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Recognition of Elastic Characteristic of Object Using Pneumatic Parallel Manipulator

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Abstract: The goal of this study is to develop a mechanical system that can display elastic characteristic of an object aiming at the application in the field of virtual reality. Pneumatic parallel manipulator is introduced as a driving mechanism, consequently, which brings capability of minute force displaying property owing to the air compressibility. Compliance control system without using force/moment sensor is constructed by introducing a disturbance observer and a compliance display scheme is proposed. The validity of the proposed scheme is verified experimentally.

Keywords: Pneumatic driving system, Parallel Manipulator, VR, Compliance control, Disturbance observer

1. Introdution

Virtual reality technologies have become one of the recent attracts in the industrial field, where, such as, the application to the virtual prototyping in mechanical CAD or the surgery simulation[1] are expected. Among the virtual reality technologies, the development of the instruments, which display force or tactile feeling, is important because such a feeling, besides of the vision, plays an important role for human to recognize an environment. Pneumatic actuators are effective for this kind of mechanical system[2][3] since its inherent features of softness and safety are indispensable for the mechanical device which contact with human directly.

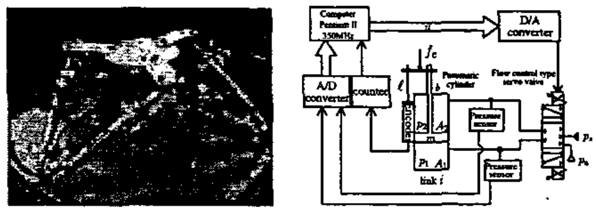
In this paper, we aim at developing a mechanical equipment that displays elastic characteristic of an object. Concretely, Stewart type parallel manipulator is introduced as a mechanical structure from a view that it can drive multiple d.o.f. for its compactness and pneumatic cylinders are employed as the driving actuators, which bring capability of minute force control property owing to the air compressibility.

The compliance display scheme is proposed, where a compliance control is constructed based on the estimated external force and its validity is confirmed through some experiments and analysis.

2. Outline of Pneumatic Parallel Manipulator

Fig. 1 (a) shows the developed pneumatic parallel manipulator. 6 pneumatic cylinders (10 mm in diameter and 15 mm in stroke) are employed and they drive an upper platform in 6 d.o.f..

The position/orientation of the upper platform is expressed by a hand vector $\boldsymbol{h} = [x, y, z, \phi, \theta, \psi]^T$ using roll-pitch-yaw angle notation. The origin of hand coordinate frame $\boldsymbol{h}$ is set at a center point of upper platform when manipulator stands in a standard posture. Similarly a link vector is defined as $\boldsymbol{\ell} = [\ell_a, ..., \ell_f]^T$ with an element of a displacement of each piston rod. Force/moment vector works at an origin of $\boldsymbol{h}$ is defined as $\boldsymbol{f_m} = [f_x, f_y, f_z, \tau_\phi, \tau_\theta, \tau_\psi]^T$. The equivalent force vector acts on piston rod is denoted with $\boldsymbol{f_e}$ which satisfy the following relation.



(a) Parallel Link Mechanism (b) Pneumatic Driving Circuit

Figure 1: Developed Pneumatic Parallel Manipulator

$$\boldsymbol{f_m} = J^T \boldsymbol{f_e} \tag{1}$$

, where J is a Jacobi matrix which forms the next relation.

$$\frac{d\ell}{dt} = J\frac{dh}{dt} \tag{2}$$

In the mean while, Fig.1(b) shows the pneumatic driving circuit of one cylinder. Low friction type pneumatic cylinder is employed (Airpel Co. Ltd., 9mm in diameter, 50mm in rod stroke). Pressure in each cylinder's chamber, p_1, p_2 are detected by pressure sensors and the displacement of piston rod ℓ is measured by potentiometer. The A/D converter is of 12 bit resolution.

A control signal u calculated every sampling period(10 ms) in a computer corresponds to an input voltage of a servo valve (FESTO, 50 ℓ/mine) through D/A converter(resolution of 12 bit), which regulates the difference pressure of each cylinder. Supply pressure p_s=400 kPa.

Table 1 shows the control parameters. The linearized state equations of pressure in cylinder's chamber are

Table 1: Systems parameters

m	Equivalent mass for one cylinder
b	Viscous coefficient
f_e	External force applied on a link
A_1, A_2	cross sectional area of cylinder chamber
p_1, p_2	pressure in chamber
ℓ	displacement of piston rod
T_p	Time constant of pressure response
k_p	Steady gain of pressure response
T_q	Time constant of filter

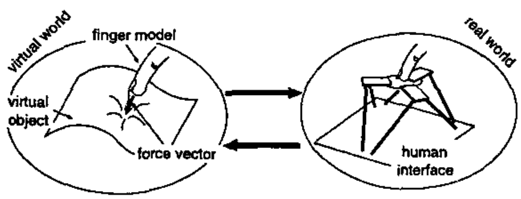


Figure 2: Concept image of compliance display

described by the following equation.

$$T_p \frac{dp_1}{dt} = -p_1 + k_p u - k_v \frac{d\ell}{dt} \quad (3.a)$$

$$T_p \frac{dp_2}{dt} = -p_2 - k_p u + k_v \frac{d\ell}{dt} \quad (3.b)$$

Equation of motion of piston rod is expressed by Eq.(4).

$$p_1 A_1 - p_2 A_2 = f_c = m \frac{d^2\ell}{dt^2} + b \frac{d\ell}{dt} + f_e \quad (4)$$

3. Recognition of Elastic characteristic

Fig.2 shows the concept image of compliance display. Human contacts with their fingertip at a center point of upper platform of manipulator and apply force for a various direction. The manipulator displays a prospective compliance in arbitrary direction and make human feel(recognize) an object through a force feeling.

Fig.3 shows the proposed position based compliance control system[4]. The inner position control system is designed in order that the closed loop transfer function may follow the 3rd order system shown in Eq.(5).

$$\frac{\boldsymbol{H}}{\boldsymbol{H}_r} = \boldsymbol{G}_r = \mathrm{diag}\{\frac{C}{s^3 + As^2 + Bs + C}\} \quad (5)$$

The inner block with a doublet represents a control system of generating force F_c as shown in Fig.4, which works to lower the influence of piston rod velocity that acts as disturbance on pressure response as shown in Eq.(3) as well as to make F_c to follow to the reference value with time constant T_{pn}[4].

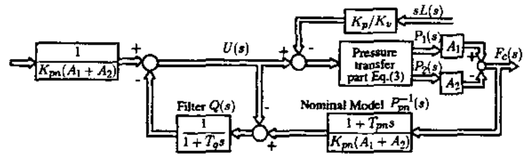


Figure 4: Generation force control system

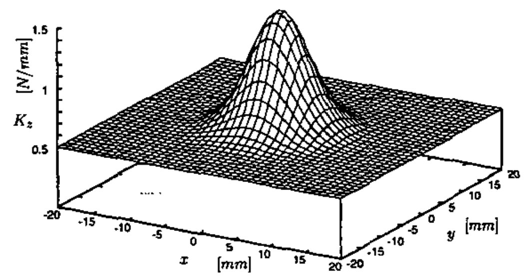


Figure 5: Compliance model

First of all, the applied external force which works on a link equivalently is not measured by a force sensor but estimated by introducing a disturbance observer for the transfer part $P_k(s)$. The estimated disturbance $D(s)(= -F_e(s))$ is transfered to the hand coordinate force/moment vector $\boldsymbol{f_m}$ through a transpose of Jacobi matrix J^T and then fed back by being multiplied with a compliance matrix $\boldsymbol{K}^{-1} = \mathrm{diag}\{K_x^{-1}, K_y^{-1}, ..., K_\psi^{-1}\}^T$.

4. Experimental results

A recognizing of compliance change in local area is carried out experimentally. We set a compliance model as shown in Fig.5, where the stiffness for z direction K_z become larger when the contact point closes to the origin $(x = y = 0)$ as shown in Eq.(6).

$$K_z = 1.0 \times \exp\left\{\frac{-(x^2+y^2)}{10.0}\right\} + 0.5 \quad (6)$$

Fig.7 shows the obtained control performances for this case. Figure (a) shows the experimental situation.

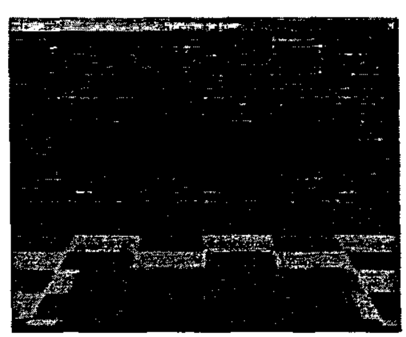


Figure 6: Graphic scene

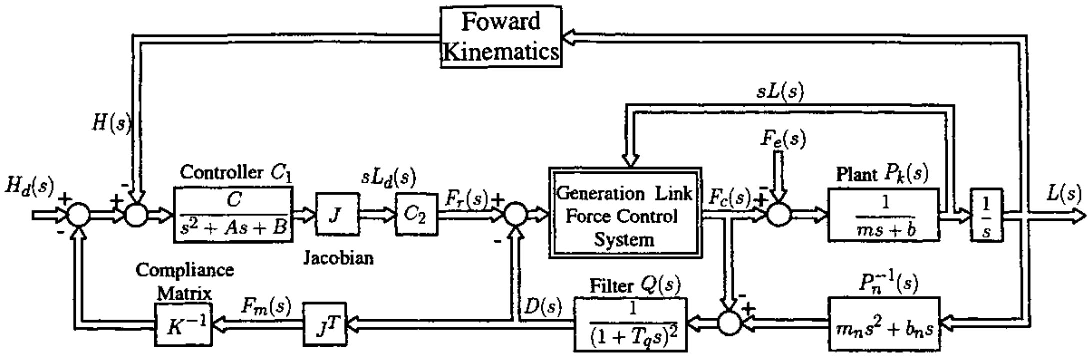


Figure 3: Position control system

Human contact with a manipulator at a center point of upper platform and moves it with a reciprocation motion according with y axis giving a constant force for z axis continuously. The stiffness for horizontal direction is set as a small value of $K_x = K_y = 0.1$ N/mm not to prevent the motion for the horizontal direction.

Figure (b) shows the applied force on manipulator for z axis, where solid and dotted line indicate the estimated force and measured one by using a force sensor as shown in figure (a). An estimation error(about 1 N) is confirmed, which is mainly resulted from identification error between $P_k(s)$ and $P_n(s)$. The improvement of estimation accuracy is the matter to be settled at present.

Figure (c) shows the displacement of manipulator, where solid line indicates that for y direction while dotted one corresponds to that for z direction. When the contact point across over the most rigid point($x = y = 0$) at t=40 s and 60 s, since applying force is almost constant, an increase of displacement for z axis can be confirmed, which makes human feel getting over an projection.

Figure (d) shows the realized stiffness, where dotted line is a value from a model shown in Eq.(6) and dashed line solid one shows the calculated stiffness based on the estimated force and based on the measured one by a force sensor, respectively. These obtained stiffness are almost the same and match with the model quantitatively.

Fig.8 is the results of the same experiment with Fig.7 except that the stiffness model shown in Fig.5 is set for the x direction K_x in $y - z$ plane as

$$K_x = 1.5 \times \exp\left\{\frac{-(y^2 + (z+10)^2)}{10.0}\right\} + 0.5 \quad (7)$$

In this case, at the point (y=0 and z=-10 mm) the stiffness become most large value of 2.0 N/mm.

Fig.6 shows the graphics model corresponding to the experiment of Fig.7 constructed with OpenGL. The displacement of manipulator is reflected on graphics model in real time. The effect of visual aid in recognizing an object is also a matter of future problem.

5. Conclusion

In this study, we developed a pneumatic parallel manipulator to display a compliance of an object for human. A compliance displaying scheme is proposed, where the applied force is estimated using a disturbance observer and the desired compliance is realized by constructing a basic compliance control system.

The compliance displaying properties has been confirmed through the basic direction in hand coordinate frame, which proves the effectiveness of the proposed control system. In the next step, development of a control scheme to display an arbitrary compliance for the arbitrary direction and verifying the effectiveness of our displaying equipment by applying to the practical recognition motion are the matter to be settled at present.

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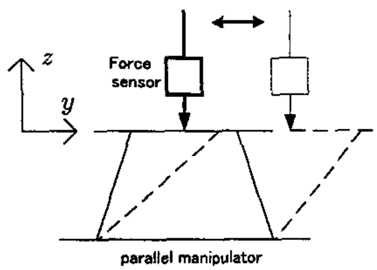
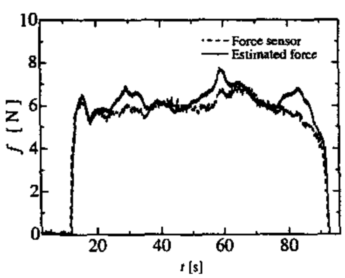
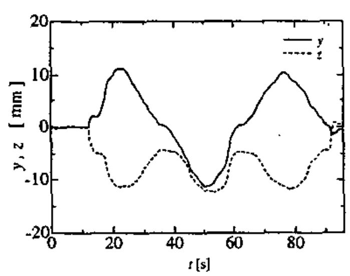


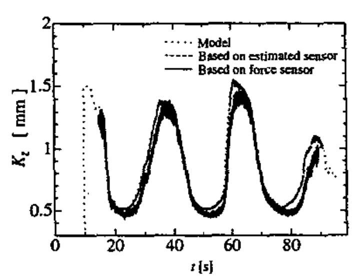
(a) Experimental situation



(b) Contact force for z axis

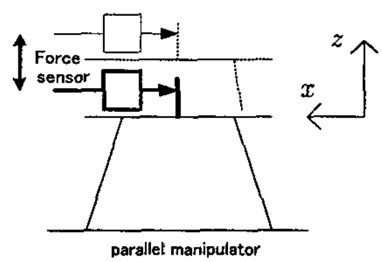


(c) Displacement in hand coordinate frame

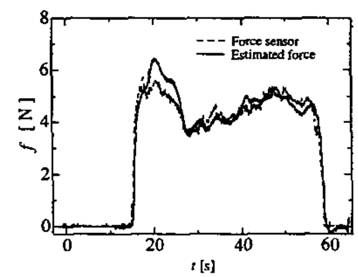


(d) Compliance display performance

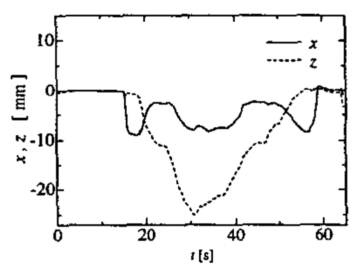
Figure 7: Recognition of object in y-z plane



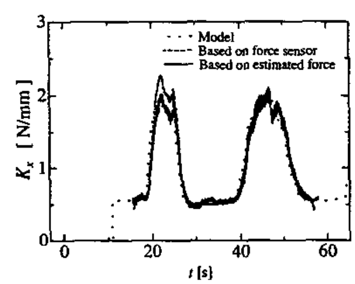
(a) Experimental situation



(b) Contact force for z axis



(c) Displacement in hand coordinate frame



(d) Compliance display performance

Figure 8: Recognition of object in x-z plane