The Sixteenth International Symposium on Artificial Life and Robotics 2011 (AROB 16th '11),
B-Con Plaza, Beppu,Oita, Japan, January 27-29, 2011

Development of 6-DOF Force Feedback System for Rehabilitation of Wrist Paralysis

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Abstract: The increasing number of paralyzed persons and a shortage of the physical therapist is becoming an increasing problem, focusing attention on rehabilitation support. Noting the increase in wrist paralysis, we are developing corresponding rehabilitation support. Our basic approach centers on force feedback system based on the parallel 6-degree-of-freedom (DOF) Stewart platform. In this paper, we focus on the generation of a desired force which is a resultant force of the six cylinder forces of the parallel mechanism. Also we focus on drawing a 3D computer graphic (CG) model which shows harmonic movement with the parallel mechanism in virtual space. It is the feedback information for wrist rehabilitation. In this paper, we show that the experimental results of the desired for ce generation and the 3D-CG model moves harmonically with the parallel mechanism assigned distance place via the Local Area Network.

Keywords: Stewart type parallel mechanism, six degree of freedom,

I. INTRODUCTION

For the cases of persons afflicted with paralysis increasing, due to adult disease, traffic accidents and aging, the shortage of physical therapists is a growing problem requiring rehabilitation support. In our focus on wrist paralysis, we considered rehabilitation support, requiring multiple degrees of freedom (DOF) and compactness, taking into account the parallel Stewart platform, which generates 6-DOF force and provides high power and rigidity [1]. It applies 6-DOF force to wrist of a patient through a gripper on the platform for rehabilitation therapy instead of the physical therapist.

In our past research, we developed a prototype of the parallel Stewart platform with six pneumatic air cylinder actuators and achieved the thrust control of individual pneumatic cylinder by a pulse width modulator (PWM) control [2]. The goal of our research is that one physical therapist can treat multiple patients at the same time by remote controlling the parallel mechanisms. To achieve the purpose, it is necessary that the parallel mechanism can output the desired force on the platform gripper. It is also necessary that the physical therapist can see the situation of rehabilitation treatment.

This paper focuses on controlling force act on the platform gripper. It is a resultant force of six pneumatic cylinder forces. Thus, to generate a desired force on the platform gripper, the component forces generated by individual cylinders must be calculated. They are calculated by solving six simultaneous equations representing static force relationships.

This paper also focuses on drawing a 3D computer graphic (CG) model showing synchronized movement with the parallel mechanism in virtual space. It is the feedback information for wrist rehabilitation. The therapist can recognize the situation of treatment at a distant place on real time by viewing the movement of the 3D-CG model. The model is drawn from the 6-DOF attitude information. It is calculated by solving direct kinematics of the parallel mechanism with data on cylinder length. From the calculation result, the PC draws a similar parallel mechanism which shows the synchronized movement with the real one in a virtual workspace displayed.

The desired force generation and 3D-CG model drawing can be achieved for the parallel mechanism assigned a distance place via LAN by using the TCP/IP connection.

This paper is organized as follows: Section 2 introduces the system configuration. Section 3 focuses on controlling force act on the platform gripper and gives the results of force control experiments. Section 4 focuses on drawing a 3D-CG model of the parallel mechanism and shows that the 3D-CG model moves harmonically with the parallel mechanism assigned distance place via the Local Area Network. Section 5 is conclusions.

Ⅱ. SYSTEM CONFIGURATION

Figure 1 shows the force feedback configuration we propose, which consists of a pneumatic parallel mechanism and two personal computers (PC). The one is for the physical therapist and the other is for a patient. The parallel mechanism is connected with the patient side PC through I/O board. These PCs communicate with each other by TCP/IP via LAN. When a desired force which will act on the platform gripper is input at the therapist side PC, six cylinder forces corresponding to the desired force are calculated by solving six simultaneous equations representing static force relationships. The calculated cylinder forces are sent to the patient side PC and translated into PWM signals and sent to twelve solenoid valves mounted the parallel mechanism. Each cylinder has two valves and one is used for pushing the cylinder and the other is for pulling. The force resulting from six cylinders should be equivalent to the desired force.

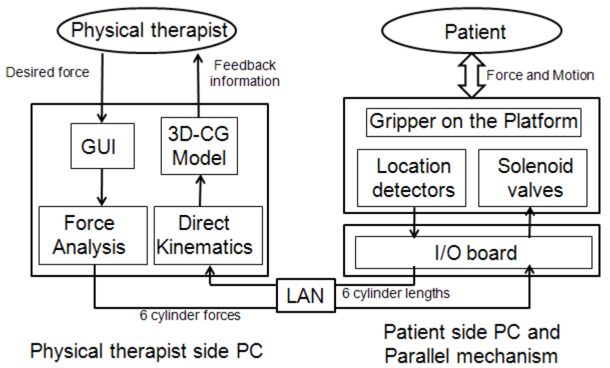

Fig1. Force feedback configuration

When the parallel mechanism is moved, the patient side PC detects the six cylinders length by the six location detectors, each of which is mounted on the cylinder. The patient's PC sends the cylinder length data to the physical therapist side PC. The therapist side PC calculates the parallel mechanism attitude by solving the direct kinematic equations with the cylinder data. From calculation results, the therapist side PC draws a 3D-CG model of the parallel mechanism. It shows the movement synchronized with the real parallel mechanism in a virtual work space displayed. The CG model in virtual space is drawn using OpenGL.

By this way, the physical therapist can see the situation of rehabilitation treatment in detail even if he isn't around the patient. Moreover, if multiple parallel mechanisms are prepared, it is expected that one physical therapist can treat multiple patients at the same time by sending rehabilitation commands to the individual parallel mechanisms of the patients.

Ⅲ. FORCE GENERATION

To generate a desired force on the gripper, cylinders must generate the component forces of output by the six equations representing the relationship of static force act on the gripper, shown in Figure 2.

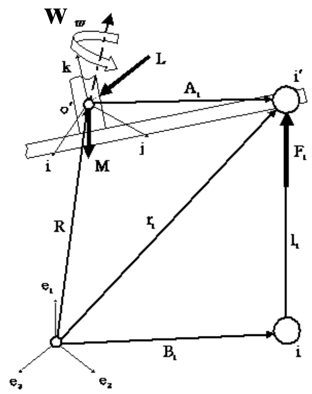

Fig2. Analytical model of parallel mechanism

These are i-th cylinder force $\mathbf{F}_i$ $(i=1,\ldots,6)$, desired output force $\mathbf{L}$, desired moment $\mathbf{w}$ and force of gravity $\mathbf{M}$. These force vectors have coordinates (F_{ix}, F_{iy}, F_{iz}), (L_x, L_y, L_z), (w_x, w_y, w_z) and $(0, 0, -mg)$ for the fixed frame, m is platform mass and g is gravity acceleration.

The static force relationship for translational movement is as follows:

$$\sum_{\mathbf{i}=\mathbf{1}}^{\mathbf{6}} \mathbf{F_i} + \mathbf{L} + \mathbf{M} = \mathbf{0}\,. \tag{1}$$

For rotational movement, the relationship is as follows:

$$\sum_{i=1}^{6} (\mathbf{r}_i \times \mathbf{F}_i) + (\mathbf{R} \times \mathbf{L}) + (\mathbf{R} \times \mathbf{M}) + \mathbf{w} = \mathbf{0}\,. \tag{2}$$

Eq.(1) and Eq.(2) are the six simultaneous equations for cylinder force $\mathbf{F}_i$, and solving them by using following relationship

$$(F_{ix}, F_{iy}, F_{iz}) = \frac{\mathbf{F_i}}{\sqrt{{l_{ix}}^2 + {l_{iy}}^2 + {l_{iz}}^2}} (l_{ix}, l_{iy}, l_{iz})\ ,$$

the component forces $\mathbf{F}_i$ of the desired output $\mathbf{L}$ and desired moment $\mathbf{w}$ are obtained. When a desired force is input at the physical therapist's PC, $\mathbf{F}_i$ are calculated by above analysis, sent to the patient's PC. At patient's PC, they are translated into PWM signals to control the solenoid valves [2].

The force control experiments are conducted and results are presented. Figure 3 shows the overall view of force control experiments for the pneumatic parallel mechanism.

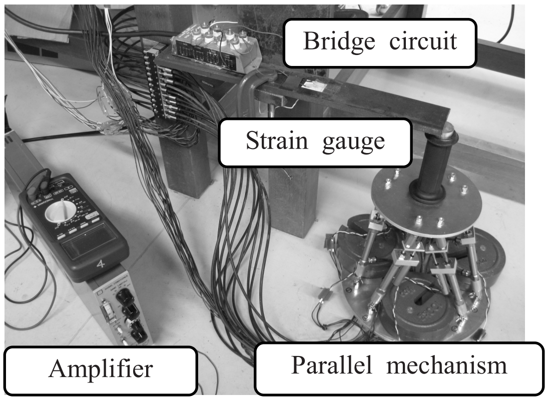

Fig.3: Parallel mechanism experiments

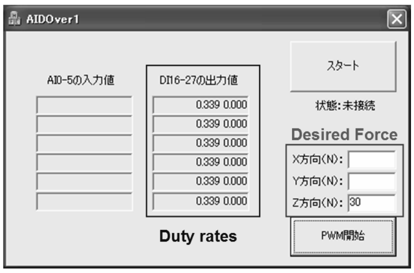

Fig4. Force controller interface

Figure 4 is the interface of the force input on the physical therapist' PC. Inputting components of a desired force along x, y and z direction, corresponding duty rates for the twelve solenoid valves are calculated and sent to the I/O board. Also, these values are displayed on the interface.

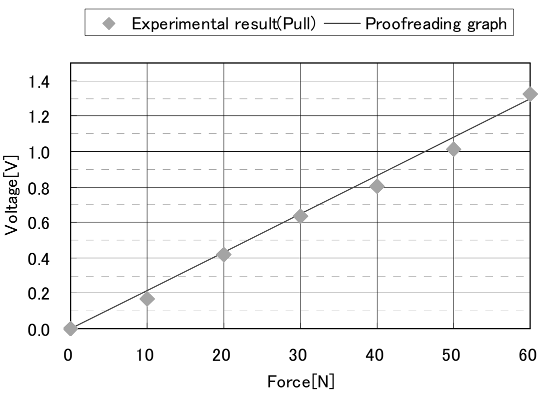

Fig.5: Experimental results (z direction (+))

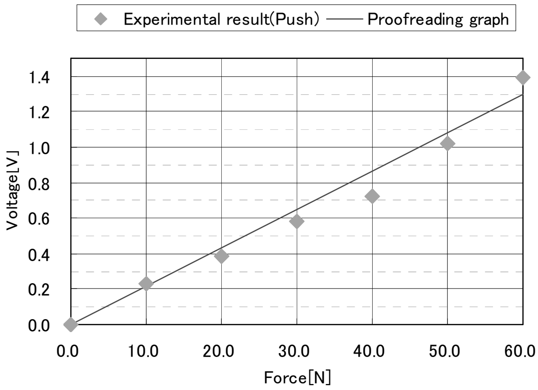

Fig.6: Experimental results (z direction (-))

Figure 5 shows the results for plus direction and Fig. 6 for minus direction. Initial positioning is adjusted as neutral position (cylinder expansion and contraction: 15mm) and supply pressure is 0.15Mpa. For both directions, measurement and proofreading results coincide well confirming that arbitrary force is generated in the z direction.

Ⅳ. 3D-CG DRAWING BASED ON DIRECT KINEMATICS

To draw a 3D-CG model showing the movement synchronized with the parallel mechanism, it is necessary 6-DOF attitude information of the platform. The parallel mechanism has six location detectors detecting each cylinder length. Thus, by solving the direct kinematics of the parallel mechanism with data on cylinder length, 6-DOF attitude can be obtained.

Figure 3 is i-th cylinder vector diagram. $\mathbf{o}$ is the origin of the fixed frame, $\mathbf{o}'$ is the origin of the motion frame assigned at the centroid of the platform. It shows a relationship as follows:

$$\mathbf{l}_i = \mathbf{A}_{im}T + \mathbf{R} - \mathbf{B}_i \quad (3)$$

Where, $\mathbf{l}_i$ is a cylinder vector, $\mathbf{R}$ is a position vector of centroid of the platform, and $\mathbf{B}_i$ is a position vector of lower attachment point and there vectors are with respect to the fixed frame. $\mathbf{A}_{im}T$ denotes upper attachment point with respect to the motion frame and the coordinate transform matrix T is

$$T = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi - \sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{bmatrix}$$

, where, ϕ, θ, and φ are "roll", "pitch", and "yaw" angles of the platform with respect to the motion frame.

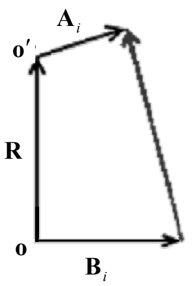

Fig3. Vector diagram for i-th cylinder

Here, let l_{if} be the measured value of i-th cylinder vector and $\boldsymbol{\alpha}$ be the vector of the platform attitude and define a function $\mathbf{f}(\boldsymbol{\alpha})$ as follows:

$$\mathbf{f}(\boldsymbol{\alpha}) = \left(f_1(\boldsymbol{\alpha}), f_2(\boldsymbol{\alpha}), f_3(\boldsymbol{\alpha}), f_4(\boldsymbol{\alpha}), f_5(\boldsymbol{\alpha}), f_6(\boldsymbol{\alpha})\right)$$
$$f_i(\boldsymbol{\alpha}) = A_{im}A_{im}{}^T + RR^T + B_iB_i^T$$
$$+2RT^T A_{im}{}^T - 2\psi B_i T^T A_{im}{}^T - 2RB_i^T - l_{if}{}^2 = 0$$
$$\boldsymbol{\alpha} = (x, y, z, \phi, \theta, \psi)^T \qquad i = 1,...,6 \tag{4}$$

Equation (4) is a couple of nonlinear 6 dimensional equations and it is difficult to derive the solution $\boldsymbol{\alpha}$ by any analytical ways. Thus, by using the Newton-Rapthon method which is one of a numerical method, approximate solution of $\boldsymbol{\alpha}$ is derived.

Let $\boldsymbol{\alpha}^{(n)}$ be an approximate solution which is in the n times iterations and applied the Newton-Rapthon method to the Eq. (4), following equation is obtained.

$$\mathbf{M}\left(\boldsymbol{\alpha}^{(n+1)} - \boldsymbol{\alpha}^{(n)}\right) = -\mathbf{f}\left(\boldsymbol{\alpha}^{(n)}\right) \tag{5}$$

Where, $\mathbf{M}$ is a matrix of the partial differentiation of $\mathbf{f}\left(\boldsymbol{\alpha}^{(n)}\right)$.

By solving Eq. (5) iteratively, approximate solution of $\boldsymbol{\alpha}$ can be derived.

By this way, PC of the force feedback system calculates the 6 DOF attitude of the platform. From the result, it draws the 3D-CG model of the parallel mechanism.

Figure 7 is set of the still images of the 3D-CG model and the parallel mechanism. These pictures are clips of the experiment of the synchronized movement.

In this figure, the parallel mechanism is moved by hand. It is shown that the 3D-CG model moves synchronized with the parallel mechanism.

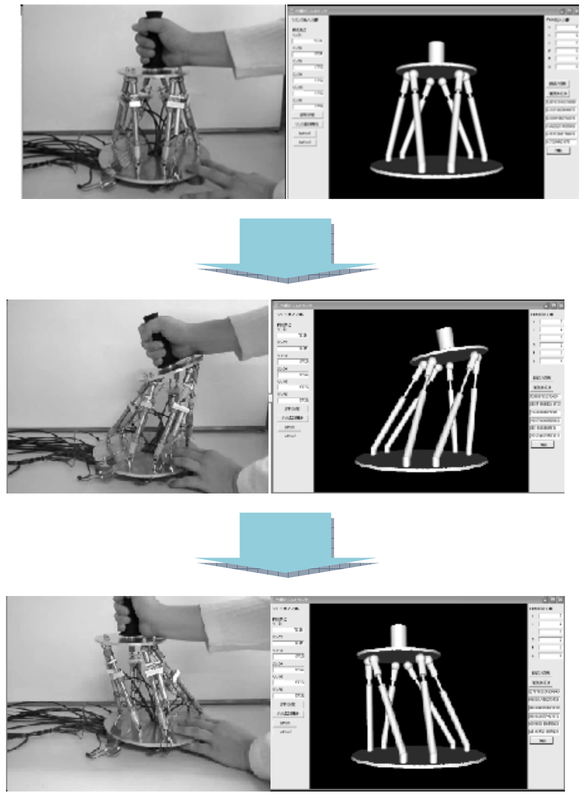

Fig7. Experiments of harmonic movement

Ⅵ. CONCLUSION

In this paper, for the development of the force feedback system applied to the wrist rehabilitation support system, generating desired force act on the platform gripper was detailed. Also, drawing a 3D-CG model showing the movement synchronized with the parallel mechanism in virtual space was detailed. These can be achieved for the parallel mechanism assigned a distance place via LAN by using the TCP/IP connection.

In projected works, we plan to measure force for other direction, to display detail information on the 3D-CG model, like force value, vector image of force, etc.

References

[1] Stewart, D., A Platform with 6 degrees of freedom, Proc. Inst. Mech. Eng., Vol.180, Part I, No.15, pp.371-386, 1965-66.

[2] Hitaka, Y., Tanaka, Y., Tanaka, Y., Ishii, J., Development of 6DOF Force Feedback System with Pneumatic Parallel Mechanism, Proceedings of the 15th International Symposium on Artificial Life and Robotics in Beppu, Japan(2010).