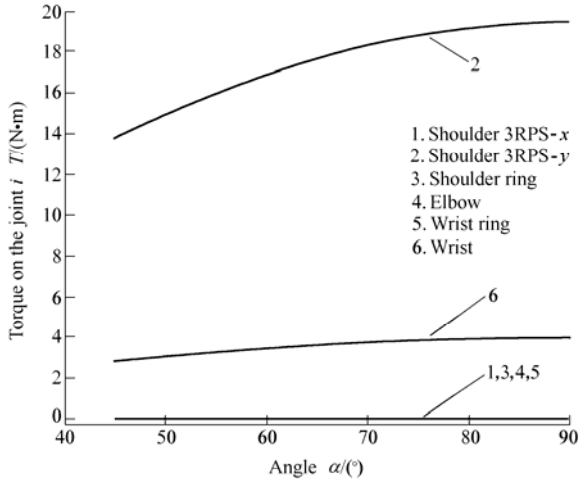

Fig. 14.　Torques on the joints of the shoulder abduction/adduction for 5 kg load lifting

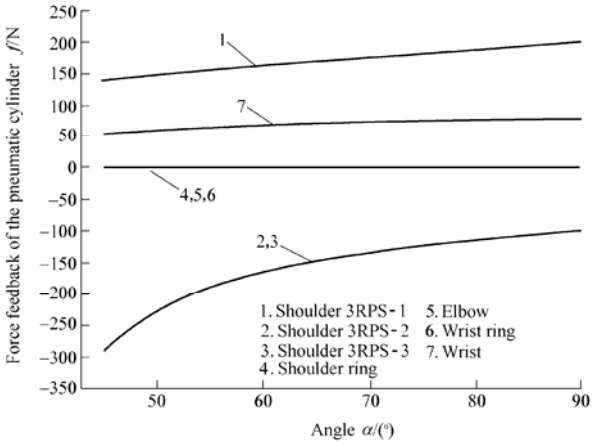

Fig. 15.　Force feedback on the cylinders of the shoulder abduction/adduction for 5 kg load lifting

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.

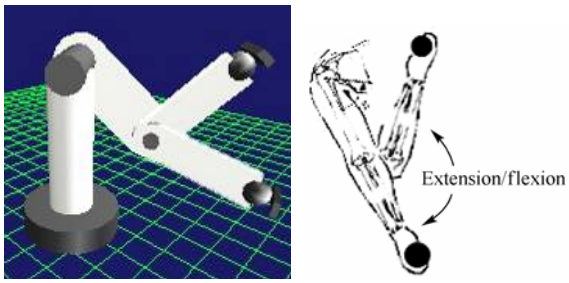

Fig. 16.　Extension/flexion for elbow teleoperation

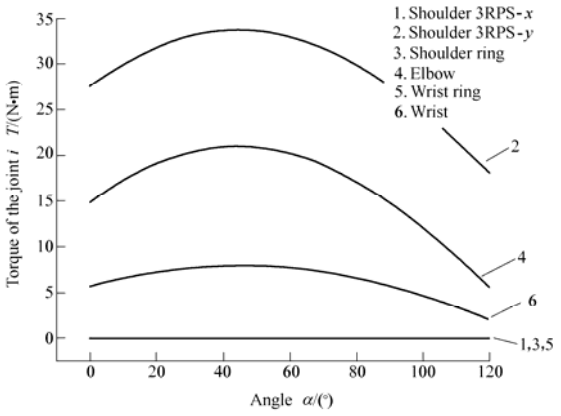

Fig. 17.　Torques on the joints of the elbow extension/flexion for 10 kg load lifting

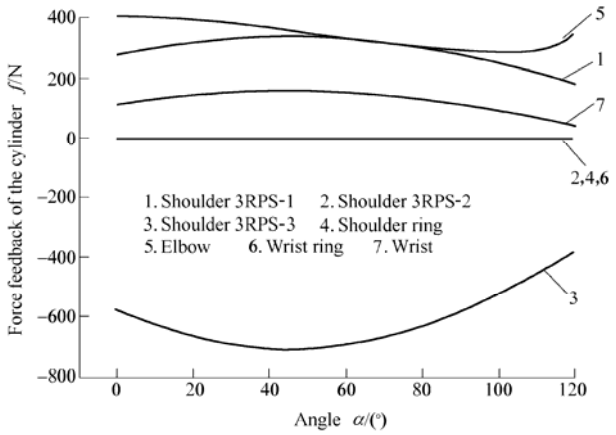

Fig. 18 Force feedback on the pneumatic cylinders of the elbow extension/flexion for 10 kg load lifting

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 performance, and a good agreement is found between the reference curves 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-[illegible]e pneu

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Appendix

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Appendix and supplement both mean ... terial 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.