Active link mechanisms for physical man-machine interaction

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Abstract— **In this paper, we propose a new type of haptic interface, named active link mechanism. This device realizes Physical Man-machine Interaction (PMI) between machines and persons. Two prototypes were developed to demonstrate the potential of the active link mechanisms. Developed interface devices are an active tetrahedron and an active icosahedron. Nine-DOF micro spherical joints and pressure control pneumatic cylinders were developed to realize the active tetrahedron, while fifteen-DOF micro spherical joints and intelligent pneumatic cylinders were developed for the active icosahedron. The tetrahedron successfully realizes "virtual touch"; the operators feel actions, forces, and shapes of the virtual objects in PC and also move and deform them. Real time PMI is realized by building the developed devices into MSC.VisualNastran4D. MSC.Visual-Nastran4D is a mechanism analysis software, which can make motion analysis in real time. The active icosahedron also realized dynamic interaction with virtual objects in PC, showing the potential of the devices as a haptic interface.**

Keywords- active link mechanism; PMI; haptic interface

I. Introduction

The research aims at designing and developing a new type of haptic mechanisms realizing physical man-machine interaction with virtual continuous objects involving distributed information of force and deformation.

Haptic devices are applied to various situations such as medical rehabilitation, E-learning, web contents and so on. Many researchers have developed variety of haptic interface for various applications. Those interfaces are classified into six groups as follows, arm type, parallel link type, mouse type, wearable type and other type. PHANTOM [1] is a typical model classified into arm type. As parallel link types, there are a force-displaying device using pneumatic parallel manipulator [2] and a compact six DOF haptic interface [3] and so on. As mouse types, there are 2 DOF flat actuator for tactile display [4], active mouse [5,6] and so on. As wearable types, there are spider-8 [7] and so on. As other types, there are electro magnetically driven high-density tactile interface [8] and Digital Clay [9] and so on.

Focusing on the device appearance, haptic interfaces are divided into concentrated models and distributed models. Arm types, parallel link types and mouse types are classified into a category of concentrated model, which shows physical information at one point. Wearable types and some of other types are classified into distributed models, which deal with distributed physical information. The number of distributed types is relatively smaller than that of concentrated models.

Attempts to realize high-performance haptic interfaces have been made by many researchers. Key components are micro functional devices such as micro actuators, micro sensors, and micro mechanical elements. By integrating these devices haptic interfaces can realize presentation of finer deformation, forces and movement. These days micro/MEMS devices are commercialized and easily obtained. We aim at realizing a haptic device by building these micro/MEMS devices into it.

As shown in Figure 1, physical man-machine interaction (PMI) [10] is based on bilateral physical information exchanges between man and machine. Most of conventional man-machine interfaces except for haptic interfaces deal with one-way physical information from man to machine.

Sensors and actuators have been downsized and enable to be built into small haptic devices. Those devices permit physical man-machine interaction with information of shape, motion, force, stiffness and inertia bi-directionally. Operators can feel "virtual touch" of virtual objects simulated in PC and give them physical influences through these interfaces.

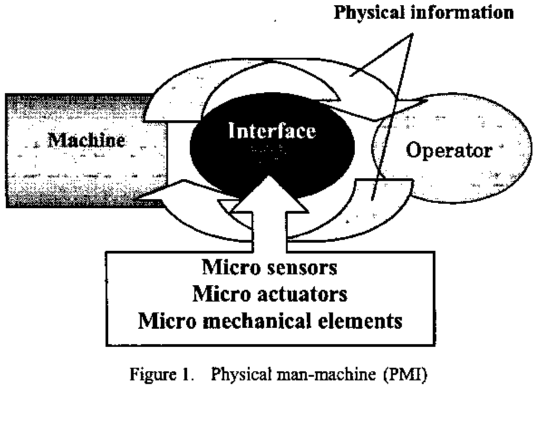

Figure 1. Physical man-machine (PMI)

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II. DESIGN OF ACTIVE POLYHEDRONS

A. Restrain Conditon

Before designing a link mechanism we need to analyze its mechanical restrain condition to decide its form uniquely by length of links. In the case of building active polyhedron, the condition to decide its shape is that planes of polyhedron are triangles. The condition is derived from geometrical analysis. This leads that regular polyhedrons, whose shape depends only on the length of the links are tetrahedron, octahedron and icosahedron.

Generally speaking, degree of freedom of a mechanism is shown as follows:

$$f = 6(n-1) - \sum_{i=1}^{6} (6-i) p_i \qquad (1)$$

where f represents degree of freedom of the mechanism, n represents the number of machine elements and p_i represents the number of pairing elements that have i degree of freedom. We applied the law to an active tetrahedron and an active icosahedron.

Before applying the equation (1) to active polyhedrons, we assume as follows: (1) a joint of each apex consists of spherical joints, (2) one of the spherical joints is fixed to base not to move, (3) the joint corresponding to the each apex is small enough to neglect its mechanical play, and (4) an active polyhedron consists of liner actuators with one DOF paring elements.

B. Design of an Active tetrahedron

The number of machine element of active tetrahedron is twelve because the tetrahedron consists of 6 pneumatic cylinders. The number of one DOF paring elements, P_1, is 6. The number of three DOF paring element, P_3, which comes from spherical joint's DOF, is twelve in total. Applying these numbers to equation (1), the result is found to be twelve.

Six of these twelve DOF mean spherical joint's rotation around the axis of cylinder. They have no effect on the shape of an active tetrahedron. And the other DOF means expansions of the cylinders. Thus the shape of the active tetrahedron can be controlled uniquely by the length of cylinders.

C. Design of an Active Icosahedron

In the same way we can calculate DOF of an active icosahedron. The numbers of the machine elements, one-DOF paring elements, and three-DOF paring elements are 60, 30, and 48, respectively.

Applying those numbers to Eq(1) results in sixty DOF. Thirty of those sixty DOF come from cylinder rotation. Those DOF have no effect on shape of the icosahedron. The other thirty DOF mean expansions of the cylinder. Therefore the shape of the active icosahedron is controlled by the cylinder length.

D. Simple model of Icosahedron

We can confirm how the icosahedron mechanism changes its shape by using simple model. As shown in Figure 2, the icosahedron model shown at upper left can be modified to various shapes. The model at upper left shows normal shape with all links contracting .The model at the upper right is formed like a rugby ball. At the lower left the model is very flat. This shape can become very flat holding down. The other model shows expansion shape.

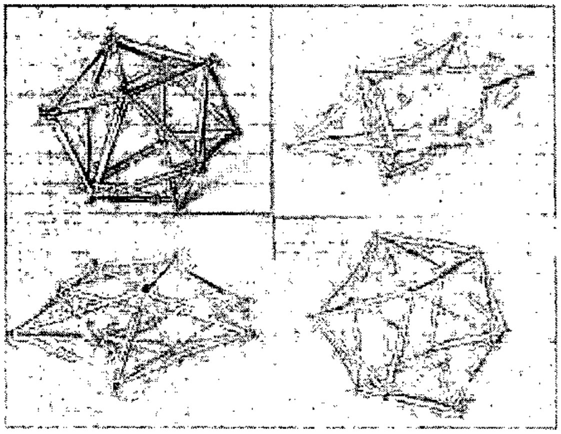

Figure 2. Simple model of icosahedron

III. DESIGN AND EXPERIMENTS OF THE ACTIVE TETRAHEDRON

Figure 3 shows a prototype model of active tetrahedron. It consists of six pneumatic cylinders, six liner encoders and four spherical joints. Active links are connected by spherical joints. The length of cylinder is 180 mm in normal and the moving stroke is 40 mm. Motions of cylinders are detected by liner encoders mounted on the cylinders. The cross sectional area of the pneumatic cylinder is 28.3 mm^2. The diameter of a pneumatic tube is 2 mm and it makes the size of link mechanism reduced

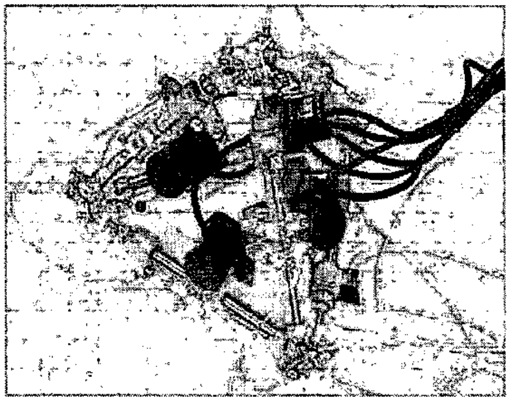

Figure 3. Active tetrahedron

A. Spherical joint for active tetrahedron

One key component realizing active polyhedron is spherical joint with multi degree of freedom. Figure 4 shows the spherical joint for the active tetrahedron. This joint has nine DOF in total. It consists of three teflon balls and three aluminum plates. Teflon balls are mounted on each end of pneumatic cylinder and piston, enabling free-orientation of the cylinders in every direction. Moving range of the joint is 49 degree in vertical direction and 30 degree in horizontal direction.

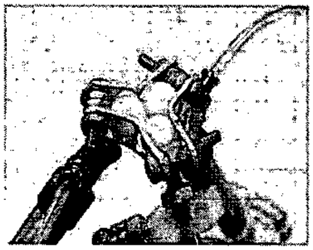
Figure 4. Micro spherical joint for active tetrahedron

B. Control system of active tetrahedron

A control system of active tetrahedron as shown in Fig. 5 consists of a virtual model in PC, a control board, a pneumatic pressure controller and an active tetrahedron. On the display the virtual model is shown by a mechanical simulator. The control board exchanges the data between PC and external devices such as the pressure controller and the active tetrahedron. The board also supplies power to these devices. The pressure controller has six valves and controls the active links of tetrahedron.

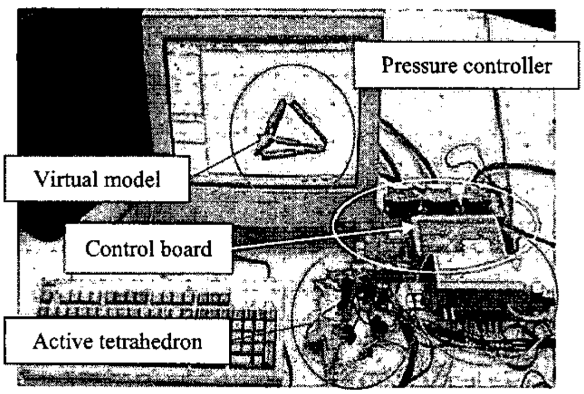

Figure 5. Appearance of active tetrahedron system

As shown in Fig. 6 key components of this system are an active tetrahedron, V/P controllers (pneumatic pressure valves), driver program and a linkage mechanism simulator, Visual Nastran4D. Shape of the active tetrahedron deformed by an operator is detected with the liner encoders, and is sent to the driver through the counter board, while axial force acting on the cylinder is acquired with the pressure sensors and is sent to the driver program. The driver program receives physical information from the active links and exchanges data with the mechanical simulator. The simulator has a mathematical model of a virtual object that has a same mechanical structure as the active tetrahedron; the mathematical model has characteristic parameters of force, stiffness, shape and motion, which users can set arbitrarily. When an operator deforms the real active tetrahedron, the virtual model in the PC also changes its shape. The driver program receives the results from the simulator promptly. Based on them the driver controls force and length of the pneumatic cylinder through V/P controller. Operator can feel "virtual touch" in real time, with visual information of the model on display.

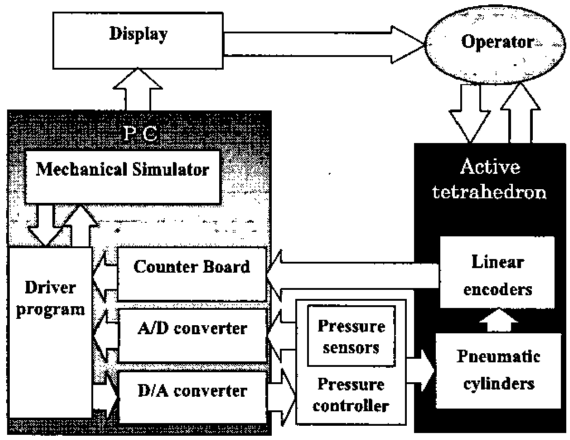

Figure 6. Block diagram of active link mechanism system

C. Interaction using general mechanical simulator

As the first step of this research, we aim at building the system of active tetrahedron into general mechanism simulators. VisualNastran4D is one of the popular mechanical simulators and it comes into wide uses and accepts input data from other programs in real time. Therefore we built the system using VisualNastran4D.

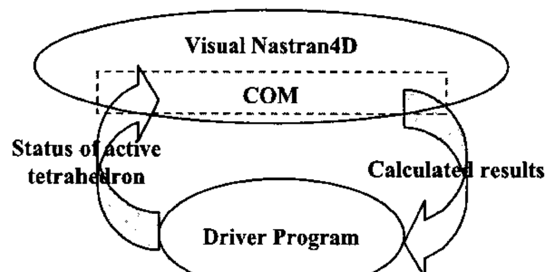

Figure 7. Communication with COM

The role of the driver program is to exchange the data between VisualNastran4D and PC boards, and to control active link mechanisms through pressure controller. This program is coded with Visual Basic. The program, as shown in Fig. 6, communicates with VisualNastran4D by using COM (Component Object Model) that it provides. The program interfaces input/output data with values of internal valuables, which VisualNastran4D has. In other words, the values from the counter board are converted to actual length so as to make VisualNastran4D calculates behavior of the virtual model. Calculated results are converted into voltage value to control pressure controller. Each active link is operated with proportional control. Communicating rate is 50ms.

D. Physical interaction with the active tetrahedron

We conducted the experimental test to confirm that the active tetrahedron system works successfully to realize physical man-machine interaction. When an operator deformed the active tetrahedron, VisualNastran4D calculated kinematics and dynamics to transform the results to the active links and the virtual model in PC. Based on the obtained results the driver program made the operator feel its stiffness, force, motion and shape.

We found two problems in this experimental test. They were still unsatisfactory operationality and time lag between the movements of the actual model and the virtual model. The operator can't skillfully handle the active tetrahedron because the mechanism consists of pneumatic cylinders and this makes difficult the operator to touch the slide parts of the cylinders.

The other problem of time lag occurred because the current driver program doesn't synchronize well with VisualNastran4D. These problems are now at improving stage.

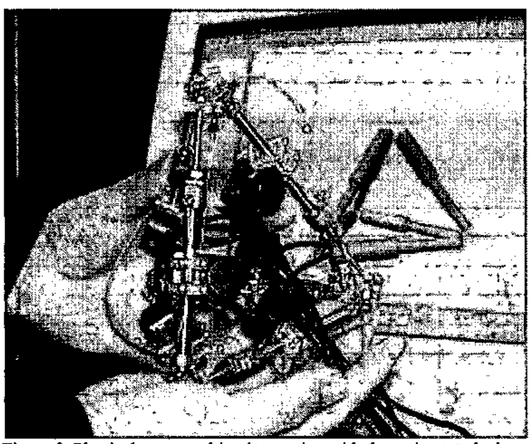

Figure 8. Physical man-machine interaction with the active tetrahedron

IV. Design and Experiments of Active Icosahedron consisting of Inetelligent Cylinders

A. Design of intelligent cylinder with built-in sensor

To build an active icosahedron system, compact servo actuators are essential. We have developed a new intelligent pneumatic cylinder, which has a liner optical encoder in its interior. Developed cylinder is shown in Figure 9. Its length is 135 mm in normal and the moving stroke is 40 mm. Main parts of an intelligent cylinder are a micro encoder, a cylinder rod and a housing fixing the sensor. Code stripes are inscribed in 0.6 mm pitch on the cylinder rod with laser machining so as to detect the cylinder motion with the encoder. Housing holding the encoder is mounted on the end of the pneumatic cylinder.

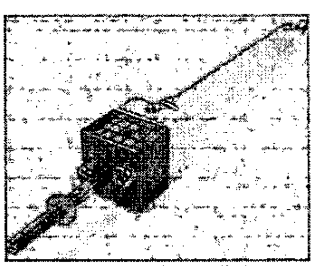

Figure 9. Intelligent cylinder

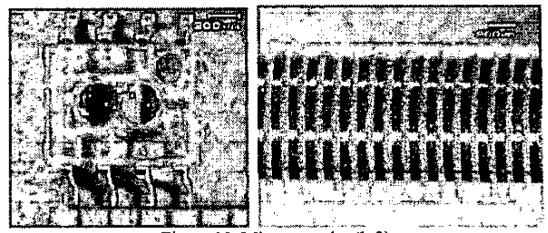

Figure 10. Micro encoder (left) and code stripe on the surface of cylinder rod (right)

Micro optical encoders shown in Figure 10 (left) were built into each pneumatic cylinder to realize analog control of pneumatic cylinder. It has a photodiode and a two-phase photo detector and is 5 by 6 mm in size. This sensor is so small that we can build it into the cylinder system. With illuminating light on the code stripe, the encoder detects the linear displacement and directions of the cylinder rod.

B. Control system of intelligent cylinder

The control system consists of a micro encoder, a generator of PWM (Pulse Width Modulation) pneumatic flow and a counter. Position control is achieved by a feedback loop with proportional control. The block diagram of this system is shown in Figure 11. Duty ratio D is calculated by e comparing the desired value X_d and the cylinder length X_c. Cylinder is driven by PWM generator based on the duty ratio D. Axial force F_c of the cylinder is controlled by pressure P from compressor and duty ratio D.

C. Active icosahedron consisteing of intelligent cylinders

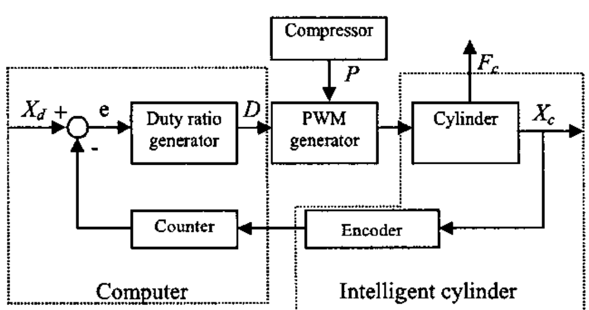

Figure 11. Control system of intelligent cylinder

We built an active icosahedron using the intelligent pneumatic cylinder. The active icosahedron is shown in Figure 12. It has thirty intelligent cylinders and twenty multi-DOF joints. Each cylinder is connected with the joint.

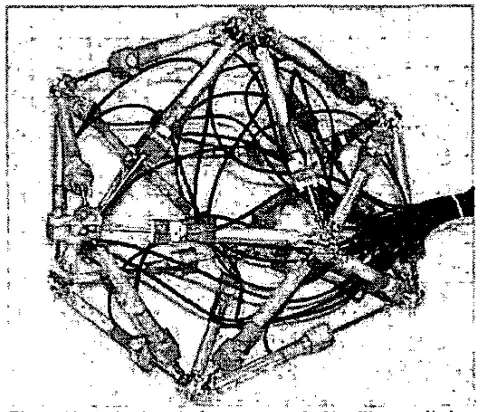

Figure 12. Active icosahedron composed of intelligent cylinders

D. Controll sytem of active icosahedron

Control system of the active icosahedron is shown in Figure 13. The difference between icosahedron system and the tetrahedron system is that icosahedron system doesn't utilize the commercialized mechanical simulator. As mentioned in Section III. D. the mechanical simulator has time lag as an operator interacts in real time. To solve the problem, we developed newly a driver program in the active icosahedron system. The driver program acquires position information from the sensors mounted on the cylinders, controls the intelligent cylinder system in order to present physical information to an operator, and also the shape of the virtual model in PC. OpenGL is used to visualize the virtual model on display. The virtual model follows the same shape as the active icosahedron, reflected its real time motion of the operator.

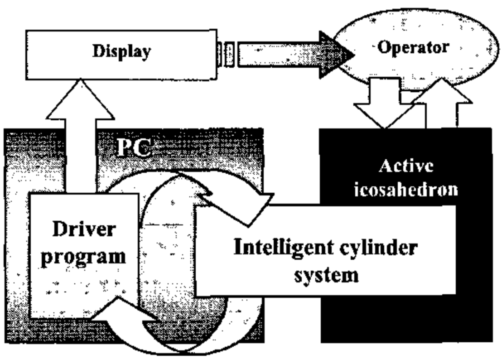

Figure 13. System of active icosahedron

E. Driver program

The driver program controlling intelligent cylinder is shown in Figure 14. X_v is a virtual position vector of virtual model's apexes. X_o is position vector of the apexes of the active icosahedron, which is value obtained from position vector from X_c of the cylinder length. X_e is given from X_v minus X_o. Driving force of each apex of the virtual model Fa is obtained by dynamic equation shown as follows:

$$F_a = (M_v s^2 + D_v s + K_v) X_e \tag{2}$$

where M_v, D_v and K_v represent math, viscosity and elasticity of the virtual model, respectively. Those values can be given arbitrarily to realize desired mechanical characteristics of the model. F_p is obtained as F_a plus F_v, which means virtual force. F_d is obtained by converting F_p to the cylinder base coordinate. F_q is F_d plus F_s that comes from force sensor. F_c is the axial force of the intelligent cylinder. This program enables the active polyhedron to realize physical interaction in real time without time lag.

F. Experiment of Physical man-machine interaction

We tested the active icosahedron to make sure that it realizes real-time PMI. At first we attempt to use it as an input interface to modify the shape of the virtual model. In this experiment we assumed a clay model as a virtual model because clay has high viscosity and it is thought to be better suited for haptic presentation with pneumatic cylinders. The appearance of experiment is shown as Figure 15.

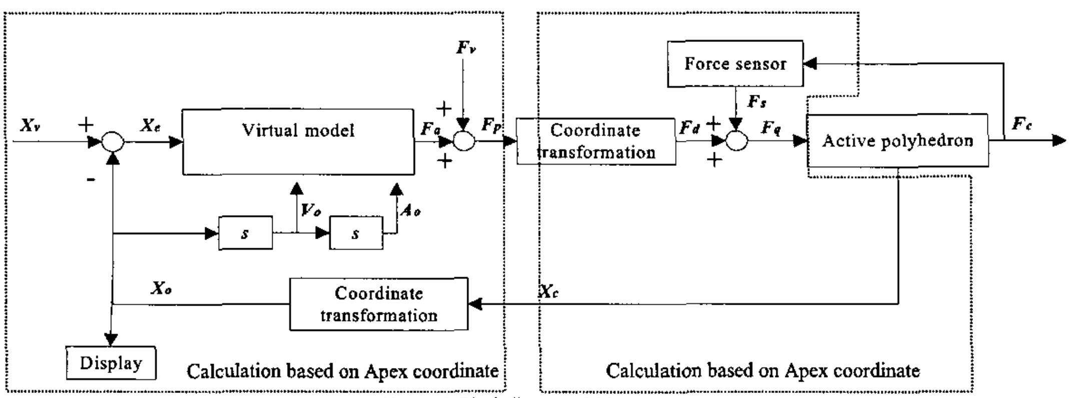

Figure 14. Block diagram of driver program

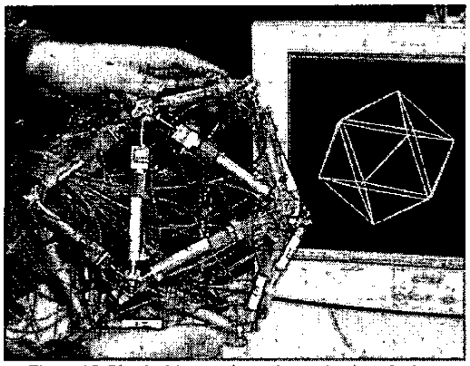

Figure 15. Physical interaction using active icosahedron

It was found that the system successfully worked to realize physical man machine interaction: the operator could (1) modifiy the shape of virtual model, (2) feel deformation of the virtual model, and (3) feel viscosity and stiffness of the virtual model as if he/she actually touched the virtual model.

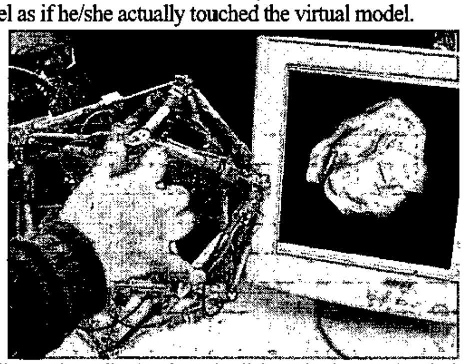

Figure 16. Application the active link mechanism to Virtual Clay

Secondly we attempted to apply the active icosahedron to clay modeling application to demonstrate its potential. The transforming virtual object, we called virtual clay, is 1280 faceplates that is configured by expanding the number of icosahedron's face.

V. CONCLUSIONS

We developed two types of new haptic devices consisting of active link mechanisms and applied them to physical man-machine interaction to prove effectiveness of these devices.

- By analyzing kinematical DOF of general polyhedrons, we made restrains conditions of active polyhedrons clear and showed a designing guide of active polyhedrons with triangle faceplates. It was found that tetrahedron, octahedron, and icosahedron had a potential to work as active link mechanisms.
- Two prototypes of active tetrahedron and icosahedron, and their control systems were designed and developed. They worked successfully as active link mechanisms.
- A driver program connecting the active tetrahedron system and a commercialized kinematical analysis software, VisualNastran4D was developed. The system worked well and a potential of the developed tetrahedron to be applied as an interface for commercial software was shown experimentally.
- An intelligent pneumatic cylinder was newly developed for the active icosahedron. The cylinder had a micro optical encoder in its inside and realized a servo mechanism very easily with a simple and compact mechanisms. This cylinder was an essential actuator for the active icosahedron.
- The driver program for the active icosahedron was developed. The program had a virtual model in it and controlled the active icosahedron and the virtual model to work them in the same way. Changing physical parameters of the virtual model made operators feel the mechanical properties such as shape, viscosity and stiffness.
- Applying the active icosahedron to virtual clay showed that the system works successfully and the operator feels as if he/she touched the virtual clay.

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