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Application of Pneumatic Parallel Manipulator as Haptic Human Interface

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***Abstract*—When human and robot implement a cooperative task, information(intention) transfer between them comes up as an important problem as the task becomes complicated. In this paper, a haptic interface using a pneumatic parallel manipulator is developed to realize "information transfer by means of contact". Concretely saying, the contact information given by human, namely contact force vector and contact point on the manipulator, is detected by the interface itself and such information are transfered to the robot by being connected with some reference signal. Pneumatic parallel manipulator works as a kind of elastic body even when its position is controlled owing to the air compressibility. Focusing on this characteristic and introducing an idea of compliance center with spherical shell, contact force vector and contact point are detected without force sensor. The validity of proposed method is confirmed through some experiments.**

***Keywords*— Haptic Interface, Pneumatic Driving System, Parallel Manipulator, Elastic Characteristic**

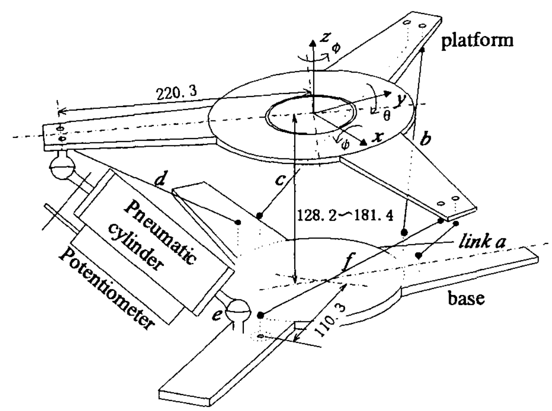

Fig. 1. Developed pneumatic parallel manipulator

I. Introduction

In an environment where human and robot coexist, such as carrying out a cooperative tasks, information transfer between human and robot is indispensable.

In this study we consider an idea of "information (intention) transfer by means of contact" and aim at developing a haptic human interface to realize such an idea. Concretely saying, the several force information applied by human, namely the applied force vector and the contact point on the interface's body, are detected by the interface itself and they are transfered to the robot by connecting with some reference signal.

For the sake of this purpose, the interface itself must have a function to detect contact point and contact force vector (magnitude and direction). Distributing a tactile sensor[1] on the surface of the interface's body may contribute to detect a contact point and magnitude of the contact force(if it is from normal direction), but it seems to be difficult to detect the direction of the contact force vector.

In this study, Stewart[2] type parallel manipulator whose degree of freedom is driven by pneumatic cylinders is employed as our human interface. Parallel mechanism is effective as this kind of haptic interface since it has multiple degree of freedom for its compact mechanism. Consequently, the interface can work as a kind of elastic body even when its position is controlled owing to air compressibility[3]. Utilizing this elastic characteristic, a detection scheme of the applied force vector and contact point with no use of general force/moment sensor is suggested. The validity of the proposed scheme is confirmed through some experiments and analysis in the bellow.

Unlike a passive interface, such as distributing tactile sensor on a body, our interface not only act as an omni directional force sensor itself but has a function to be an multiple d.o.f. actuator, which has possibility to implement various complicated contact motion.

II. Outline of Pneumatic Parallel Manipulator

Fig. 1 shows the schematic diagram of the developed pneumatic parallel manipulator. 6 pneumatic cylinders (31.5 mm in diameter and 35mm in stroke) are employed

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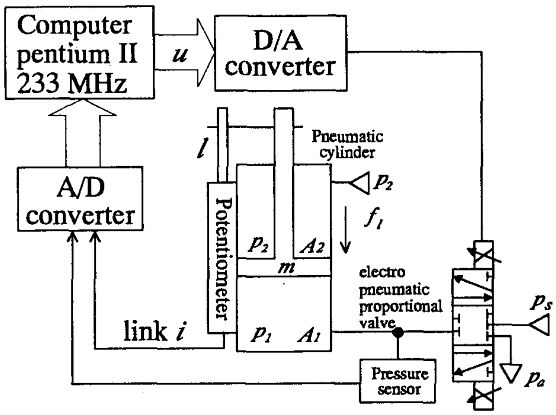


Fig. 2. Pneumatic driving circuit

as its driving actuators.

The position/orientation is described by a hand coordinate vector $h = [x, y, z, \phi, \theta, \psi]^T$ where x, y, z are horizontal displacement and ϕ, θ, ψ expressed by roll-pitch-yaw angle indicate the manipulator's posture. A link vector is defined as $\ell = [\ell_a, ..., \ell_f]^T$ with a element of a displacement of each piston rod.

Fig.2 shows the pneumatic driving circuit of one cylinder. The rod side cylinder chamber is pressurized by constant pressure p_2=236 kPa, while a pressure in a head side one p_1 is regulated by electro-pneumatic proportional valve. The displacement of piston rod is measured by potentiometer(12.2μm in resolution) and p_1 is detected by a pressure sensor(29.4 Pa in resolution).

A control signal u calculated every sampling period(2.5 ms) in a computer corresponds to an input voltage of D/A converter.

III. Position Control System

Proposed force detection scheme is based on the manipulator's elastic characteristic when position control is implemented. Fig.3 shows the position control system[4] employed in this study. It is constructed based on the pressure control system from a view that pressure control is indispensable for an improvement of control performance in fluid power systems. A variable with upper-case letter represents *Laplace* transformed one and (s) is neglected for simplicity.

Reference length of link L_r is calculated through inverse kinematics and position control system is constructed at each link independently.

State equation of air in a head side chamber and equation of motion of piston rod are described as follows

$$T_p \frac{dp_1}{dt} = -p_1 + K_p u - K_v \frac{d\ell}{dt} \qquad (1)$$

TABLE I

System parameters

ℓ	displacement of piston stroke
p_1, p_2	pressure of each chamber
A_1, A_2	effective sectional area of chamber
K_p	static gain between u and p_1
K_v	static gain between piston velocity and p_1
T_p	time constant of p_1 against u
m	equivalent mass including that of piston rod
b	damping coefficient
f_e	total amount of external force (coulomb friction, interaction force etc.)

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

,where each parameter is represented in TABLE I. The variable with a subscript n means a nominal model of its correspondence.

First, disturbance observer[5] is introduced to the mechanical transfer part, namely from pressure P_1 to link velocity sL. Consequently the estimated disturbance D includes the influence of parameter change and disturbance at the same time. Therefore if a pressure P_1 could be generated so as to contour pressure reference P_r and D then influence of disturbance and parameter change would not affect on the control performances at all. Then pressure control system using disturbance observer is constructed to compensate nonlinear pressure response characteristic and to contour P_r with estimated disturbance D(actually $\hat{D}$ through a filter) derived from the former disturbance observer.

In the case when these disturbance observer worked effectively, the transfer function between P_r and sL is represented by the products of two nominal models as

$$\frac{sL}{P_r} = P_{pn} K_{pn}^{-1} A_1 P_{kn} = \frac{1}{1 + T_{pn}s} \frac{A_1}{m_n s + b_n} \qquad (3)$$

Supposing that either of time constant of each nominal model T_{pn}, m_n/b_n can be set enough small compared to the other, closed loop system can be represented by a desired second order system shown in eq.(4) by producing P_r through a controller C explained in eq.(5).

$$\frac{L}{L_r} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (4)$$

$T_{pn} \ll m_n/b_n$:

$$C = \frac{\omega_n^2 (m_n s + b_n)}{A_1 (s + 2\zeta\omega_n)} \qquad (5.a)$$

$m_n/b_n \ll T_{pn}$:

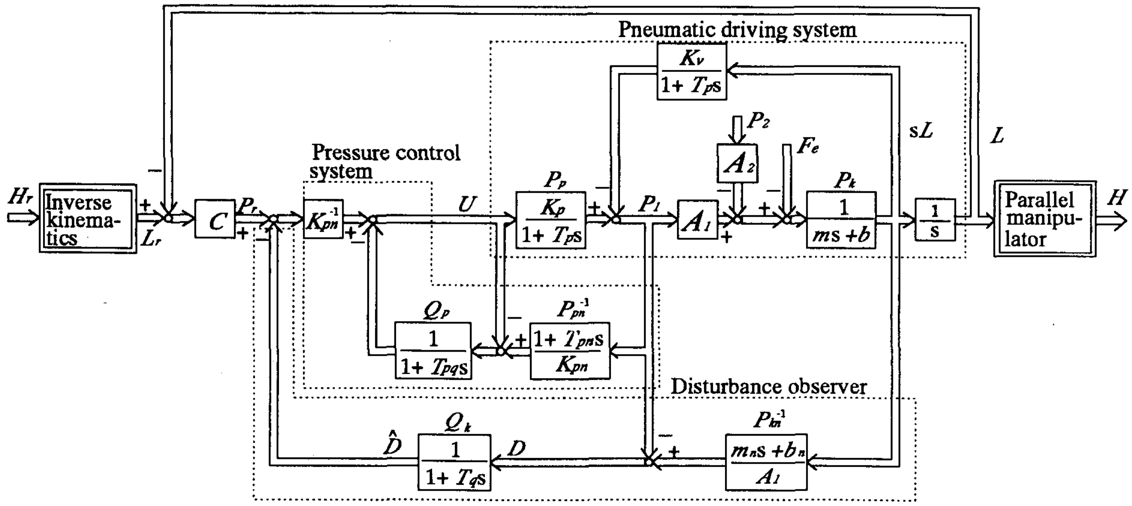


Fig. 3. Position control system

$$C = \frac{\omega_n^2 b_n(1+T_{pn}s)}{A_1(s+2\zeta\omega_n)} \quad (5.b)$$

IV. Detection of Force Vector and Contact Point

From Fig.3 closed loop relation between L_r and L is simply described as

$$L = \alpha L_r - I_{mp}^{-1} F_e \quad (6)$$

where α is a closed loop transfer function and it becomes equivalent to eq.(4) when the position control system worked ideally. I_{mp} corresponds to a mechanical impedance per one link, which is represented as a form of

$$I_{mp} = \frac{(sP_{kn}^{-1} + CG)A_1}{1 - Q_k G} \quad (7)$$

where G is a closed loop transfer function of inner pressure control system.

In pneumatic systems, $|I_{mp}|$ becomes small in the low frequency range. This is one of reasons why it is not easy to improve a positioning accuracy in pneumatic system since inverse of I_{mp} is equivalent to a sensitivity function. However this characteristic gives manipulator a compliance(softness) and it must be effective for a human friendly machine.

From a principle of virtual work, a force/torque applied at an origin of h, $f_m = [f_{mx}, f_{my}, f_{mz}, f_{m\phi}, f_{m\theta}, f_{\psi}]^T$ is related with a force equivalently acting on a link f_e as

$$f_m = J^T f_e \quad (8)$$

where J is a Jacobi matrix, which satisfy the following relation.

$$\frac{d\ell}{dt} = J\frac{dh}{dt} \quad (9)$$

In a parallel manipulator, contrary with a serial one, h can not be obtained analytically. In this study convergence calculation(*Newton -Raphson* method) is employed to obtain h and its sufficient convergence accuracy has been confirmed [4].

Substituting *Laplace* transformed eq.(8) into eq.(6) by considering eq.(9), yields eq.(10)

$$F_m = I_{mp} J^T J(\alpha H_r - H) \quad (10)$$

Therefore if mechanical impedance of link I_{mp} is known, then force/torque F_m at an origin of h can be estimated without using a force/moment sensor.

Utilizing the F_m calculated in eq.(10), the detection scheme of the applied force vector and its contact point are described bellow. Fig.4 shows a geometrical model, in which contact point of the force vector f is expressed by poler coordinates (r, α, β).

As you see that, concerning to the force vector f, it is simply derived from the balance of translational force as

$$f = [f_{mx}, f_{my}, f_{mz}]^T \quad (11)$$

On the other hand, contact point (r, α, β) is derived by considering the balance of moment around the origin of h. The moment around an origin made by f is described by $R \times f$, where $R = [r\cos\beta\cos\alpha, r\cos\beta\sin\alpha, r\sin\beta]^T$ is a position vector of

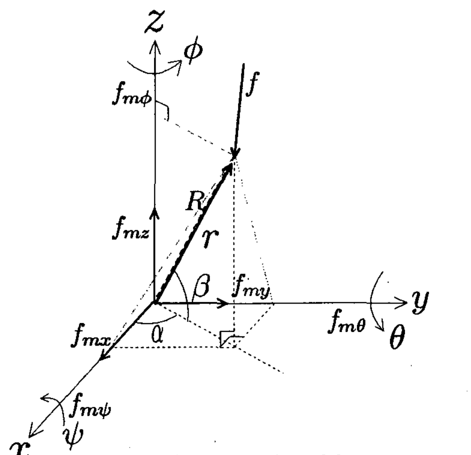


Fig. 4. Geometrical model

contact point. Therefore equations of a balance of moment around the origin of h is described as the following.

$$-f_{mx} r \sin\alpha\cos\beta + f_{my} r \cos\alpha\cos\beta = f_{m\phi} \quad (12.a)$$

$$f_{mx} r \sin\beta - f_{mz} r \cos\alpha\cos\beta = f_{m\theta} \quad (12.b)$$

$$-f_{my} r \sin\beta + f_{mz} r \cos\beta\sin\alpha = f_{m\psi} \quad (12.c)$$

In this study a convergence calculation (*Newton-Raphson* method) is also employed to solve eq.(12) for the variables r, α, β since it is too complicated to solve analytically. This method needs an inverse of Jacobi matrix of the equation, however it proves to be irregular. Therefore we assume r is constant by considering that contact force f is applied on a newly introduced spherical shell which cover the manipulator and whose center matches the origin of h. Consequently α and β can be obtained by the following iteration.

$$\begin{bmatrix} \alpha(n+1) \\ \beta(n+1) \end{bmatrix} = \begin{bmatrix} \alpha(n) \\ \beta(n) \end{bmatrix} - J_e^* \begin{bmatrix} f_{m\phi}(n) - f_{m\phi}(0) \\ f_{m\theta}(n) - f_{m\theta}(0) \\ f_{m\psi}(n) - f_{m\psi}(0) \end{bmatrix} \quad (13)$$

$$n = 0, 1, 2, \ldots$$

where J_e^* is a pseudo inverse of the Jacobi matrix shown in the following equation.

$$J_e^* = (J_e^T J_e)^{-1} J_e^T, \quad J_e = \begin{bmatrix} \frac{\partial f_{m\phi}}{\partial\alpha} & \frac{\partial f_{m\phi}}{\partial\beta} \\ \frac{\partial f_{m\theta}}{\partial\alpha} & \frac{\partial f_{m\theta}}{\partial\beta} \\ \frac{\partial f_{m\psi}}{\partial\alpha} & \frac{\partial f_{m\psi}}{\partial\beta} \end{bmatrix} \quad (14)$$

Here, as you see that the accuracy of the proposed estimation method depends on that of calculated force/moment f_m works at origin of h. Then a new hand coordinate system is introduced so that $J^T J$ in eq.(10) becomes diagonal matrix at its origin. In generally such a point is called "compliance center". It is expected to

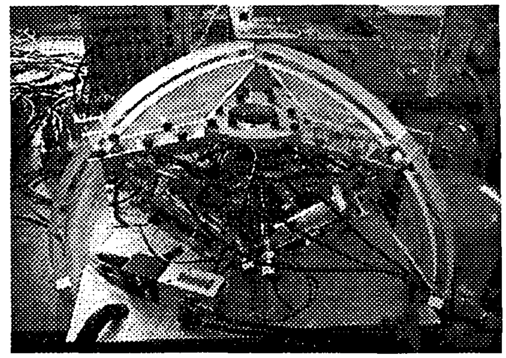


Fig. 5. Manipulator covered by shell

improve the estimation accuracy of f_m by considering at point of compliance center.

In our manipulator, a compliance center was found to be at 15mm under the center of bottom plane and $J^T J$ at that point is represented as follows, where non-diagonal element is neglected to be 0 since their contribution for the force generation are significantly low compared to the diagonal one.

$$J^T J = \quad (15)$$

$$\begin{bmatrix} 1.6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.7\times10^{-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.7\times10^{-2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.7\times10^{-2} \end{bmatrix}$$

Hence the spherical shell is constructed so as to make its center to match the compliance center, which is shown in Fig.5(a part in the figure).

Here if the force vector is previously known to be applied through the normal direction for the spherical shell, contact point(α, β) is simply and directly given by on line as shown in eq.(16) since no moment is generated around compliance center owing to its physical characteristic.

$$\alpha = \tan^{-1}\left(\frac{f_{my}}{f_{mx}}\right) \quad (16.a)$$

$$\beta = \tan^{-1}\left(\frac{f_{mz}}{\sqrt{f_{mx}^2 + f_{my}^2}}\right) \quad (16.b)$$

V. Experiments and Discussion

Fig.6 shows the positioning step response at horizontal direction, in which • indicates the response of a model shown in eq.(4). For all links, ω_n and ζ are set to 8.0 rad/s and 1.0, respectively. From identification, the

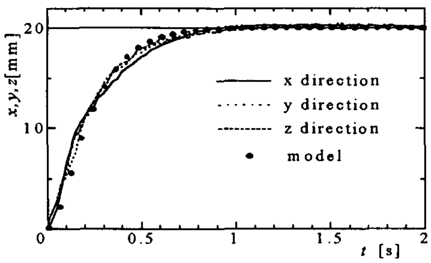


Fig. 6. Position control performance

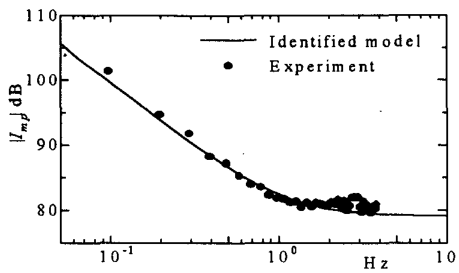


Fig. 7. Identification of impedance characteristic

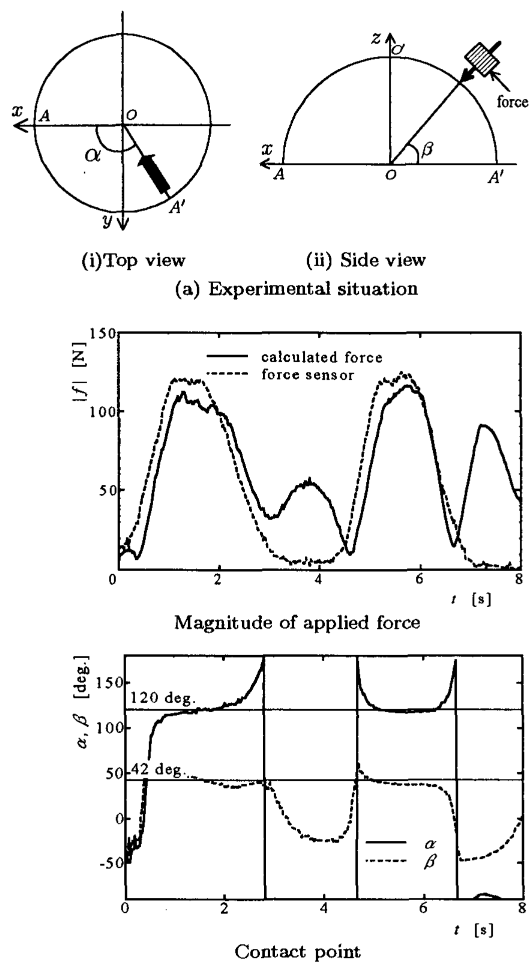


Fig. 8. Estimation performance (normal direction)

time constant of P_k in Fig.3 is much smaller than that of P_p, so the controller given in eq.(5.b) is employed.

The obtained responses for each direction are almost the same with that of the desired model, which proves an effectiveness of a proposed position control system.

A. Detection of Force Vector and Contact Point

For the force detection, mechanical impedance characteristic of a link I_{mp} must be previously known. It may be essential to use eq.(7) as a mathematical model of impedance characteristic, however it seems to be so complicated for implementation that an approximated model obtained from the following experimental identification is employed for a simplicity. In the static state of positioning step response, random frequency force is applied on a piston rod through a temporarily attached force sensor. In Fig.7, • indicates a bode diagram of a mechanical impedance characteristic analyzed by FFT algorithm, while solid line corresponds to that of the approximated model described by eq.(17) where K=6.0 $\times 10^4$ N/m and T_1=0.13 s.

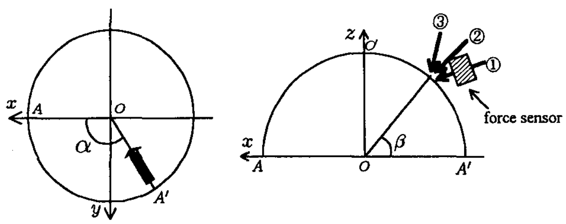
$$I_{mp} = \frac{K(1+T_1 s)}{s} \tag{17}$$

Fig.8 indicates the estimation performance when contact force is constrained to be applied from normal direction for the shell at the point of $\alpha = 120$ deg. $\beta = 42$ deg. as shown in (a). Magnitude of the applied force is shown in (b), in which dotted and solid line indicate the force measured by force sensor and that calculated according to eq.(11), respectively. Almost satisfactory estimation performance can be confirmed, but it is getting worse while a force is not applied. It causes that positioning error are still remaining even a force is not applied, which yield a 'lie' force according to eq.(11). Contact point calculated from eq.(16) is shown in (c), where solid and dotted line correspond to α and β, respectively.

From these results, almost the satisfactory estimation performance in both of the magnitude and the contact point can be confirmed.

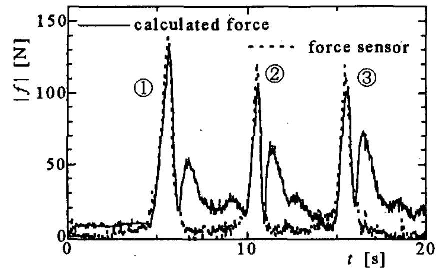
Subsequently, Fig.9 shows an estimation performance of a force vector(arbitrary direction) and contact point.

A human holds a force sensor and gives an impulsive force 3 times continuously at the point of α=120 deg. and β= 42 deg. as shown in Fig.9(a) in the sequence ①, ② and ③. All of the 3 force vectors ① ② ③ lie in the O'-O-A' plane but angle from x-y plane is about 20 deg.

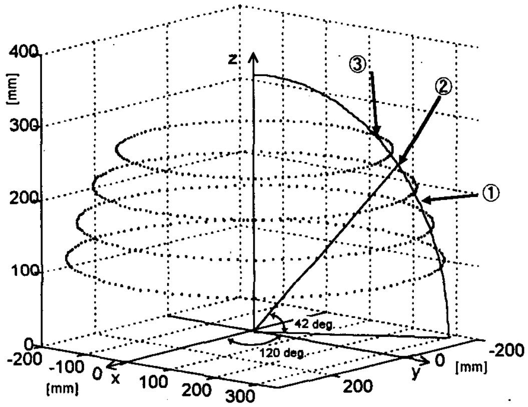


(i)Top view (ii) Side view

(a) Experimental situation



(b) Magnitude of applied force



(c) Estimated force vector and contact point

Fig. 9. Estimation performance (arbitrary direction)

for ①, about 40 deg. for ② and about 60 deg. for ③.

Fig.9 (b) shows the magnitude of the applied force, in which dotted and solid line are the force measured by force sensor and that calculated according to eq.(11), respectively. Almost the satisfactory estimation performance can be confirmed, except while a force is not applied from the same reason mensioned in Fig.8(b).

Fig.9 (c) shows the estimated contact point and force vector which are calculated from eq.(12) by "off-line" convergence calculation method using f_m at the time when each applied force has a maximum value. Here, contact point(α, β) was converged to be (125 deg., 32 deg.) for ①, (120 deg., 42 deg.) for ② and (121 deg., 51 deg.) for ③.

Through the all cases, almost sufficinet estimation results were obtained in the directions of force vector and an element of contact point of α. However, except for the case ②, the element of contact point β is differerent from its original. In generally it has been confirmed that the estimation performance of contact point(especially β) is getting worse as the direction of force vector deviated from the normal direction for the spherical shell. There is much left to improve the estimation performances concerning to the contact point.

VI. Conclusion

In this paper a human-robot haptic interface which detect a contact information given by human, namely applied force vector and contact point, is proposed to realize an idea of "information(intention) transfer by means of contact".

In order to fulfil the intended function, a parallel manipulator driven by pneumatic actuator is employed by focusing that it works as a kind of elastic body even when its position is controlled owing to air compressibility.

Utilizing this elastic characteristic and newly introduced combination of spherical shell and compliance center, one detection scheme of applied force vector and contact point is proposed with no use of general force/moment sensor.

In the case force vector is constrained to be normal for the spherical shell, the magnitude of a force and the contact point are almost accurately estimated owing to the characteristic of compliance center. On the other hand, in the case when the applied direcion of the force is arbitrary, estimation accuracy of contact point get worse compared to that of force vector.

It can be said that the obtained experimental performance proved the effectiveness of the proposed scheme, but there is still much room for further improvement of the estimation accuracy. This is the matter to be settled at present.

References

[1] D.Johnston, P. Zhang, J. Hollerbach, S.Jacobsen, *A Full Tactile Sensing Suite for Dextrous Robot Hands and Use in Contact Force Control*, Proc. IEEE ICRA Minneapolis,Minnesota, vol. 4, 3222/3227, 1996

[2] D.Stewart, *A Platform with Six degrees of Freedom*, Proc. Inst. Mechanical Engineers, 180-15, 371/386, 1965-1966

[3] M. Takaiwa *and* T. Noritsugu, *Sensor-less Force Detection by Pneumatic Parallel Link Manipulator and Its Application for Contact Task*, Proc. of FLUCOME'97, vol.1, 469/474, 1997

[4] T. Noritsugu *and* M. Takaiwa, *Motion Control of Pneumatic Parallel Manipulator Using Disturbance observer*, Japan-U.S.A. Flexible Automations, 1986.

[5] T. Murakami *and* K. Ohnishi, *Advanced Control Technique in Motion Control*, The Nikkan Kogyo Shinbun Ltd., Japan, 1990