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DEVELOPMENT OF PALPATION SIMULATOR USING PNEUMATIC PARALLEL MANIPULATOR

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Abstract

Nowadays, the breast cancer, over ahead of stomach one, holds the highest cancer incidence rate among Japanese women. Detection of breast cancer is done by palpation diagnosis, which require doctor to have highly experienced technique. In this study, we develop a palpation simulator which forms a woman's actual breast model holding active controlled variable stiffness property. A pneumatic parallel manipulator is employed as mechanical part of our simulator. In order to display a concrete stiffness feeling to human (doctor), control strategy is proposed where the contact point is detected using an idea of graphical intersection test. A reference stiffness is realized by constructing a compliance control system. By regulating the reference stiffness value according to the contact point, a palpation motion is executed. The validity of the proposed palpation system are confirmed through some experiments and analysis.

KEYWORDS
Palpation simulator, Pneumatic servo system, Parallel Manipulator

INTRODUCTION

Among the Japanese women, The disease rate of breast cancer became the most highest one, over ahead of that of stomach cancer[1]. However, if the cancer is identified as it is still just a part of breast, the existence rate is reported to be 92 %, which shows the importance of early detection simultaneously.

Detection of breast cancer is implemented by both palpation diagnosis and Mammography (X-ray photograph of breast). Palpation motion requires for doctor to have a highly skilled technique. From a view of medical education, there is strong need for palpation simulator and some equipment using robot technology or VR one are being developed[2][3].

In this study, we aim at developing a palpation simulator which has a actual breast model to be touched by human in natural manner. In the mean while, importance of self diagnosis is also pointed out. Our simulator can be also used as a reference model of women's self diagnosis.

In order to realize such an palpation simulator, 3-D breast model holding a spatially different stiffness on its surface is required. Actually, some palpation simulators has already come onto the market, but they don't have function to adjust position or magnitude of stiffness as we will.

In this study, a pneumatic parallel manipulator is introduced to sustain a 3-D breast model. Parallel manipulator has a feature of multiple d.o.f. for its compactness and it enables minute force regulation property owing to the air compressibility. A contact point is detected using an idea of graphical intersec-

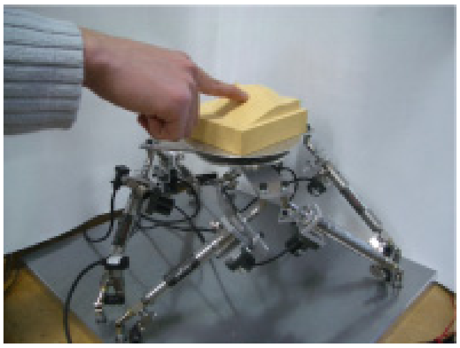


Figure 1: Developed Palpation Simulator

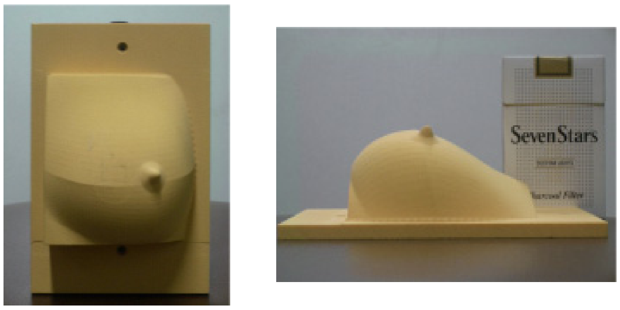


Figure 2: Breast shape model

tion test and the reference compliance is realized by constructing a compliance control system on the parallel manipulator.

The validity of the proposed palpation equipment are confirmed through some experiments.

Developed Palpation Simulator

Outline of Simulator

Fig.1 shows the developed palpation simulator. A 3-D breast model is attached with a upper platform of a pneumatic parallel manipulator via 6 axis force/moment sensor. Human(doctor or woman) pushes or trace any point of the model as shown in the figure and feels spatially different stiffness, which is realized by a parallel manipulator.

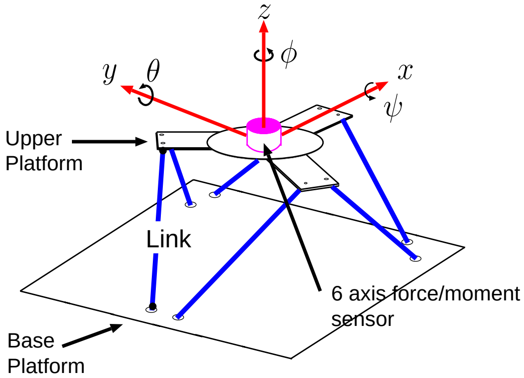
Fig.2 shows the manufactured breast shape model designed using 3-D modeling software and manufactured by 3-D modeling machine with the material of chemical wood.

Pneumatic Parallel Manipulator

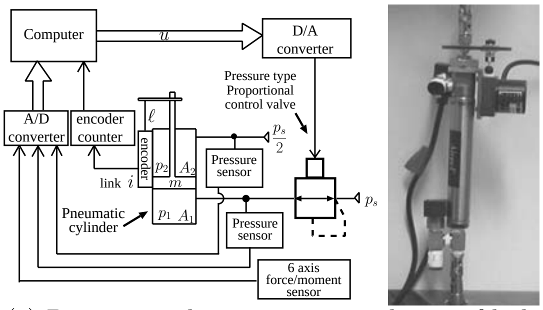
Fig.3 (a) shows the developed pneumatic parallel manipulator works as compliance displaying mechanism.

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

(a) Pneumatic parallel manipulator



(b) Schematic diagram



(c) Pneumatic driving circuit and unit of link

Figure 3: Pneumatic parallel manipulator

coordinate frame $\boldsymbol{h}$ is set at a center point of upper platform(namely at center point of force/moment sensor) when manipulator stands in a standard posture. Force/moment vector works at an origin of $\boldsymbol{h}$ is defined as $\boldsymbol{f_m} = [f_x, f_y, f_z, \tau_\phi, \tau_\theta, \tau_\psi]^T = [\boldsymbol{f_t}^T, \boldsymbol{\tau}^T]^T$.

In the mean while, Fig.3(c) shows the pneumatic driving circuit of one cylinder. A friction in a cylinder makes compliance control performance worth. The employed pneumatic cylinder(Airpel Co. Ltd., 9.3 mm in internal diameter, 50mm in rod stroke) is a special made type ant its friction is negligible. 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 wire type linear encoder. The

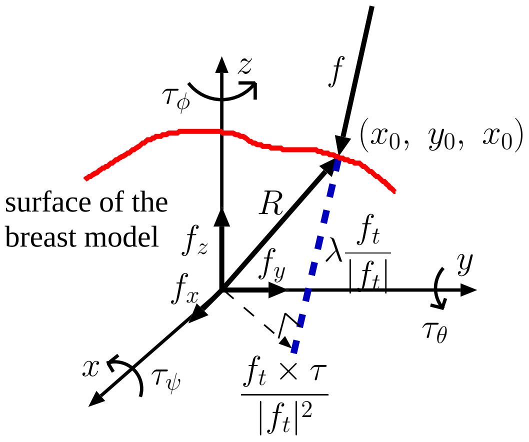


Figure 4: Geometrical model

A/D converter is of 12 bit resolution.

A control signal u calculated every sampling period(5 ms) in a computer corresponds to an input voltage of a pressure control valve through D/A converter(resolution of 12 bit), which regulates the pressure of head side chamber. The piston rod side chamber is pressurized at constant pressure. Supply pressure p_s is set to be 400 kPa. Control algorithm is implemented based on RT-Linux.

Detection of Contact point

Fig.4 shows the geometrical model of breast surface, where contact force $\boldsymbol{f}$ is applied at a contact point represented by position vector $\boldsymbol{R} = [x_0, y_0, z_0]^T$.

As you see that, force vector $\boldsymbol{f}$ is simply derived from the balance of translational force around the origin of $\boldsymbol{h}$ as

$$\boldsymbol{f} = \boldsymbol{f}_t \tag{1}$$

As shown in Fig.4, position vector $\boldsymbol{R}$ can be described using an arbitrary parameter λ as the following equation[4].

$$\boldsymbol{R} = \frac{\boldsymbol{f_t} \times \boldsymbol{\tau}}{|\boldsymbol{f_t}|^2} + \lambda \frac{\boldsymbol{f_t}}{|\boldsymbol{f_t}|} \tag{2}$$

Up to the former work, we assumed that the surface of breast model could be expressed by numerical formula and we obtained $\boldsymbol{R}$ by substituting Eq.2 into that formula, therefore the shape of the breast model is limited to be a simple geometric one like a spherical shell[5].

In this study, a novel scheme to detect contact point is proposed to eliminate the geometric limitation in the former work based on an idea of graphical intersection test.

When we design a geometric breast model using 3-D CAD at a computer, an output file of "DXF file" is obtained, which is widely used as a standard CAD data file. In this study, this DXF file is utilized not only to manufacture the actual breast model at a modeling machine but also to detect contact point.

```
  0
SECTION
  2
ENTITIES
  0
3DFACE
  8
  3
 10 //...the 1st point x coordinate value
103.669060
 20 //                 y coordinate value
0.211670
 30 //                 z coordinate value
0.000008
 11 //...the 2nd point x coordinate value
103.632797
 21 //                 y coordinate value
0.000122
 31 //                 z coordinate value
0.000008
 12 //..the 3rd point  x coordinate value
104.156570
                    .
                    .
                    .
```

Figure 5: Sample of DXF file

DXF file is a text type one as shown in Fig.5 and it contains position data of all polygon which form the surface of a breast model. Begin with a phrase of "3DFACE", the x, y, z position of each vertex of a polygon is described in the sequence and these "3DFACE" notation blocks are described for all polygons.

Therefore by repeating a trial of intersection test between one polygon and a line vector shown as blue dot line in Fig.4 for all prisons, contact point can be detected[6].

COMPLIANCE DISPLAYING SCHEME

Control system

Fig.6 shows the proposed position based compliance control system[5]. The measured force/moment $\boldsymbol{F_m}$ is fed back through a compliance matrix K^{-1} =

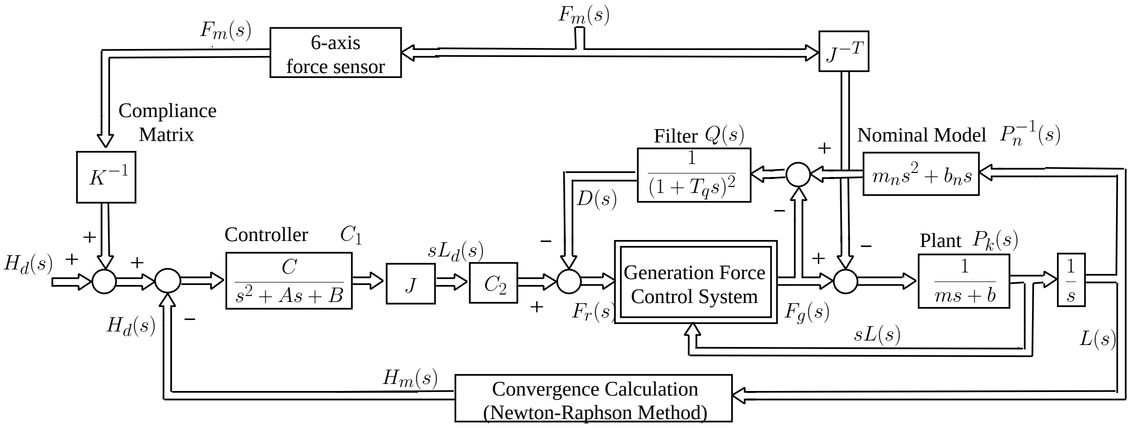


Figure 6: Compliance control system

$diag[K_x^{-1}, K_y^{-1}, K_z^{-1}, 0, 0, 0]$. The inner position control system is designed in order that the closed loop transfer function may follow the 3rd order system shown in Eq.(3).

$$\frac{\boldsymbol{H}}{\boldsymbol{H_d}} = \boldsymbol{G_r} = diag\left\{\frac{C}{s^3 + As^2 + Bs + C}\right\} \quad (3)$$

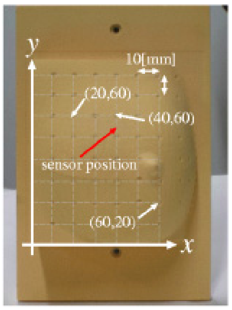
The inner block with a doublet represents a force control system of generating force F_g based on disturbance observer, which works to lower the influence of piston rod velocity that acts as disturbance on force response as well as to make F_g to follow to the reference value with time constant T_{pn}[5].

EXPERIMENTAL RESULTS

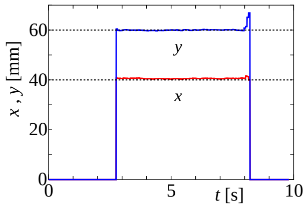
Detection property of contact point

Fig.7 shows the result of contact point detection. As shown in figure (a), small hollows are arrayed on the surface of a breast model in a lattice with 10 mm intervals and force is applied at these hollows in normal direction for the surface. Figure (b), (c), (d) show the detected contact point for (x,y)=(40mm,60mm)(most closer to sensor), (20mm,60mm) and (60mm,20mm)(most apart from sensor), respectively. A force/moment sensor is mounted at a position of (40mm,50mm). A large detection error(maximum 2 mm in the case (d)) can be confirmed as the contact point apart from the point of a force/moment sensor. Improvement of detection accuracy is under the current consideration.

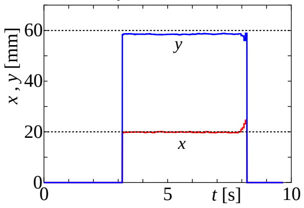
The contact detection property for continuous following contact motion as shown in Fig.8 is also verified. Fig.9 shows the static pictures cut out with 0.1 s interval on OpenGL graphic screen, where a white line shows the contact force vector. The state of continuous contact motion is well confirmed.



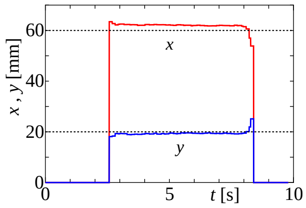
(a) breast model with arrayed hollow



(b) x=40[mm],y=60[mm]



(c) x=20[mm],y=60[mm]



(d) x=60[mm],y=20[mm]

Figure 7: static contact point detection

Compliance control property

First the basic compliance control property is verified. Through actual measurement of breast stiffness of a subject(woman,36 years old), the stiffness is obtained to be about 0.03 N/mm on an average. It is said that the stiffness of lump is as about 5 times stiff as that of peripheral region of lump. Therefore we set the reference stiffness of lump as 0.15 N/mm and that of peripheral region as 0.03 N/mm.

Fig.10 shows the basic compliance control property, where all of the stiffness K_x, K_y, K_z are set as equal

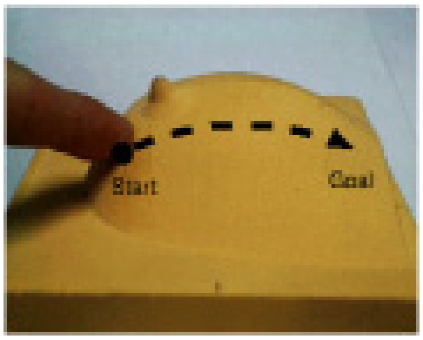


Figure 8: Continuous contact motion

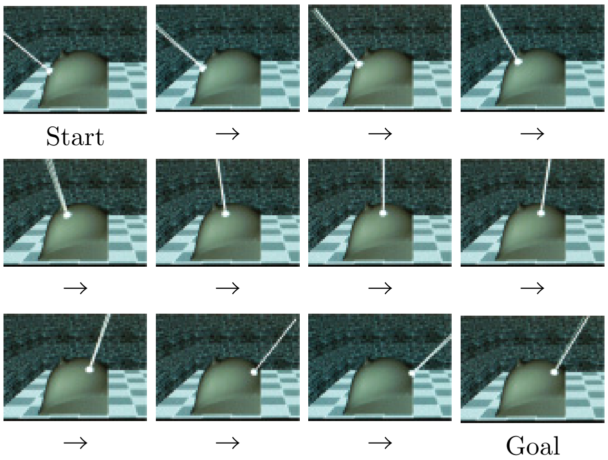
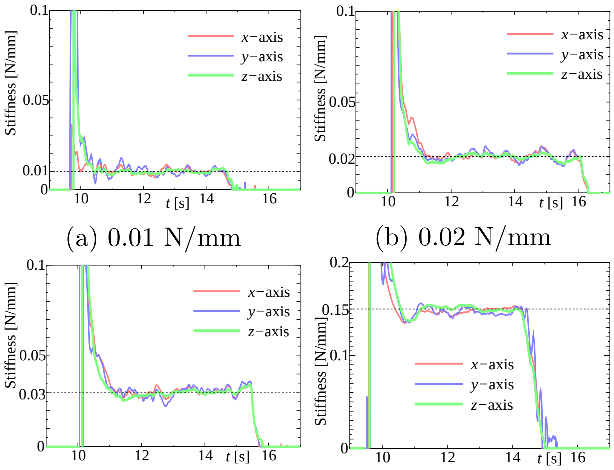
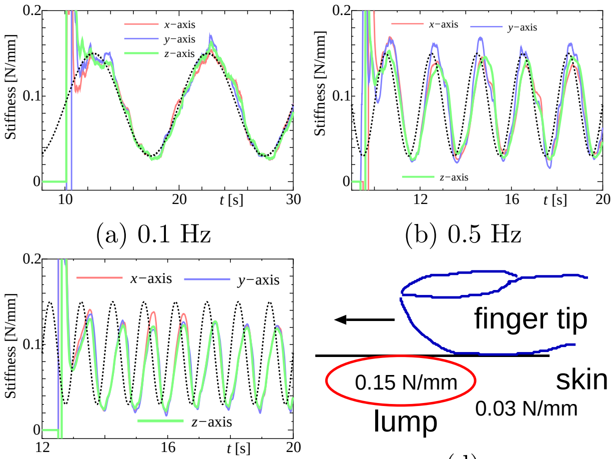


Figure 9: Contact point detection for continuous motion



(a) 0.01 N/mm (b) 0.02 N/mm (c) 0.03 N/mm (d) 0.15 N/mm

Figure 10: compliance control property (for static state)



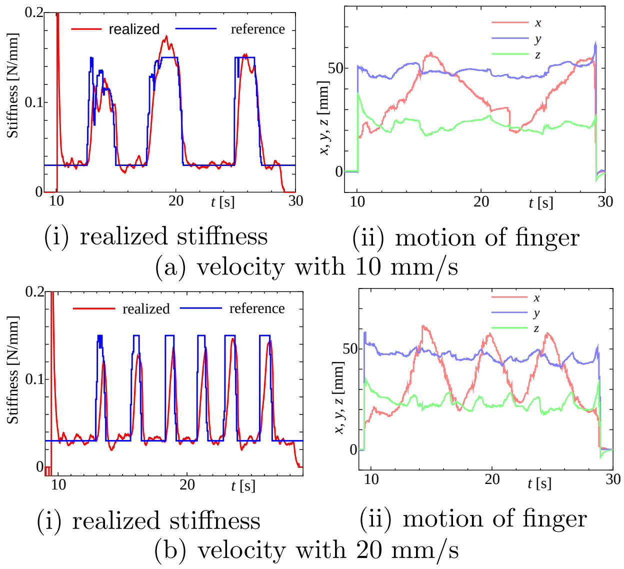
(a) 0.1 Hz (b) 0.5 Hz (c) 1.0 Hz (d)

Figure 11: compliance control property (for sinusoidal variation)

and a force is applied for the direction in order that the displacement for all x, y, z axis may become almost equal. The minimum realizable stiffness was 0.01 N/mm as shown in Figure (a) and it is confirmed that the stiffness can be regulated every 0.01 N/mm from Figure (a), (b) and (c). By the way, a most popular force displaying device on the market, PHANTOM Desktop, has a minimum realizable stiffness of 1.5 N/mm, which show that our palpation simulator can display 1/150 times soft feature as that of this market device. The reference stiffness of lump(0.15 N/mm) and that of peripheral one(0.03 N/mm) is confirmed to be realized in the steady state. Happening of large stiffness at transient time is mainly caused by a positioning response lag.

Fig.11 shows the compliance control property, where reference stiffness is changed from 0.03 to 0.15 N/mm for several angular frequency. Until the stiffness change with 0.5 Hz, almost the reference stiffness can be realized, which corresponds to the case, for example, that human can feel lump with 20mm diameter of 0.15 N/mm stiffness by moving over by their finger with velocity of 10mm/s as shown in figure (d).

Fig.12 shows the recognition property of virtual lump. A sphere with diameter of 20 mm as a lump model is considered within the breast model and human traces over the lump by reciprocating motion in parallel with x axis. The spatial position of finger is obtained by the contact point of breast model and position/orientation of parallel manipulator. The figure (a) and (b) correspond to the case of moving velocity of 10 mm/s and 20 mm/s, respectively. In both figures, (i) shows the realized stiffness(red line) and (ii) expresses the trajectory of finger tip. As mentioned in the former experiment of Fig.11, almost satisfactory recognition property can be confirmed for the case of motion of 10 mm/s. However for the case of smaller lump such as 10 mm diameter, which equiva-



(i) realized stiffness (ii) motion of finger
(a) velocity with 10 mm/s
(i) realized stiffness (ii) motion of finger
(b) velocity with 20 mm/s

Figure 12: recognition of lump

lent to the case of (b)(20 mm diameter with 20 mm/s motion), the recognition property is lowered. This is mainly caused by a dynamics of inner position control system and that control system is cased by pressure response lag. Further improvement in the dynamic recognition is under consideration.

CONCLUSION

In this study, we developed a mechanical equipment to be applied as a palpation simulator using a pneumatic parallel manipulator.

We proposed a contact point detection scheme using an idea of graphical intersection test, which brought an advantage that any form of 3-D model could be applied as the object surface. Consequently the palpation simulator for, such as, stomach or abdomen can be developed.

Compliance control system is constructed on a parallel manipulator to display desired compliance corresponds to that of lump.

Through some experiments, control performances both in detecting the contact point and in displaying the reference stiffness are confirmed. The minimum realizable stiffness is attained to be 0.01 [N/mm] and the stiffness can be regulated with a resolution of 0.01 N/mm.

The further improvement of compliance displaying performance for the recognition in dynamic motion to feel a realistic lump is under the current investigation.

Acknowledgment

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References

[1] *T.Kitagawa, H.Tsukuma et al*, Prediction of cancer incident in Japan, *Cancer statistics 1999, Shinohara Shuppan, Tokyo*

[2] *V.Daniulaitis, M.O.Alhalabi, H.Kawasaki, Y.Tanaka, T.Hori*, Medical Palpation of Deformable Tissue using Physics-Based Model for Haptic Interface RObot(HIRO), *Proc. of 2004 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp.3907-3911*

[3] *K.Inoue, R.Uesugi, T.Arai, Y.Mae*, Development of Haptic Device Using Flexible Sheet, *Journal of Robotics and Mechatronics, Vol.15, No.2, pp.121-127, 2003*

[4] *J.K.Salisbury, Jr.*, Interpretation of Contact Geometries from Force Measurements, *Proc. of*

[5] *M. Takaiwa and T. Noritsugu*, Development of Force Displaying Device Using Pneumatic Parallel Manipulator and Application to Palpation Motion, *Proc. of ICRA 2003, CD-ROM pp.4098/4103*

[6] *Samuel R. Buss*, 3-D Computer Graphics, *CAMBRIDGE UNIVERSITY PRESS, pp.99-107, 260-263, 2003*

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